Efficient soil water use: the key to sustainable crop production in dry areas

OSWU

SWNMP - The Soil, Water and Nutrient Management Program

International Center for Agricultural Research in the Dry Areas
International Crops Research Institute for the Semi-Arid Tropics

About OSWU

The Optimizing Soil Water Use (OSWU) Consortium is a constituent of the CGIAR System-wide Soil, Water, and Nutrient Management Program (SWNMP). The overall goal of the consortium is sustainable and profitable agricultural production in dry areas based upon the optimal use of the available water. The consortium is convened by ICARDA, ICRISAT, and by IER of Mali as a NARS partner. Its member countries include Burkina Faso, Egypt, Iran, Jordan, Kenya, Mali, Morocco, Niger, South Africa, Syria, Turkey, and Zimbabwe.

Considering the rapidly-growing population in the arid and semi-arid regions with erratic and variable rainfall, and the limited possibilities of increasing the cultivated area, the agricultural priority across all the dry-area farming systems in Sub-Saharan Africa (SSA) and West Asia and North Africa (WANA) is to increase the biological and economic yield per unit of water. The actual water-use efficiency in current farming systems in the drought-prone countries of WANA and SSA is often low. The consortium, therefore, aims at developing and disseminating effective and practicable solutions for resource-poor farmers, adapted to local biophysical and socioeconomic conditions, being aware of the uncertainties of applying the classical principles of soil-crop-water relations in rainfed and marginal environments. A holistic approach considering the entire production system and socioeconomic environment will help increase production in a sustainable way and minimize the risk of crop failure for farmers in the dry areas of SSA and WANA.

Partnership is the key word in the consortium's approach towards achieving its goal: the national agricultural research systems (NARSs), international agricultural research centers (IARCs), non-governmental organizations (NGOs), and advanced research organizations (AROs) are partners in one program. Further, the participation of local (farming) communities together with research and extension teams allows the total incorporation of their perceptions of the problems, their indigenous knowledge, and their production objectives and priorities, with a view to developing and testing the potential improvements together. By bringing together researchers and farmers from different environments, the OSWU Consortium promotes a fruitful exchange of ideas, experiences and, most importantly practical techniques to combat the effects of water scarcity, and to sustainably improve production, security, and livelihood of the farmers in the dry areas of WANA and SSA.

The OSWU Consortium organized two workshops to assess the state-of-the-art research in the domain of optimizing soil water use in its 12 member countries, and to make a preliminary assessment of the impact of that research. The results of these workshops, presented here, provide a broad overview on research, results, and impact in the field of optimizing soil water use under different environments, and help in sharpening the focus of the consortium and the prioritization of future research activities.

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Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia, and North and Sub-Saharan Africa

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Mots-cles

Utilisation de l'eau du sol, efficacite de l'utilisation de l'eau, gestion eau-sol-plante, gestion integree des bassins versants, bilan de l'eau, evapotranspiration, evaporation, transpiration, infiltration, ruissellement, drainage, approvisionnement de l'eau, collecte de l'eau, irrigation complementaire, conservation de l'eau et du sol, mesures anti-erosives, amendement de sol, labour, agriculture pluviale, durabilite, risque, strat6gie culturale, jachere, culture continue, ble, lentilles, mais, mil, orge, pois d'Angole, sorgho, vesce approche de recherche participative, impact, outils d'information, banques de donnees, modeles de simulation, systemes d'aide a la decision, modeles bio-economiques, methodologies, transfert de technologies terre ferme, regions arides, Burkina Faso, Egypte, Iran, Jordanie, Kenya, Mali, Maroc, Niger, Afrique du Sud, Syrie, Turquie, Zimbabwe.

Contents

Part C. Impact and Information Tools

Part D. Workshop Results

Foreword

Within the next 30 years, the world's population will rise to 7-8 billion, bringing in its wake an urgent need to double the existing levels of world food production. Agenda 21 of the 1992 United Nations Rio Earth Summit makes a specific call for an improved knowledge base for sustainable production, coupled with the ability to make better long-term predictions and build extra scientific capacity with clear research priorities at the national, regional, and global levels. Sustainable agriculture has, therefore, become a key component of production systems all over the world, given the evolution of certain important factors: increasing concern about the degradation of the natural resource base; low commodity prices leading to low-input systems; and an increasing concern about food quality and improving the welfare of the rural life. Sustainable agricultural systems are designed to make optimal use of existing natural resources to produce food and feed which are both nutritious and safe.

International studies estimate that nearly a quarter of the world's agricultural, pasture, and forest land has been degraded in the last 50 years. Soil quality, fertility, and water supplies need to be managed effectively and conserved through husbandry of natural resources and land-improving investments. Effective soil, water, and nutrient management (SWNM) requires action not only at the farm level, but also at the community, watershed, regional, and national levels.

Within the framework of the CGIAR System-wide Initiative on Soil, Water and Nutrient Management (SWNM), four consortia are adopting this approach: managing soil erosion, acid soils, soil nutrients, and soil water. The Optimizing Soil Water Use (OSWU) Consortium is convened by ICARDA and ICRISAT, with the Institut d'Economie Rurale (IER) of Mali as their National Agricultural Research System (NARS) partner. Given the ever-growing populations of the world's arid and semi-arid regions, the erratic and variable rainfall in these regions, and the limited possibilities of increasing the area cultivated, the agricultural priority across all dry-area farming systems in Sub-Saharan Africa (SSA), and West Asia and North Africa (WANA) is to increase the biological and economic yield per unit of water. Actual water-use efficiency in current farming systems in the drought-prone countries of WANA and SSA is often low. Therefore, the challenge is to devise effective and practicable solutions for resource-poor farmers in the context of local biophysical and socioeconomic constraints and of the uncertainties of applying the classical principles of soil-crop-water relations in rainfed and marginal environments. It is only by fostering technologies integrating both improved soil water use and nutrient availability to crops, that production can be increased in a sustainable way and the risk of crop failure minimized for farmers in the dry areas of SSA and WANA.

Within the above-mentioned constraints in both ecoregions, the long-term goal of OSWU is to attain *sustainable and profitable agricultural production in dry areas based upon the optimal use of the available water.* The driving force behind the

OSWU Consortium is partnership through a multi-institutional research approach, in which the national agricultural research systems (NARSs), international agricultural research centers (IARCs), non-governmental organizations (NGOs), advanced research organizations (AROs), local farming communities, and extension personnel work together. In this way, potential improvements can fully incorporate farmers' perceptions of their problems, their indigenous knowledge, and their production objectives and priorities, for development and testing at an early stage.

Due to the diversity of biophysical and socioeconomic conditions, the OSWU Consortium has to deal with a wide range of location-specific agroecological conditions. This requires a variety of interventions adapted to the specific environment to improve water-use efficiency. The OSWU Consortium, by bringing together researchers and farmers from all these different environments, promotes a fruitful exchange of ideas, experience and, most importantly, practical techniques to combat the effects of water scarcity, and to improve the production, security, and livelihood of farmers in the dry areas of SSA and WANA in a sustainable way. This process will be enhanced and stimulated through local research activities, supported by OSWU, to meet local needs and priorities and, as far as possible, to generate complementary expertise among partner countries, including Burkina Faso, Egypt, Iran, Jordan, Kenya, Mali, Morocco, Niger, South Africa, Syria, Turkey, and Zimbabwe.To pursue the above-mentioned objectives, the OSWU Consortium organized two workshops: one in Niamey, Niger, 26-30 April 1998, and the other in Amman, Jordan, 9-13 May 1999, to assess the state-of-art of research in the domain of optimizing soil water use in the 12 member countries, and to make a preliminary assessment of the impact of that research. This volume contains the proceedings of those workshops.

The proceedings provide a wealth of knowledge, and yet point to the need for further research in this domain with a holistic approach. We hope the reader will find the material presented in this publication useful. The OSWU Consortium is open to comments and to collaboration in this effort to reach its goal of using scarce water resources efficiently and effectively for sustainable and profitable agricultural production.

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An Overview of the Optimizing Soil Water Use Consortium and Objectives of the Workshops

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Introduction

It is an alarming reality that within 30 years the world's population will rise to 7-8 billion, and this will demand a doubling of food production. Agenda 21 and the 2020 Vision Initiative (IDRC 1993) have expressed concern regarding the capacity of the available production systems to satisfy the demands of this growing population for food and other agricultural commodities, particularly without accelerating natural resource degradation.

A specific call was made in Agenda 21 to improve the knowledge base for sustainable production, including an ability to improve long-term predictions and build scientific capacity. The Agenda emphasizes the need to determine research priorities at the global, national, and regional levels. Its Chapter 14 calls for a coherent policy framework for sustainable agriculture and rural development (including policy advice).

Land available for expansion of agricultural area is limited to a few parts of South America and Africa, where the production potential has been proven but the current output is marginal due to inherent soil constraints, rapid nutrient depletion, and mismanagement. Production increases from fertile lands have been reported to be declining. Both marginal and fertile lands are currently undergoing varying degrees of degradation (Table 1), including nutrient depletion, soil acidification, soil erosion, and reduction of soil water retention. As a result, water is becoming contaminated and scarce in some areas. The annual basic water requirement for domestic purposes is about 20 m^3 per capita, which is small compared to the minimum of 200 m^3 per capita needed for basic food production in a self-reliance-in-food scenario. In developed countries, annual water need exceeds 1000 m^3 per capita, predominantly determined by industry in contrast with developing countries where it is mainly needed for agriculture (McNeill 1998).

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N. van Duivenbooden, M. Pala, C. Studer and C.L. Bielders (eds). 1999. Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia, and North and Sub-Saharan Africa. Proceedings of the 1998 (Niger) and 1999 (Jordan) workshops of the Optimizing Soil Water Use (OSWU) Consortium. Aleppo, Syria: ICARDA; and Patancheru, India: ICRISAT. pp 1-14.

Table 1. Major pathways of change in rainfed agricultural land use in developing countries and associated degradation problems. (Adapted from Scherr 1999).

Land type	Main changes	On-site soil degradation	Other resource degradation
High-quality rainfed lands	Transition from short fallow to continuous cropping, HYVs, mechanization	* Nutrient depletion * Soil compaction and physical degradation from overcultivation, machinery * Acidification * Removal of natural vegetation, perennials * Soil erosion * Biological degradation (agrochemicals)	* Pesticide pollution * Deforestation of commons
Densely populated marginal lands	Transition from long to short fallows or continuous cropping; cropping in new landscape niches	* Soil erosion * Soil fertility depletion * Removal of natural vegetation, perennials from landscape * Soil compaction, physical degradation from overcultivation * Acidification	* Loss of biodiversity * Watershed degradation
Extensively managed marginal lands	Immigration and land-clearing for low-input agriculture	* Soil erosion from land-clearing * Soil erosion from crop/ livestock production * Soil nutrient depletion * Weed infestation * Biological degradation from topsoil removal	* Deforestation * Loss of biodiversity * Watershed degradation

International studies estimate that nearly a quarter of the world's agricultural, pasture, and forest land has been degraded since the mid 1900s. Application of fertilizers is generally insufficient to reverse the degradation process. Rather, soil quality, fertility, and water supply need to be managed effectively, conserved through husbandry of natural resources, and through land-improving investments. Effective soil, water, and nutrient management (SWNM) requires action not only at the farm level, but also at the community, regional, and national levels (SWNMI 1996).

The Greenland Report (Greenland et al. 1994) and the TAC study on Priorities and Strategies for Soil and Water Aspects of Natural Resource Management Research in the CGIAR (TAC 1995) conclude that to promote more widespread use of sustainable SWNM systems requires a change in the research approach. In past research, there has often been inadequate understanding of the socioeconomic and policy factors influencing land degradation and improvement. Research on SWNM has been fragmented with little coordination at the regional, national, and international levels. Hence, the SWNM Program (SWNMP) is adopting a research approach explicitly designed for impact. Its research principles include:

- use of participatory, community-based research, involving farm families in project development and evaluation;
- a focus on policy and institutional issues which influence farmer and community decisions;
- explicit consideration of equity concerns in research planning and implementation, including gender analysis and gender-specific approaches;
- interdisciplinary research design, implementation, and evaluation, incorporating ecological perspectives;
- a focus on a range of scales from plot to landscape, to achieve a comprehensive understanding of the interaction between people and water in the landscape, including on-site and off-site linkages;
- utilization of the full research and development continuum, linking strategic, applied, and adaptive research, testing and dissemination, based on identified needs and constraints of farmers;
- reliance on both indigenous and innovative scientific knowledge;
- linkage between production increases and natural resource conservation in land-use system development.

These research principles call for a new organizational approach. This approach must first ensure that the whole range of stakeholders, including land-users, community organizations, development actors, extension agents, researchers, and policy-makers, is involved in the generation and promotion of improved land-use practices. Secondly, the approach must generate synergies and efficiencies from the involvement of multiple partners, making use of existing national, regional, and international capacities and their comparative advantages (SWNMI 1996).

Regarding technology development and adoption, Gyiele and Drechsel (1998) concluded that the major problem is the transfer gap. The wealth of information and equipment available worldwide through the many appropriate or intermediate technology networks and organizations is not being fully tapped. Technologies appropriate for small-scale farmers need to be identified and collected widely, under consideration of farmers' indigenous technologies, screened for local suitability, tested under farmers' conditions, and their local manufacture promoted. Their adaptation has to be done in a participatory manner so that the chances of their adoption and their appropriation will be high. Some research for technology development is still necessary where there is a lack of it and also to keep up with the changing conditions.

Four consortia working in priority areas of land degradation are adopting this approach: managing soil erosion, acid soils, soil nutrients, and soil water. In order, they are Managing Soil Erosion (MSE, convened by IBSRAM and PCAARD), Managing Acid Soils (MAS, convened by CIAT and EMBRAPA), Combating Nutrient Depletion Consortium (CNDC, convened by TSBF, IFDC, KARI, and IAR), and Optimizing Soil Water Use Consortium (OSWU, convened by ICARDA, ICRISAX and IER).

Background and Goals of the OSWU Consortium

Problem Identification

Given the ever-growing population in arid and semi-arid regions with their erratic and variable rainfall, and the limited possibilities of increasing the cultivated area, the agricultural priority across all dry-area farming systems in Sub-Saharan Africa (SSA) and West Asia and North Africa (WANA) is to increase biological and economic yield per unit of water. In rainfed fields, improvement can come only from conserving rainwater in the rooting zone of crops (including shrubs and trees), and from managing the field and the crops to use this water more efficiently. Actual water-use efficiency in current farming systems in the drought-prone countries of WANA and SSA is often very low. The challenge is to devise effective and practicable solutions for resource-poor farmers in the context of local biophysical and socioeconomic constraints and of the uncertainties of applying the classical principles of soil-crop-water relations in marginal environments.

One key research and development issue in this context is soil surface management to increase infiltration and decrease runoff and evaporation. Another possibility to optimize crop water use is the manipulation and adaptation of cropping systems. In the arid and semi-arid regions of SSA, the imbalance between high solar radiation and low and unpredictable water supply from rainfall has to be managed in a way to minimize the risk of production failure. Under Mediterranean conditions in WANA, the efficiency tradeoffs between using water immediately and attempting to store it in the soil for the next crop (a function of the type of soil, rainfall pattern, and annual temperature regime) will determine the use of fallow and crop sequences.

In both regions, fertility is also a critical factor. Ways to optimize soil water use in low-input production systems will often be different from those in high-input situations, and soil water research must work in the context of the most practicable options for soil-fertility management in the system it is targeting. Only by fostering technologies integrating both improved soil water use and nutrient availability to crops, can production be increased in a sustainable way and the risk of crop failure minimized for farmers in the dry areas of SSA and WANA.

The development of water-use efficient crop cultivars (with traits such as short duration, drought resistance, plasticity, or winter hardiness) may facilitate better use of limited and irregular rainfall. In many situations, however, major contributions can be anticipated from improved soil, crop, and cropping system management. The challenge is to coordinate land and water management with the use of water and nutrient-efficient cultivars in sustainable cropping systems to increase biological and economic outputs while taking into account the conservation of the natural resource base. To be effective, this challenge must be met primarily by interventions that individual farmers can apply. However, recognizing that such interventions often have wider social and hydrological implications at, e.g., the village or catchment level, they should be developed and utilized within a community and with a multiscale perspective.

Goal, Objective, and Expected Outputs

The long-term goal of OSWU is defined as: ***Sustainable and profitable agricultural production in dry areas based upon the optimal use of available water.***

The overall objective of the project is: The integration of land management techniques that capture and retain rainwater with crop husbandry techniques that maximize productive transpiration and minimize evaporative and drainage losses within water-efficient, productive and sustainable cropping systems, to improve the productivity of cropping systems and welfare of farmers in WANA and SSA.

The key word in the OSWU Consortium is partnership towards the long-term goal; on the one hand, through a multiinstitutional research approach, in which the national agricultural research systems (NARS), international agricultural research centers (IARCs), nongovernmental organizations (NGOs), and advanced research organizations (AROs) are partners in one program; and on the other hand, through the participation of local (farming) communities. Research and extension teams will work in a participatory way with local people, in order to fully incorporate their perceptions of the problems, their indigenous knowledge, and their production objectives and priorities, with a view to develop and test the potential improvements together with them.

To optimize efficiency of use of limited physical and human resources, linkages to ongoing activities will be sought whenever possible. Particular attention will be given to sites already supporting research and development activities on soil and fertility management, crop rotation, water-harvesting and/or supplemental irrigation within existing projects, national and international, within watershed and community contexts.

The general products to be delivered (SWNMI 1996) include:

- Updated knowledge base and problem appraisal for crop water use-efficiency in dry areas;
- Techniques for soil surface management that increase the availability of water to crops through improved interception and infiltration of rainwater;
- Enhanced uptake and use of soil water through improved crops, crop husbandry, and cropping systems;
- Spatial extrapolation of site-specific findings on optimizing soil water use; and
- Enhanced human skills and policy guidelines.

These proceedings relate predominantly to the first output and to increasing the efficiency in the other ones.

Target Agroecological Zones and Production Systems

OSWU focuses on the following two broad agroecological zones and their associated production systems:

WANA: Systems of dryland annual cropping, based mainly on winter cereals (barley and wheat), that occupy most of the arable land between the 150 and 400 mm isohyets, including locally important areas in which rainfall is supplemented with groundwater or surface water.

SSA: Systems of dryland annual cropping, based on summer cereals (barley, wheat, millet, sorghum, and maize) that lie mainly between the 250 and 800 mm isohyets, including systems in which water harvesting is used to concentrate sparse rainfall onto cropped land.

These two agroecological zones have the following biophysical and socioeconomic conditions in common: (1) a low, unreliable, single-season rainfall regime with a large variability in both time and space, requiring particular focus on soil-moisture storage and water-use efficiency; (2) low soil fertility; (3) surface crusting and restricted infiltration; and (4) low purchasing power of farmers (high poverty level).

Other commonalities in the production systems include a predominance of traditional small-farmer enterprises (except South Africa) and a strong interdependence between crop and livestock production (sheep and goats in WANA; cattle, sheep, and goats in SSA), which becomes more important with increasing aridity of the environment. Subsistence farming is widespread; but at the same time commercial production and market opportunities are important in both SSA and WANA, as is the use of animals and, particularly, tractors for tillage (except in West Africa) and local transport.

The production systems differ, however, in the season of rainfall (the main growing season) and thus in the balance between the two basic atmospheric resources for plant growth, solar energy and water. In WANA, precipitation is received during winter and is distributed erratically over a period of approximately six months, characterized for the most part by a relatively low evaporative demand (1-4 mm d^{-1}). In arid and semi-arid SSA, the rainy season is shorter and falls in the summer months with a high evaporative demand (about 10 mm d^{-1}), onset and distribution of rains depending on location in West, East, or southern Africa. This difference between WANA and SSA affects both the nature of the crops that can be grown and the effectiveness of rainfall; to a first approximation, winter rainfall may be almost twice as productive in terms of biomass production as summer rainfall.

There are also differences in the soil characteristics of the two target regions, with important implications for soil water-holding capacity and land management both in terms of physical and chemical aspects. In SSA, soil textures range mainly from sandy to clay, with 1:1 kaolinitic as well as 2:1 montmorillonitic types of clay minerals present. The soils are often acidic (low pH). In WANA, except in the driest desert fringes, soils are usually loams, clay loams or even clays, and the clay minerals are mainly of the 2:1 montmorillonitic (or smectite) type. The soils are often high in calcium carbonate with a high pH, and salinity may be an important problem.

In conclusion, the OSWU Consortium has to deal with five different agroecological zones (Fig. 1) with a wide range of locally specific agricultural conditions. This diversity of biophysical and socioeconomic conditions requires a variety of interventions adapted to the specific environment to improve water-use efficiency. The OSWU Consortium, by bringing together researchers (and farmers) from all these different environments, aims to promote fruitful exchanges of ideas, experiences and, most important, practical techniques to combat the effects of water scarcity, and to sustainably improve production, security, and livelihood of the farmers in dry areas of WANA and SSA. This process will be enhanced and stimulated through a set of local research activities, supported by OSWU, to meet local needs and priorities and, as far as possible, to generate complementary expertise among partner countries.

The predominant focus of OSWU will be on rainfed farming, and to a lesser extent also on cropping systems using supplemental irrigation, which have many important issues related to water-use efficiency in common with rainfed farming systems.

Definition of Water-Use Efficiency

The definition of the term water-use efficiency (WUE) is not strictly standardized and varies according to the purpose for which it is used. In addition, it can be defined on different spatial and temporal (daily, weekly, seasonal, yearly) scales. Regarding spatial scales, it can be defined, for instance on:

- the watershed scale, as the ratio of the amount of biomass produced to the amount of water flowing into this watershed (precipitation) minus the amount of water flowing out [kg biomass per m^3 water or kg per mm];
- the farm scale, as the ratio of the economic value of the produce to the amount of water consumed by the crop (US$ per m^3 water);
- the field scale, as the ratio of the amount of biomass produced (total dry matter, grain yield, tuber yield, etc.) to the amount of water evapotranspired (i.e., transpiration by crop and evaporation from soil) [kg biomass per mm water evapotranspired].
- the individual plant scale, as the ratio of the amount of biomass produced to the amount of water transpired by the plant (kg biomass per mm water transpired).
- the leaf scale, as the ratio of the photosynthesis per unit leaf area to transpiration per unit leaf area [g CO_2 assimilated per mm water transpired per unit leaf area] (Cooper et al. 1983, 1987; Sinclair et al. 1984; Gregory 1991; Jones 1992).

Hence, whenever possible, WUE should be replaced with more specific definitions such as precipitation-use efficiency (PUE), irrigation-use efficiency, transpiration-use efficiency, etc. This is particularly important if WUE is not equal to yield over evapotranspiration.

Another difficulty in using WUE is that quite often incorrect assumptions are made in the calculations e.g., evapotranspiration (ET), leading to erroneous and misleading values of WUE. An example is ET being estimated from the difference

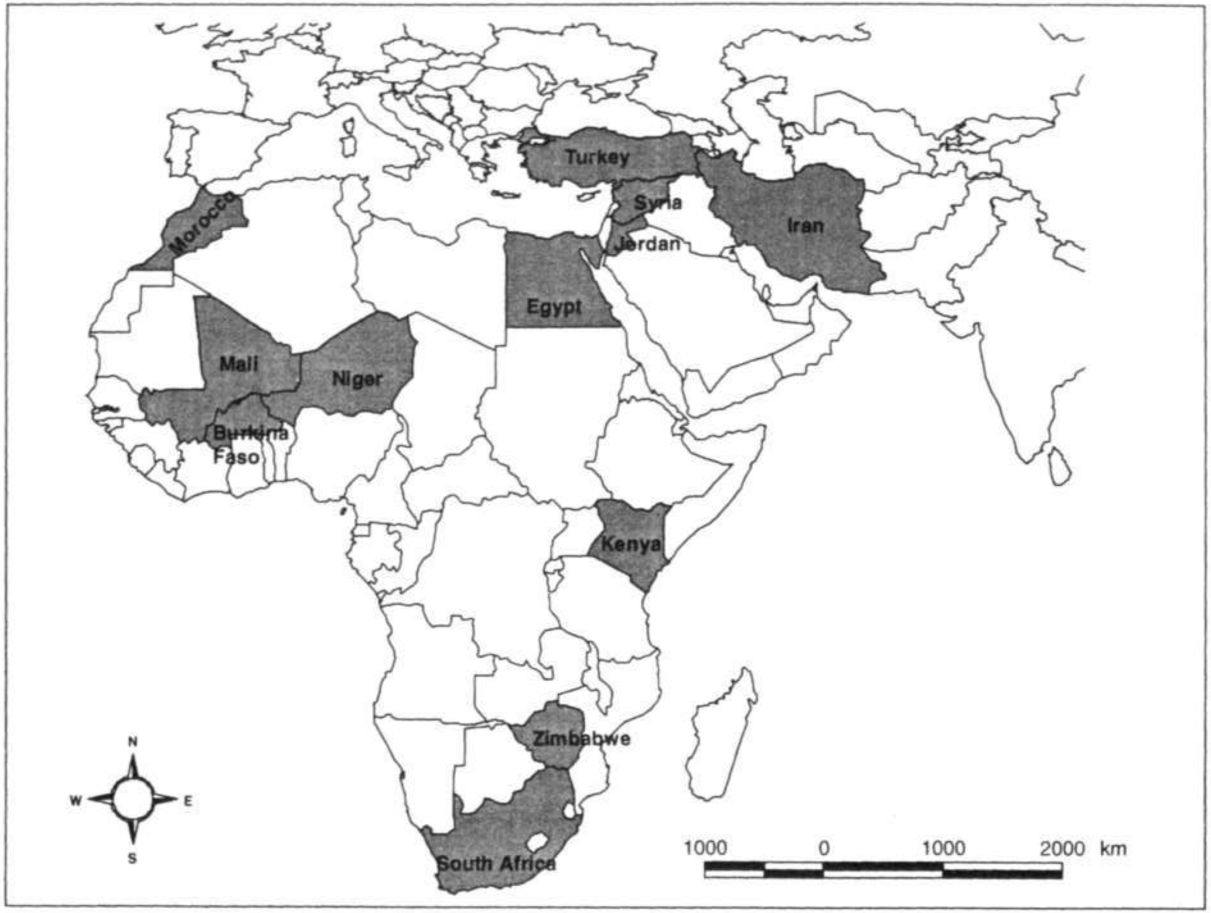


Figure 1. Map showing OSWU countries.

between precipitation and change in soil water stock, in which losses such as deep drainage (on sandy soils) and runoff (on slopes) are neglected. Therefore, the calculation of WUE should be clearly explained.

In these proceedings, the meaning of WUE may vary from paper to paper according to the prevailing norms and procedures used in different countries and the origin of the data. Consequently, the reader attempting to compare results obtained in different countries is advised to check carefully that the same definitions of WUE have been used, that the procedure used for estimating transpiration (T) or ET are comparable, and that the calculations have been applied on the same temporal and spatial scales.

Evolution of the OSWU Consortium

The first OSWU activity, funded by the SWNM Initiative (SWNMI), was a planning workshop at the ICARDA headquarters in Syria in February 1996. Eleven countries from WANA and SSA as well as from ICRISAT Sahelian Center and ICARDA were represented. The research proposal generated by this meeting was reviewed by the steering committee of SWNMI and incorporated in the full SWNMI proposal submitted in March 1996 to the Technical Advisory Committee (TAC) of the CGIAR (SWNMI 1996), and subsequently approved. Following a delay occasioned by uncertainties over funding, and departure of initiators from ICRISAT and ICARDA, OSWU was revived by ICRISAT and ICARDA in January 1997. Today, OSWU includes the following countries: Burkina Faso, Egypt, Iran, Jordan, Kenya, Mali, Morocco, Niger, South Africa, Syria, Turkey, and Zimbabwe (Fig. 1).

The next OSWU activity was the OSWU Steering Committee meeting in Morocco in May 1997. It made two decisions:

1. To utilize existing consortium funds (obtained through the SWNM Program) to: (i) commission at the national level full-scale review reports of past research on soil water and related issues and also the impact of that research on farm-level practices; and (ii) hold a workshop early in 1998 on the outcome of these studies to define the state-of-the-art in soil water studies in the dry areas of the WANA and SSA and set priorities on the basis of these outcomes before initiating new field studies.
2. To seek substantial additional funding to enable new field studies and associated support activities, to be conducted at the national level among consortium members.

Although no funds were made available to the NARS out of available OSWU funds, the NARS continued research that fits within the overall goal and objective of OSWU. The outputs of that work were included in the national review papers.

Furthermore, OSWU was represented during the World Soil Congress in Montpellier, France (Jones et al. 1998), and contributed financially to the organization of a training workshop in the use of the WOCAT database at ICRISAT, Niger.

Finally, OSWU organized two workshops (1998 and 1999), of which this publication is one of the results.

Objectives of the Workshops

Workshop on National Review of Past Research (1998)

The topic of efficient use of soil water by crops is somewhat controversial. Some experts claim that the general principles of cropping for efficient water utilization are well understood, that improvements at the local level depend only upon applying the known principles correctly, and that no new basic research is needed. Many agronomists working in water-deficient environments are not convinced that this is true; they perceive a large gap between textbook wisdom and farm-level realities. Nevertheless, the difference between the potential afforded by the rainfall and the actual dry-area yields is often poorly quantified, as is the extent to which this difference is directly attributable to inefficiencies in soil water utilization. Furthermore, some authorities insist that the management of soil water should not be studied in isolation but in the wider context of catchment hydrology, to include the phenomena of runon, runoff, and deep percolation.

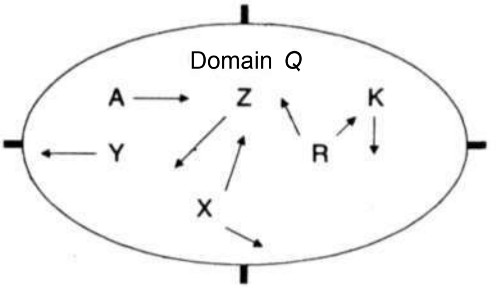
This broad controversial topic forms the subject matter of the OSWU Consortium, and subsequently forces OSWU to be sure to base its proposed future research on a firm knowledge basis—what is known and not known, and what are the real yield-limiting problems that need to be solved in water-deficient production systems. For this purpose, it is essential to review, at the national and regional levels, past and present experience relating to crop use of soil water.

The 1998 OSWU Workshop held at ICRISAT Sahelian Center, Sadore, Niger was conducted in this context to:

- find ways and means of demonstrating the greatest possible coherence and complementarity in OSWU's project goals and objectives, and redistillate outputs and activities;
- place greater justification and clearer targeting of activities on the basis of the needs and strengths of each member country (detailed current knowledge and knowledge gaps, and identified priority areas for action as distilled from the national review papers) with input from invited external soil water specialists;
- clarify the Consortium's knowledge base and priority areas, and identify the complementarities and synergisms across countries and regions;
- emphasize the linkages with other SWNMP consortia, the Desert Margins Program in Sub-Saharan Africa and the On-farm Water Husbandry Program in WANA;
- improve the Consortium's chances of attracting sufficient funding to support an integrated program of field research across all participating countries; and
- align the activities in such a way that research efficiency is increased (Fig. 2).

Each OSWU member country was asked to present a review of past and current research on soil water-use efficiency and ways to improve it in low-rainfall dryland production systems. Being aware that it *is* hardly possible to fully cover all systems or all the literature (from old reports to new publications), it was recognized that the

With 'individual' goals in the same domain Q, but without alignment/dovetailing:



With common goals and alignment/dovetailing:

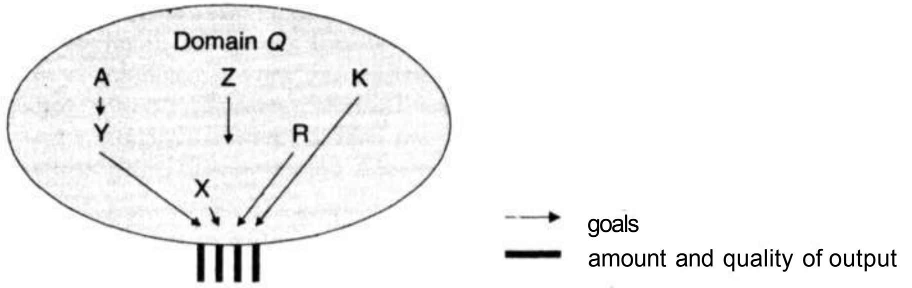


Figure* 2. *Schematic diagram showing the difference in output with and without alignment of goals and dovetailing of activities by institutions represented by a character (van Duivenbooden 1997).

reviews would be selective and that the reviewers would exercise personal judgement. However, the reviews were expected to not only contribute to OSWU objectives, but also to provide an authoritative document of local value to the national research community.

Workshop on Impact and Information Tools (1999)

During the 1998 Workshop and subsequent interactions related to the proceedings among the convenors and member countries, it became clear that the material presented in the national review papers was very valuable, but that one important issue had not been tackled: What was the *impact* of all that work on optimizing soil water use? However, the impact of research on natural resources management (NRM) issues such as water-use efficiency is more difficult to measure than that on commodity improvement, primarily because the NRM technologies are knowledge-intensive and improvements usually occur in small increments (Maglinao 1998).

Nevertheless, the rate of adoption of OSWU technologies could be a measure of this impact.

Three major kinds of impact are considered, i.e., institutional, production, and environmental impact. Institutional impact refers to the effects of new R&D technology on the capacity of research and extension organizations, while production impact focuses on the effect on the farmers. Environmental impact has only received attention recently, but is becoming a good measure of the performance of natural resources management programs. Impact assessment is done not only after the project is completed, but also before and during project implementation. Thus, it is best conceived as an integral dimension of the entire research process, ranging from planning and prioritizing research (ex ante), to monitoring research progress (operational), to appraisal of the ultimate outcomes (ex post) (Maglinao 1998).

Further, it was felt that the OSWU Consortium should make better use of modern information tools available and/or to be developed among the members to better identify and facilitate the transfer (in a participatory way) of technologies to similar agroecological and socioeconomic areas. These observations set the topics and objectives of the 1999 Workshop, which was held in Amman, Jordan:

- Identify and discuss the impact of past and present research in the domain of optimizing soil water use; and
- Illustrate the use of information tools and technologies in the OSWU member countries, and discuss further needs for modern technologies in order to increase efficiency and impact of OSWU-related research.

Each OSWU member country was asked to provide a presentation on these subjects. The impact of pre-OSWU and recent research in the domain of optimizing soil water use on farmers (poverty, food security, income), resources, science, and capacity building of NARS was presented, and future expectations elaborated. With regard to the use of information tools, availability and actual use of databases, GIS facilities, and decision support systems (DSS) was illustrated and evaluated, and future needs and priorities identified.

Structure of These Proceedings

National reviews are presented in Part A, while keynote presentations are given in Part B. Part C contains papers on impact and information tools. Finally, in Part D, the workshops are summarized and the next steps by OSWU are described.

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Part A. National Review Papers

Efficient Soil Water Use in Rainfed Agriculture in Egypt

A T A Moustafa and N M El-Mowelhi[1]

Abstract

Rainfed agriculture in Egypt occupies about 2-3% of the agricultural land. It is mainly concentrated in the North West Coastal Zone (northern area of Matrouh Governorate). Land use is entirely dependent on rainfall, and cultivation depends on various forms of water harvesting. Appropriate water-harvesting methods and soil-conservation techniques are badly needed to optimize soil water use. Watershed management is a pressing need in the area, as there is no experience of it or studies dealing with it. There is a potentiality to double the current barley production, in average and better rainfall years, by improving the barley production technology. Fruit crop production could be increased to 2-3 times the current level through improved plant management such as fertilization, tillage practices, proper pruning, and integrated pest management and through introduction of better varieties. Although this may not appear significant in relation to the total agricultural land, it is important to the local communities and economies. Better management of resources would contribute to the conservation of natural resources and better sustain the livelihood of local communities. The latter are important objectives of Egypt's Environmental Action Plan.

Resume

En Egypte l'agriculture pluviale occupe 2-3% environ des terres agricoles. Elle est surtout concentree dans la zone cotiere Nord-Ouest. Lagriculture est entierement dependante des precipitations et donc des differentes formes de collecte de l'eau. Les methodes appropriees de collecte et des techniques de conservation de l'eau sont necessaires pour optimiser l'utilisation de l'eau du sol. Lamenagement des bassins versants est

1. Soil Water and Environment Research Institute (SWERI), Agricultural Research Centre, 9 EL-Gamaa Street, Giza, Egypt.

N. van Duivenbooden, M. Pala, C. Studer and C.L. Bidders (eds.). 1999. Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia, and North and Sub-Saharan Africa. Proceedings of the 1998 (Niger) and 1999 (Jordan) workshops of the Optimizing Soil Water Use (OSWU) Consortium. Aleppo, Syria: ICARDA; and Patancheru, India: ICRISAT. pp 17-35.

egalement necessaire dans la zone, puisqu'il n'existe pas d'experiences et d'etudes traitant cette gestion. Il est possible de doublet la production actuelle d'orge pendant les annees de pluviometrie moyenne et elevee en amiliorant la technologie de production de cette culture. D'autre part, les cultures, la production fruitiere peut etre doublee ou tripleee grace a une meilleure gestion des cultures, notamment la fertilization, les pratiques de labour, le bon elevage et la lutte integree contre les ennemis des cultures, ainsi que l'introduction de meilleures varietes. Meme si l'agriculture pluviale peut ne pas sembler tres importante par rapport aux superficies cultivees, il est essentiel pour les communaute's et les economies locales. Une meilleure gestion des ressources contribuerait a la conservation des ressources naturelles et permettra de mieux soutenir les moyens d'existences de communautes locales. Ces aspects constituent des objectifs majeurs deu Plan d'Action pour VEnvironnement de l'Egypte.

Introduction

Egypt forms the northeastern corner of Africa and occupies nearly 3% of the total area of that continent. Its territory extends from 22° N to 32° N, with about 25% of the land lying to the south of the Tropic of Cancer. This latitudinal position means that most of Egypt falls within Africa's dry desert region, except a narrow strip of land along the Mediterranean Sea which experiences a Mediterranean type of climate. The country measures 1073 km in length from north to south and 1262 km in width from west to east, with a total area of almost one million km^2 (Ali 1982).

Rainfed agriculture in Egypt is mainly concentrated in the North West Coastal Zone (NWCZ), which has a climate that differs from that of the inland desert area of the south. As a result of the growing population in Egypt, the NWCZ has attracted the attention of many governmental bodies for planning several agricultural and settlement projects. Accordingly, studies dealing with soil, water resources, crop production, livestock production, and other aspects have been initiated in many places along the coast.

In this paper, research and development in the domain of soil water use in rainfed agriculture is reviewed, and topics for future research are identified.

Characterization of the North West Coastal Zone

Location

The NWCZ extends westward about 600 km from Alexandria in the east at longitude 29°50' to El-Salloum on the Libyan border in the west at longitude 25°10' (Fig. 1). It is bounded on the north by the Mediterranean Sea and on the south by the Sahara desert some 50 to 80 km inland. It occupies about 4% of the total area of the country.

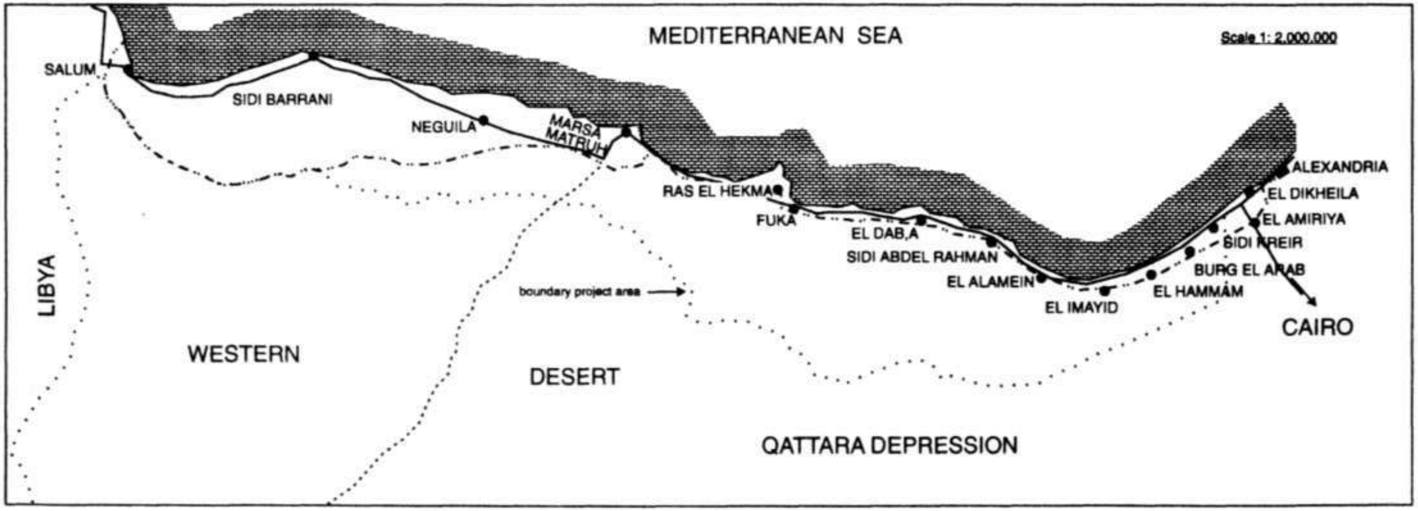

Figure 1. Map of the North West Coastal Zone of Egypt.

The area is composed of one or more parallel ridges of dunes with a narrow elongated plain in between. South of these dunes, windblown soils and alluvial fans deposited by wadis occur. Further south, at varying distances from the coast, rises the rocky Libyan plateau.

Climate

The climate of the area varies from a moderate Mediterranean coastal climate in the north to a desert climate in the south. The average annual rainfall is low; along the coast and inland for about 20 km, it ranges from 100 mm in the west to about 170 mm in the east; beyond 20 km from the coast, it drops to about half that amount. Throughout the area, rainfall is characterized by extreme annual variations.

The rainy season (average of 28 years) begins during the second half of October and by this month the whole of the NWCZ receives at least 10% of its annual precipitation, while 75% of the total amount falls from November to February. December and January are the rainiest months. Some showers still occur in March, but spring in general is dry and receives only 10% of the total amount. Figure 2 shows the distribution of rainfall along the coast, and Table 1 shows the interannual variability.

The mean annual number of rainy days is 32-42 days depending on the location. Rainfall of >5 mm day^{-1} is observed on 4-8 days per year. Rainfall exceeding 10 mm day^{-1} (generally falling with intensity enough to fill the wadis) occurs 3-4 times per year, mainly in December and January.

In both Marsa Matrouh and Sidi Barrani annual rainfall of >250 mm is exceptional. Rainfall of >200 mm occurs about twice in ten years. Dry years receiving < 100 mm occur two or three years in ten. Desert conditions with annual rainfall of < 50 mm prevail about twice in ten years.

Evaporation appears to be fairly constant from year to year and amounts to about 1500 mm. The air is humid, with a mean annual relative humidity at noon of about 55% and mean annual saturation deficit at noon about 10 mm Hg. The area is characterized by a high relative duration of sunshine 80% for the year. The winds blow mostly from the northwest at a speed of 4-5 m s^{-1}.

The climate, whose hot summers tempered by the prevailing northwesterly winds coming from the sea and very mild winters make it favorable for plant growth and animal development, has the disadvantage of seasonal gale-force winds and

Table 1. Interannual variability of rainfall at three climate stations in the North West Coastal Zone (WB 1993).

Station	Number of years of observation	Annual average (mm)	Interannual variability
Marsa Matrouh	40	145	67
Sidi Barrani	35	148	57
El-Salloum	38	106	72

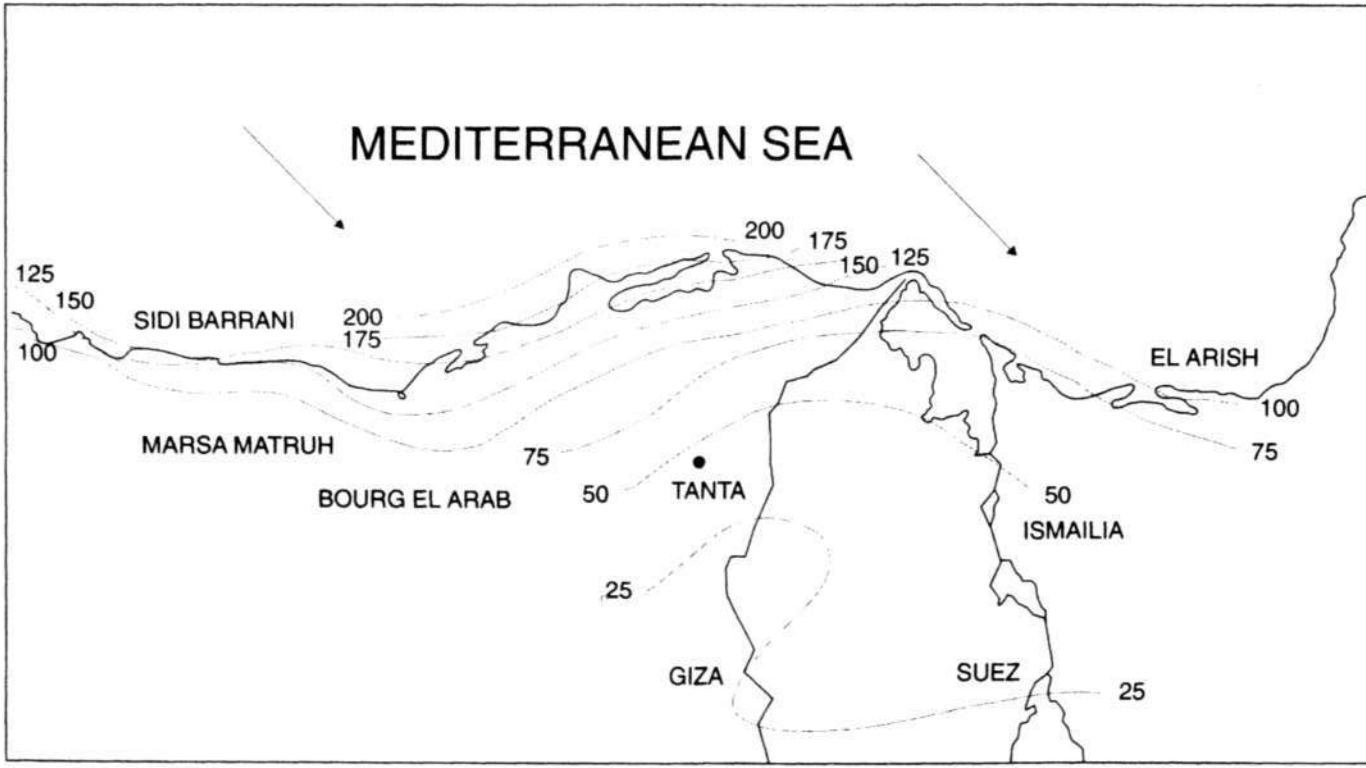

Figure 2. Rainfall isohyets in the North West Coastal Zone.

sandstorms. This climate, however, gradually changes as one moves to the south; at about 40-50 km inland, it merges into the Mediterranean Saharan climate.

Topography and Morphology

Pavlov (1962) and La Mareaux and Hyde (1966) describe the topography of the NWCZ. The region is bounded in the north by the Mediterranean Sea and in the south by an escarpment of 200 m elevation. The region consists of a narrow, almost uninterrupted, band of coastal and inland sand dunes and interdunal plains. Further inland there is an alluvial plain that slopes gradually upward to the Libyan plateau. Numerous wadis formed by runoff water from the northward sloping plateau and eroded escarpment bisect the area. Soil from the plateau and upper slopes of the wadis accumulates in the lower section below the escarpment to form local areas of deep and relatively more fertile soil.

The morphological characteristics of the region are easily distinguished. Along the coast, one or more limestone ridges of consolidated dunes are formed; the first is at shoreline and comprises the present sand dunes. Narrow lows, some of which are marshy, lie between these ridges. Beyond the ridges follows a succession of transitional surface drainage channels up to the escarpment. The general slopes of the region run south to north. There are large land areas of irregular relief from a series of closed depressions surrounded by low hills. These areas are dissected by many intermittent streambeds (wadis) flowing from south to north.

Soils

Soils suitable for agriculture are found in small areas isolated by unsuitable land. Generally, soils are underlain by cliche or rock determining the depth of the soil (Ismail et al. 1976). A few studies have been done for survey and classification of soils in the NWCZ (Abd El-Samie et al. 1957; Harga and Rabie 1974; ASRT 1980). The main factors that were taken into consideration in grouping the soils of the area are (1) depth of profile to the hard rock or water table; (2) some characteristics of profile layers including texture, structure, colour, and stoniness; (3) salinity of the saturated extract; (4) presence and depth of cliche and gypsic horizons; (5) calcium carbonate content; and (6) position and topography. Ismail et al. (1985) estimated the rainfed areas to be 20,700 ha.

As an example of the great variability in these soils, Abd El-Samie et al. (1957) found eight different soil types in an area of 2270 ha scattered and interspersed with each other.

A reconnaissance survey carried out in the coastal zone from Alexandria to Sidi Barrani (UNDP/FAO 1970) covering an area of about 10,000 km^2 identified five mapping units: (1) windblown soils; (2) soils in the former beach plains and dune depressions; (3) soils of the elongated depression in the plateau; (4) soils of the alluvial fans and outwash plains; and (5) soils of the wadis.

Discussing the reliability of using the reconnaissance soil maps, the authors of this study stated that many details couldn't be indicated on such small-scale maps. For instance, small areas were not represented on the map, soil boundaries were generalized, and small differences not indicated. They concluded that these reconnaissance maps could not be used for detailed planning.

In general, the most promising soils are those having a deep sandy loam to loam or clayey loam texture which are found in large areas near Marsa Matrouh and Sidi Barrani and in small pockets scattered over the entire region. The topography is flat and the soils are well-drained. A typical soil profile near Sidi Barrani is as follows: (1) 0-30 cm sandy loam, friable, any roots, many pores; (2) 30-60 cm loam, compact when dry, subangular, blocky, some small and big roots, some pores; and (3) 60-100 cm loam, compact when dry, compactness increasing with depth, some 6mall lime concretions, no roots, and some small pores. These soils are exclusively used for cultivation of barley but are suitable for many other crops (El-Naggar et al. 1988).

The field capacity of these soils is about 12-16%, the wilting point 6-8 %, and the available water 6-8%. Soil pH is in the range of 7.5-8.4. The soils are very poor in organic matter content (< 0.1 % to < 1.00). Calcium carbonate content varies greatly in the area as a whole as well as through the soil profile (from about 20% to >60%). The soils are deficient in available macronutrients (nitrogen and phosphorus) and/or micronutrients (copper, zinc, and manganese) as a result of the high content of calcium carbonate and aridity. Salinity varies greatly from a nonsaline condition to very highly saline (DRI 1988; Moustafa et al. 1991).

Water Resources and Utilization

Water resources in the NWCZ are available in two forms, i.e., surface water and groundwater (Darweesh et al. 1970; Ezzat et al. 1970). Apart from domestic consumption, water is used in limited quantities for irrigation (small quantities of water are used for the fruit trees only during the critical first years of sowing). It is also used, but much more effectively, for animal consumption. Human consumption is estimated at 5 L $person^{-1}$ d^{-1}.

Surface Water

The main source of water is rainfall. Natural watering of land takes place in winter in the depressions, where the topography favors the accumulation of runoff from wadis or the surface runoff from the higher-lying areas, and in the water-spreading zones where the runoff from wadis spreads freely, following the slope and accumulating behind natural obstacles (sand dunes or rocky hills). This natural watering is very uneven, depending mainly on the topography. At the same time there is artificial watering done on a small scale by:

- Constructing dikes to prevent the flow of runoff from wadis into the sea.
- Constructing dikes in the spreading zones to divert the runoff of the wadis. In some cases, the opening of small channels through which the runoff water reaches some isolated fields facilitates spreading.

- Constructing traversal stone or earth barrages in the beds of the small wadis to facilitate sedimentation and create terraces which receive abundant runoff from the wadis.
- Constructing small dikes (earth, stone, and/or cemented) parallel to the contour lines to retain the surface runoff.

The five methods of utilizing surface water are:

Flooding. Suggested in the wadis of gently sloping areas that are free from gullies or depressions, and when the runoff from the wadis is relatively important.

Water spreading. Suggested in the wadis of the more steeply sloping areas and when the runoff is not sufficient to submerge the whole beneficiary area.

Terracing. Suggested in the wadis with bank slopes and in cases where there is no land suitable for cultivation downstream of the wadis.

Sheet runoff. In the flat areas where there are no wadis, sheet runoff can be utilized through the construction of water conservation works for immediate use. The main aim of such works is to conduct the sheet runoff into restricted areas of good soil. By reducing the area which receives the sheet runoff, the amount of water available per surface unit is increased.

Storage of sheet runoff in cisterns. Sheet runoff can also be stored in the numerous cisterns existing in the coastal region after they have been cleaned and repaired. A large number of cisterns dating to the Roman period exists in the region. These cisterns were excavated from the rock and their capacity varies from 100 m^3 to 3000 m^3. Some small dikes or ditches are sometimes necessary to lead the sheet runoff into the cisterns. Many new cisterns have been excavated in the last twenty years by the Matrouh Development and Reconstruction Sector with the help of the World Food Program (WFP). This is in addition to the cemented water reservoirs constructed in areas that are not suitable for cistern excavation. The stored water can be used for human and animal consumption and, in some cases, for establishing tree plantations.

Groundwater

Fresh groundwater for agriculture in the NWCZ is generally available along the coast. The present situation of these water sources is as follows:

Dug wells. They are generally one meter in diameter, and lined with limestone to a depth of about 7 m. The depth of water is between 0.50 m and 1.00 m. Water lifting is done by buckets, shadoofs, small pumps or windmills.

Collecting galleries. Groundwater stored in the coastal, sand dunes is exploited through collecting galleries. The most extensive gallery system is in the El-Qasr area, where there are now about 16 km of galleries. Different methods including pipes and open canals have been used for delivery of water to the cultivable areas (over a distance of 1-3 km).

Land Use

In the NWCZ, 10% of the land has been identified as suitable for cultivation. Less than half of this identified area is used for rainfed farming. A land survey carried out by the Ministry of Public Works and Water Resources in 1989 for the Matrouh Governorate showed that there is about 1000 km^2 of land suitable for agriculture. A small fraction of this area (about 5%) is irrigated from cisterns, wells, and reservoirs. The main field crop is barley which suits the environmental conditions and the needs of the Bedouin, but in the last few years there have been some attempts to introduce wheat cultivation in the area. The main tree crops are figs and olives. There are also grapes, almonds, plums, and citrus. In 1992, the major crops occupied around 53,500 ha. Cereals account for about 75% of this area, while orchards account for < 10%. The World Bank (WB 1993) has stated that the potential area for orchards in the entire NWCZ could be 84,000 ha, and for barley 210,000 ha.

Six production systems can be distinguished in the region on the basis of their ecological characteristics (Table 2). Owing to the edaphic nature of the region in

Table 2. Environmental characteristics of the production systems in the North West Coastal Zone (El-Naggar et al. 1988).

System	Distance inland (km)	Main characteristics
Coastal production	0-5	Deltas of the wadis; annual rainfall of 140 mm, good agronomic soils, cultivation of orchards and vegetables. Inhabitants are settled.
Inland production	5-15	Annual rainfall of 100-140 mm, poor soils, livestock (especially sheep and goats) and barley cropping, no reliable water supply. Inhabitants are sedentary.
Livestock/Barley cropping	15-50	Annual rainfall of 50-100 mm, grazing for sheep and goats, some barley ripping. Bedouins are predominant; sedentary and nomadic mixes.
Communal grazing	50-100	Annual rainfall about 50 mm, livestock grazing (especially camels). Nomadic Bedouin tent society.
Severe desert	100-200	Little or no rainfall. Severe desert environment, limited camel grazing. Scarce human habitation.
Oases	> 200	Oasis region (Siwa). Groundwater. A unique environment with an isolated climate.

combination with variability in climate and physiographic features, three production strips can be distinguished: a coastal strip, a mixed production strip, and a rangeland strip.

The NWCZ is distinguished as one phytogeographical region, i.e., the Mediterranean region. This region is one of the richest in Egypt for natural vegetation because of its relatively high rainfall. The natural vegetation includes many species of annuals, mostly herbs and a few grasses, perennial herbs, shrubs, subshrubs, and a few subtrees. These species represent 50% of the total flora of Egypt. The botanical composition is spatially heterogeneous depending on soil fertility, topography, and climatic conditions, but with subshrubs dominating the vegetation (Ayyad and Ghabbour 1977). Grazing of subshrubs extends the growing period of these plants due to the lower water use compared to the nongrazed plants (van Duivenbooden 1993).

There are many shrub types, which are usually removed before sowing. The majority of the fruit farmers remove shrubs from their fields manually with axes. Sometimes, the shrubs are left in the fields to serve as protective shelters for the young trees against livestock browsing and sand accumulation, e.g. *Ammophila arenaria* and *Thymelaea hirsuta.* The Bedouins are familiar with the unpalatable shrubs and subtrees and collect them to be used as fuelwood, e.g., El-Mathnan, El-Agram, and El-Onsul. In some areas due to the shortage of fuelwood plants they use the palatable shrubs instead.

Coastal Strip

The coastal strip extends 5-10 km inland from the seashore. Geographically, it is a small strip that includes the beach and the coastal plain. The southern boundary of the coastal plain has ridges running parallel to the sea. These are at a distance of 200 km south of Ras El-Hekma and 3 km south of the town of Marsa Matrouh. West of Marsa Matrouh, the coastal plain is narrow, intermittent, or absent. Between Sidi Barrani and El-Salloum, there is a flat coastal band 2-4 km wide, behind a ridge of dunes about 10 km east of El-Salloum. Trees and vegetables are cultivated with wadi runoff as well as water from sanias, galleries, and some cisterns. The farmers collect runoff for horticultural production.

Mixed Production Strip

The second production strip is located between 10 km and 20 km inland. Rainfall is the main water source here with use of runoff and no lateral movement of water. There are a few nonartesian wells but the farmers consider them as a secondary water supply. This area is comprised of ridges, wadis, and depressions, and is located just behind the ridges of the coastal system. The topography is generally uniform with a gradual slope from south to north. Streambeds (218 wadis) are located here flowing south to north in a hydrographic network of distinct organization with narrow, elongated plains and closed depressions. There are some lands suitable for use of rainfall runoff to improve barley cultivation and horticultural production. Sheep and goats are raised in this strip.

Rangeland Strip

The third production strip is situated between 20 km and 50 km inland. This land system extends southward to the bluffs of the Libyan Plateau and constitutes a major portion of the land area. Within this strip are two subareas: the northern area which is used for grazing of sheep and goats in addition to limited barley cropping, and the interior area which is used for communal grazing of the natural vegetative cover of shrubs, subshrubs, spiny bushes, and low-quality grasses. The area has a gentle to gradual slope in a south-to-north direction. The rainfall varies from 50 mm to 100 mm, which constitutes the main water supply. However, a few wells are used in the area. Soil type influences the distribution and growth of natural plant life, infiltration rate, and water-holding capacity. Access to grazing is governed by a ranking of grazing rights by tribal membership.

Production Systems

Livestock Production Systems

Different species of livestock including sheep, goats, camels, cattle, horses, and donkeys are raised in the area. A survey by the Department of Agriculture in Matrouh Governorate showed a total of about 1,055,000 sheep and 261,000 goats (FAO/UNDP 1985). Sheep and goats are the dominant animal species.

Raising sheep and goats is the main activity of the Bedouins. Skin, wool, goat and camel hair, and manure are additional sources of income. The flocks of sheep and goats are of 40 to 50 heads. Animals graze on natural vegetation during a limited season, which is from November to March, and then they have to be moved eastward to areas with better nutritional prospects. Bedouins are faced with feed shortage problems due to the low carrying capacity of the pastures (van Duivenbooden 1989).

Camels graze on natural vegetation, usually of IOW quality, and the size of the flocks can vary from 15 to 400 heads. Cows are normally mated for the first time when they are four years old and thereafter once every 2-3 years and they calve five times during their productive life up to the age of 20.

Rangelands cover >95% of the total 2.5 million ha of land area in the NWCZ. It has been estimated, in fact, that the present livestock population is three times the carrying capacity of the rangeland (WB 1993).

Horticultural Production Systems

The main orchards grown are olives, figs, and almonds. Fruit trees are usually grown under dry farming conditions. The trees are watered during the first 3-4 years until they are established and then the watering is discontinued. The yield under these conditions is low, almost one-fourth of the irrigated trees in the case of olive. Also, the trees are widely spaced with as few as 20-70 trees ha^{-1} (compared with 500 trees ha^{-1} recommended) in order to make as much use as possible of the rainfall and surface runoff.

In orchards near the coastal sand dunes, where fresh groundwater is available from dug wells and galleries, and in areas surrounding synclinal basing, supplementary irrigation is practised all year round. The current fruit production can be increased by 2-3 times through improved plant management, such as fertilization, tillage practices, proper pruning, and integrated pest management as well as the introduction of improved varieties.

The total acreage under vegetable production varies from year to year and lies in the range of 400-1500 ha depending on the amount of rainfall. The main vegetables produced under dry farming conditions are watermelon, onion, broad beans, and tomato. Other vegetables including mint, garden rocket, radish, parsley, and squash are produced on a small scale under irrigation.

Field Crop Production Systems

In years with good rainfall, it has been estimated that barley occupies about 57,000 ha, but this figure goes down to about 35,000 ha in years with little rainfall. Production of rainfed barley by the Bedouin farmers using traditional methods of land preparation and harvesting (mainly with animal traction and hired labor) originally served a double function: (1) to meet the basic food needs of the Bedouin families, and (2) to meet the need for supplementary feed for their animals (mainly sheep and goats). The yields are about 10% of the irrigated barley yields.

Socioeconomic Characteristics

Eighty percent of the Bedouins engage in livestock production (especially sheep and goats) with cultivation of barley, fruits and vegetables. About 10% to 15% depend on commerce or transport as a source of income. The remainder work for the government or private enterprise. Often sources of income come from both agricultural activities and nonagricultural pursuits.

Although the Bedouin have traditionally been nomadic people, the government's determined policy of encouraging sedentarization has effectively meant that only a negligible proportion of the population is entirely nomadic (without a fixed place of residence to which they return for some time every year). This residual population is among the poorest and most deprived in Egypt. At present, the livelihood of about 75% of the population depends on agriculture (crop and livestock production). The primary economic unit is the extended family household, which averages about 11 persons in the region. There is only a limited role at present for the nuclear family as a separate social unit.

With assistance from the World Food Program as well as the government, the majority of the households in the area now have permanent dwellings. Only a minority of rural households still rely on tents as their only shelter. No nomads are found close to the coastline, but in the southern extremities of the area (beyond the railroad) there are still nomads who keep moving with their flocks and herds in search of seasonal pasture.

Society in this region is regulated mainly by customary laws of the local tribal population evolved in the context of nomadic and seminomadic Bedouins who combine grazing of livestock with dryland barley farming. This law was codified in the 17th century (when the tribes entered the region from Libya), and includes a legal code for moral and civil offenses, rules of order for the tribal judicial process, and a system of legal specialists.

It is estimated that 88% of cultivated holdings in Matrouh Govemorate are still under traditional tenure without legal titles. Individual land ownership is absent in the traditional system. The government's desert laws have allowed individual tribesmen to gain title over land they cultivated according to certain criteria.

There are a number of principles and mutually accepted rules for use of land, water, vegetation, and animals. It is important to note that as nomads the Bedouin did not have free and unrestricted access to pasture. Rather, there were rules to ensure distribution of access rights and conservation of water and pasture.

Land Tenure

Officially, all steppe and desert land in Egypt belongs to the government. In traditional Bedouin practice, land was communally owned. Individuals and households did not hold formal title to land, as recognized by the government. The government recognizes the *de facto* usufruct rights of established tribal territories. The Desert Law 124 of 1958 and Law 100 of 1969 allowed individual tribesmen to gain title over land they cultivated according to certain criteria. Yet, it is estimated that 88 percent of the cultivated holdings in Matrouh Governorate are still under traditional tenure without legal title. Furthermore, Law 17 of 1969 empowered the government to lease or sell state land to companies or individuals for projects considered as being in the national interest.

There have traditionally been struggles over land ownership and water rights among the tribes. Intertribal disputes are now largely under the control of the authorities, and common borders have been agreed upon. Under the traditional system there is no individual land ownership. Those who cultivate the land, or habitually and traditionally use it, have claims to it, but the land is communally owned. Nevertheless, with the exception of areas in the southernmost parts of the region the tribal territory is no longer communally or collectively cultivated by members of the tribe to which the land belongs. Rather, it has been allocated to individual tribesmen in such a way that each landholder knows quite well the boundaries of his share in the tribal area; this is in accordance with the principle 'Wada El-Yad', literally meaning 'putting one's hand on'. With continued use the land becomes virtually owned, in the sense that the claimant has exclusive rights to its use.

Communal Grazing Rights

In Bedouin society, communal land ownership means that the members of each tribe and subtribe have an exclusive right to graze their flocks in the area allocated to their tribe/subtribe. They are forbidden from grazing their animals in the area of another tribe without the latter's express permission. Within the territory of a subtribe there do not appear to be any traditional measures to control the numbers of animals or the way in which the range is grazed. However, grazing lands in the settled zone are increasingly being allocated to individual families.

Water Rights

Each tribe has its own sources of water and it respects the territorial boundaries of other tribes. Generally, water trapped with small dikes and other water harvesting structures is used for agricultural production. Water rights and disputes are subject to tribal laws. In case there is not enough well water to meet a household's domestic and production needs, a household has the right to use the nearest available stored water, regardless of whom it may belong to.

Constraints

The land in the NWCZ is being subjected to degradation as a result of desertification, salinization and/or loss of fertility. Desertification results from the exposure of the region to strong winds especially in late winter and spring, and consequent soil erosion along the coast and inland. This has been augmented by degradation of the natural vegetative cover due to overgrazing, cutting of wild shrubs and trees for fuel, and excessive plowing for cultivation of barley. It has been stated by FAO/UNDP (1985) that desertification is now threatening the potentially cultivable areas in the region. Planting windbreaks is essential to control this situation. Salinization has been observed where groundwater of low quality is used for irrigation. In general, the water of galleries and dug wells contains up to 3000 ppm of dissolved salts when overpumping takes place. In such cases, salt accumulation occurs in the root zone and at the soil surface. Water and soil salinity should be regularly monitored and measures taken to prevent salinization (e.g., leaching). Loss of soil fertility is mainly due to the fact that the Bedouin are not accustomed to using fertilizers. Therefore, the soils are subjected to nutrient depletion without any replenishment. This results in low and/or decreasing crop production. With suitable fertilization (in terms of type, amount, and timing) degradation of soil fertility and consequently degradation of the soil can be controlled.

The absence of the concept of watershed management in the NWCZ results in the loss of both water and soil through water erosion. Detailed studies of the different watersheds including soils, topography, and rainstorms are badly needed to be able to make a proper design regarding the management of each watershed.

Among the other problems related to crop production are land tenure, water rights conflicts, use and management of calcareous soils which prevail in the area, extension service for the Bedouin, and range management and improvement (Moustafa and Hamdi 1988).

Existing Adaptive Research Extension and Training Relevant to Water and Soil Conservation

Governmental organizations; i.e., Ministry of Agriculture & Land Reclamation and the Ministry of Development, New Communities, Housing & Public Utilities have a role in leading the development process in the NWCZ. However, no strong programs have been taken up concerning adaptive research, extension and training relative to water and soil conservation in the area. Such activities have been carried out depending on the availability of funds and experts in conjunction with the international aid programs. There is almost no follow up or support for permanent or long-term activities in these fields due to the lack of funds, plans, and specialized staff. The World Food Program has made a great contribution by training farmers on the techniques of soil and water conservation (WB 1993).

It is worthy of mention that among the objectives of some of the current research activities is optimizing soil water use, even indirectly. These research activities include studies of crop rotation and intercropping; fertilization and fertilizer types and application; supplemental irrigation; water-harvesting techniques and soil surface modification; and suitable crop cultivars. However, some data and information on topics such as soil moisture, rainfall and other agroclimatological data from specific experimental sites is badly needed for proper analysis of these research efforts.

A number of agricultural activities have been undertaken in the Matrouh Governorate by Egyptian and international organizations (UNDP, FAO, WFP), and through bilateral assistance (Germany, the Netherlands, USA). Many studies are available from these activities relating to optimizing soil water use, such as those covering soil and water resources and management. In addition, it has been found that the dry farming techniques of Australian farmers (e.g., construction of earth dams) could be implemented successfully in the area between Fuka and Sidi Barrani. Also much experience has been gained in the areas of development of rehabilitation and construction of cisterns, development of water sources for irrigation and domestic use, and construction of dikes or water-spreading structures in the wadis.

The following projects have been executed in the area.

Matrouh Resource Management Project

The implementation of this project started in 1994. Lessons learned during the implementation of the preceding projects were reflected in the design of this project. The first objective of the project is to implement a program of sustainable natural resource management in order to conserve the water, land, and vegetative resources of the area. The second objective is to alleviate poverty and to improve the quality of life of the local Bedouin population. Special attention will be given to promoting on-farm and off-farm income-generating activities, particularly among women and the rural poor. The underlying strategy is to develop a structure within the traditional tribal system which would serve as an effective mechanism to encourage active participation by the local Bedouin community in the sustainable management of their natural resource base and in alleviating rural poverty. The project is on schedule in executing its activities.

Experimental results from research on improvement of water-use efficiency have indicated that the highest grain and straw yields of barley were obtained by application of the recommended package of practices combined with water harvesting (WH) with dikes. The lowest yields were obtained by farmers using local practices. Barley had the highest water-use efficiency of 1.32 kg grain per m^3 of water under improved WH techniques compared with 0.46 kg grain per m^3 obtained under farmers' practices (Moselhy, personal communication).

Improved varieties of barley (Giza 12 and Giza 125) surpassed the local variety by 71% and 51%, respectively for grain yield showing improved rainwater-use efficiency (Moselhy, personal communication).

On-farm crop rotation studies showed that barley-fallow provided the highest barley yield, but considering the fact of a single crop in two years it can be seen that this system has the lowest rainwater-use efficiency. However, barley yields in barley-legumes rotations were closer to the fallow system, the lowest being under continuous barley production (Moselhy, personal communication). This is similar to what has been found in other parts of the region (Pala et al. 1997).

In another on-farm study, the results indicated that the full package of practices (improved barley variety, two times tillage, and P fertilizer) produced 70-90% more grain compared to farmers' practices on all soil types (Moselhy, personal communication).

World Food Program Projects

The first project started in 1977 and was followed by successive ones. The current project will end by the year 2001. It is being implemented in coordination with the Matrouh Resource Management Project. The project has had an important impact in the area. The assistance is specifically aimed at facilitating sedentarization of the Bedouin population; it includes financing through food-for-work (predominantly as grants) cisterns, dikes, fruit orchards, low-cost housing, and animal sheds.

The returns of the WFP projects, both social and economical, could be summarized in the following: (1) settlement of the nomadic Bedouin; (2) increase in agriculture and livestock production and minimized risk under the harsh conditions of the area; (3) creating a stable society and improving the living standards as well as minimizing poverty; (4) improving the environment through reduction of erosion; and (5) improving the socioeconomic condition of women by training them in rug and blanket weaving and other activities. Many other activities are also supported by the project such as building farm fences and animal sheds, growing fruit trees, training Bedouin girls for rug and blanket weaving, sewing, and cloth making. Recipients of the WFP assistance must pay 25% of the value of the food they receive; this money is used to create funds that are used either to provide loans for agricultural purposes or for financing rural infrastructure and training courses.

The implementation of water storage facilities and water harvesting techniques is aimed at maximization of the use of the water resources available in the area.

The project is helping the local Bedouin population to settle and to stabilize their crop and animal production, thereby insuring the sustainability of the project.

El-Qasr Rural Development Project

This project aims to develop and test new ideas and approaches for rural income generation within a limited area and in a limited time-frame. Agricultural/social activities are the main focus of the project, which attempts, through pilot actions, to look at the constraints and problems in both institutional and technical terms. The project has generally worked through interest-free "credit" and with the co-operatives to reach the Bedouin. Women's development activities have been given a particular emphasis. Other activities include establishment of agrometeorological stations, land-use planning techniques and satellite mapping. So far, the main emphasis has been on testing the technical and social feasibility of interventions (improved cisterns, greenhouses, etc.). Attention is now being directed to financial as well as technical analysis (WB 1993).

FAO/UNDP-Supported Project

This project, focusing on the area east of Marsa Matrouh, aims to increase agricultural productivity through introduction of irrigation, plastic greenhouses, and modern agricultural practices. It also has been carrying out trials on soil and water conservation works in wadis, and on rangeland management (WB 1993).

Research Priorities

The major problem affecting rainfed agricultural production is the paucity of research activities in the areas of water harvesting and soil water conservation as well as agroclimatological data. Studies on the correlation between runoff and rainfall, optimum design for water harvesting measures, crop water requirement, proper isohyet map of the area, etc., are needed for proper soil and water management. Establishment of a network of agroclimatological stations along the coast and inland, a detailed soil survey and some detailed soil studies, e.g., soil moisture characteristics, have to be considered as priority topics.

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Optimizing Soil Water Use in Iran

E Pazira and K Sadeghzadeh[1]

Abstract

Sustainable agriculture is commonly defined as the average level of output over an indefinitely long period without depleting the renewable resources on which it depends. Iran's greatest present and future need is for water to irrigate crops in order to reach self-sufficiency in agriculture, which is one of the nation's priority goals. In this paper several documents pertaining to land and water use at the national level are reviewed. The emphasis is on identifying the urgent needs of the vast dryland areas of the country with respect to climate, and soil, water, and crop management practices. Since efficient use of water and soil is an essential factor for the survival of the increasing population, methods of optimizing utilization of soil and water resources are reviewed. Priorities and suggestions are given for maintaining sustainable levels of their use. The role of supplemental irrigation in increasing yields in arid and semi-arid areas and ways of enhancing soil and water conservation and production measures are discussed.

Resume

L'agriculture durable se defini habituellement comme une productivite moyenne sur une tres longue periode, sans que cela se traduise par un epuisement des ressources renouvelables dont elle dipend. L'Iran actuellement et dans l'avenir a un besoin pressant en eau afin d'irriguer les cultures necessaires a l'autosuffisance agricole, ceci etant l'un de ses objectifs prioritaires. he present document examinera plusieurs aspects de l'utilisation du sol et de l'eau a l'echelle nationale. L'accent sera mis sur l'identification des besoins urgents des vaste zones arides de ce pays en tenant compte notamment du climat et des pratiques de gestion du sol, de l'eau et des cultures. Puisque l'utilisation efficiente de l'eau et du sol constituent un concept cle en ce qui concerne la survie de la population sans cesse croissante, le document examinera les methodes d'optimisation de

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l'utilisation des ressources en eau et en sol. Ce chapitre donne des priorites et fait des propositions pour leur utilisation durable. Cette presentation abordera igalement le role de l'irrigation d'appoint dans l'augmentation des rendements dans les zones arides et semi-arides et les moyens d'ameliorer la conservation de l'eau et du sol et les mesures relatives a la production.

Introduction

Iran is located between 25°N and 40°N latitude and 44°E and 63°E longitude. The natural boundaries are the Caspian Sea in the north, the Persian Gulf and the Gulf of Oman in the south and a few rivers along the northern, western, and eastern borders. The total area of the country is about 165 million ha, out of which 18.5 million ha (11.2%) are used for cultivation. Of this, 14.4 million ha are used for perennial and annual crops (with 6.8 million ha under dryland farming, 5.8 million ha under irrigated farming, and 1.8 million ha under horticultural crops), and the remainder is under annual fallow (BAIS 1997; DSAI 1990).

Biophysical Characterization

Climate and Rainfall

Iran is located in the earth's arid zone and desert belt. The average annual rainfall is only 257 mm. The altitude (ranging from -40 m to 5670 m) and latitude have a pronounced influence on the diversity of the climate. Although most parts of the country can be classified as arid to semi-arid, there is a wide spectrum of climatic conditions. This is illustrated by the spatial variation of annual rainfall (50 mm in the central desert and 1600 mm in Gillan province situated on the southern shore of the Caspian Sea, Fig. 1, Table 1) and the wide range of temperatures from -44°C in Borudjen/Chahar Mahal Bakhtiari province located in the central Zagrus mountains and 56°C along the Persian Gulf coast.

Table 1. Distribution of precipitation in Iran (Massoumi 1984).

Annual precipitation (mm)	Recipient area ('000 km^2)	Proportion (%)
<50	100	6
50-100	285	17
100-200	465	28
200-300	370	23
300-500	280	17
500-1000	130	8
>1000	18	1
Total	1648	100

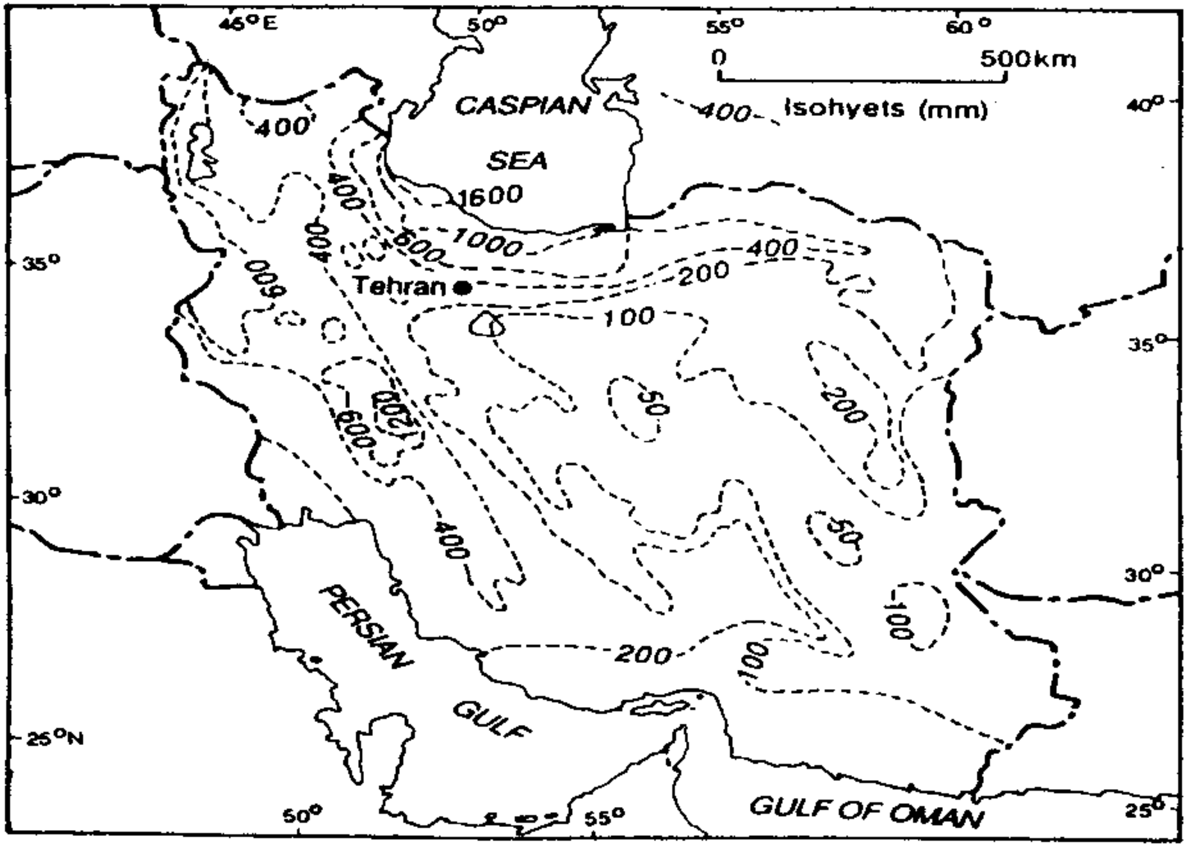

Figure 1. Average annual precipitation in Iran (Ministry of Energy 1976a).

Water Resources and Water Use

Hydrometeorological Information

Iran is divided into six main basins comprising 37 watersheds, each subdivided again into catchment areas. There are 147 catchment areas with 598 identified plains. The hydrological observation network includes 862 hydrometric stations, 428 of them equipped with water and groundwater level recorders. The groundwater observation network consists of over 7500 piezometers where groundwater level fluctuations are observed on a monthly basis. The hydrometeorological observation network in the country includes 912 rain gauges, 274 rain recorders, 448 evaporation class A pans, and 158 snow survey stations. The main characteristics of the main river basins are shown in Table 2 and Fig. 2.

Table 2. Characteristics of the major river basins in Iran during the water year 1988-89 (Ministry of Energy 1990a).

Basin	*Area* ('000 km^2)	*Annual rainfall* (mm)	*Volume of rainfall* (10^9 m^3)	Annua/ runoff (10^9 m^3)
Caspian Sea	177.0	490	86.73	16.40
Persian Gulf and Gulf of Oman	430.0	369	158.67	40.50
Lake Orumieh	52.7	445	23.45	5.75
Central Plateau	831.0	166	137.95	5.55
Lake Hamoun	105.6	110	11.62	2.85
Kara Kum	43.9	243	10.67	0.45
Total	1640.2	-	429.09	71.50

The main source of water in Iran is precipitation (rain or snow), estimated to be about 430 billion m^3 (Water and Development 1998). Of this amount, about 73% is lost to evapotranspiration, 20% is surface runoff, and about 6% percolates down as groundwater. The inflow of surface water to the country is estimated to be about 13 billion m^3, adding to the surface water resources of Iran. Hence, the internal (i.e., the sum of runoff and percolation) and total renewable water resources are 117 billion m^3 and 130 billion m^3, respectively.

Surface Water Resources

Iran's major rivers have their origin either in the Zagrus mountains in the western part of the country or in the Alborz mountains situated in the north, separating the humid lowlands along the Caspian Sea from the hot and dry central desert plateau. Most of the rivers are perennial in their upper watersheds and have very low flows or go dry in their lower watersheds in summer. Because of the importance of storage of surface water, as well as the growing demand for water for urban and industrial purposes, the long-term strategy of the government is to control and regulate the water resources for economical use in agriculture, industry, and urban development

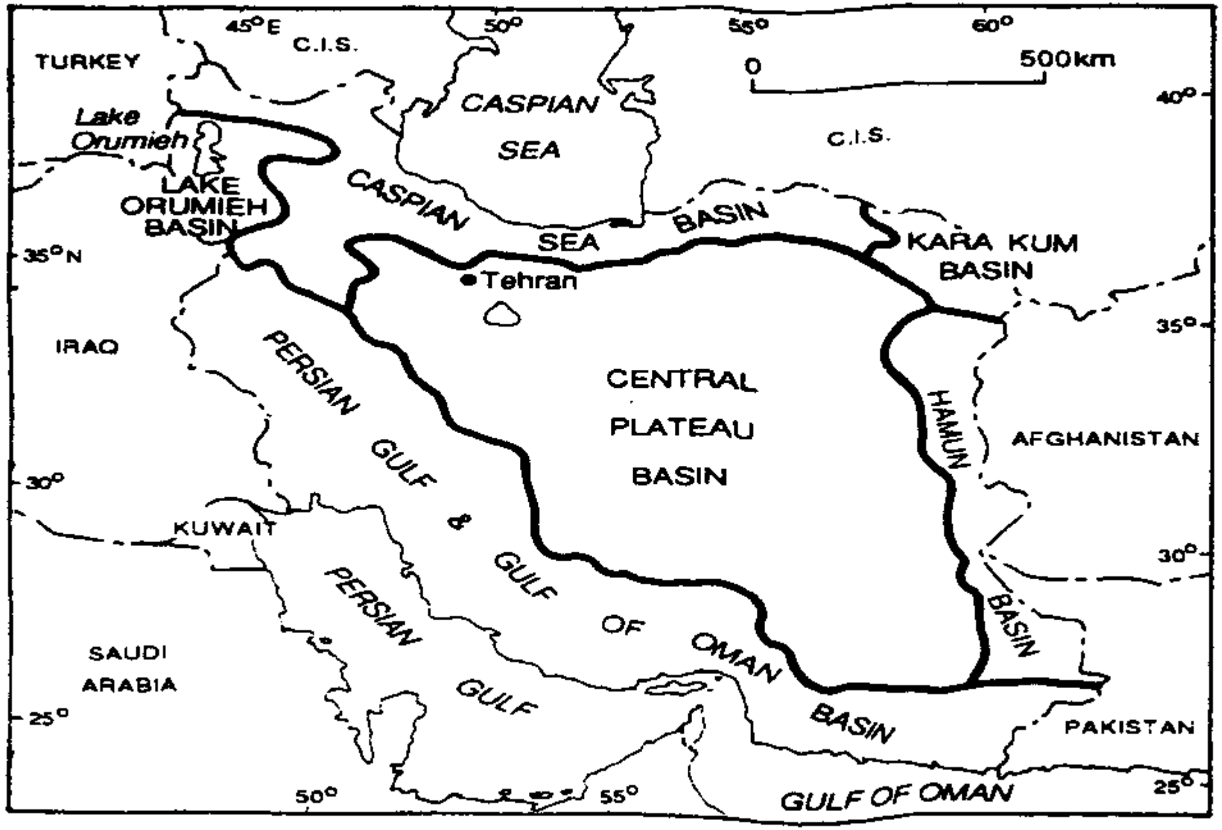

Figure 2. Main river basins in Iran (Ghassemi et al. 1995).

Table 3. Characteristics of dams constructed since 1957 in Iran (INCLD 1990).

Dam	River	Period of construction	Effective capacity (10^6 m^3)	Regulated annual flow (10^6 m^3)	Irrigated area ('000 ha)
Amir Kabir	Karaj	1958-61	195	450	21.0
Dez	Dez	1957-62	2480	6960	93.7
Droudzan	Kor	1966-72	860	640	41.0
Ekbatan	Abshineh	1959-63	5	17	0.2
Esteghlal	Minab	1974-82	271	240	14.0
Golpayegan	Golpayegan	1957-60	40	80	6.6
Kardeh	Kardeh	1978-88	35	32	3.7
Lar	Lar	1974-81	860	416	105.0
Latyan	Jaj-Rud	1963-67	85	220	30.0
Mahabad	Mahabad	1967-70	190	195	31.0
Sefid-Rud	Sefid-Rud	1957-61	1650	2000	250.0
Shahid Abas-pour	Karun	1969-72	1730	9300	43.0
Torogh	Torogh	1978-87	35	13	13.0
Zarrineh-Rud	Zarrineh-Rud	1967-71	480	535	68.0
Zayandeh-Rud	Zayandeh-Rud	1967-79	1090	1208	90.0
Total			10006	22306	810.2

schemes. As a consequence of this policy, 15 large dams have been constructed since 1957 which control more than 22 billion m^3 (Table 3). There are also six large dams under construction which will control 1.8 billion m^3, and 43 dam projects are under study (INCLD 1990).

In addition to the construction of large dams, soil and water conservation practices such as water harvesting are carried out by the Ministry of Agriculture (MA) and the Ministry of Jihad (MJ).

Groundwater Resources

The existence and importance of groundwater as a valuable source of water was known and understood by our ancestors thousands of years ago. The traditional method of groundwater extraction is *Ghanat,* which brings water to the surface by gravity. This method is one of the oldest techniques of groundwater extraction and has its historical roots in the early kingdoms in the northwest of Iran (Bybordi 1974). Although it is said that the groundwater resources of Iran occur mainly in alluvial and karstic limestone aquifers (DTCD 1982; Ministry of Energy 1990b), at present they cannot be assessed in sufficient detail. However, evaluation of hydrometeorological, hydrogeological, and hydrological data indicates that the total annual renewable groundwater volume is about 25 billion m^3 (Water and Development 1998). Evidence indicates that the annual extraction from the aquifers is about twice their annual recharge (Table 4). This has caused noticeable depletion of groundwater resources as well as land subsidence in heavily pumped areas and intrusion of saline water from the sea or internal saline bodies.

Table 4. Groundwater extraction in Iran in 1991 (Statistical Center of Iran 1992).

Means of extraction	Number (10^9 m^3)	Volume of extraction
Deep wells	65448	22.7
Shallow wells	160835	10.1
Ghanats	27210	8.3
Springs	25082	8.4
Total		49.5

Water Balance

The total sustainable renewable resources comprise 105 billion m^3 surface water and 25 billion m^3 underground water. As 33% of the renewable water resources have to remain in the river (e.g. for fishing activities) or ground, 87 billion m^3 is available for other uses: 94% for the agricultural sector, 5% for domestic use, and 1% for mining and industrial purposes (Water and Development 1998). Water for agriculture is used to irrigate annually 7.6 million ha of land, through regulated flow (18%), traditional (80%), and pressurized irrigation systems (2%).

Water use has increased tremendously over the last 15 years: surface water use at an annual rate of 6% and groundwater use at an annual rate of 5%.

Water Resource Management

As a consequence of the low overall irrigation efficiency (ranging from 20% to 35%), the irrigation potential available in the country is far greater than its present use. This is mainly due to the fact that in most cases (permanent flow) allocation of irrigation water at the head works is by far more than the crop water requirement. By reducing conveyance losses through canal lining, and distribution and application losses through improved on-farm water management, a great portion of the water presently applied could be saved. Water economy could also be achieved by allocating irrigation water, on a demand or semidemand basis, according to crop water requirements. More than 50% of the irrigated areas are supplied by groundwater, and in many regions, its exploitation exceeds twice the renewable groundwater resources, leading to an annual decrease of the groundwater level in excess of 1 cm. Where this has happened close to the saline groundwater aquifers (e.g., around lake Orumiyeh or the Caspian Sea shore), the situation has been further aggravated by deterioration of fresh groundwater through intrusion of saline water.

In addition, more than 50% of the aquifers situated in Khorasan, Sistan-va-Baluchestan, Semnan, Kerman, and Esfahan provinces are endangered and may possibly be depleted within the next 50 years if the present trend is not reversed or at least brought to a halt. At the same time soil and water conservation efforts have to be multiplied to control or reverse the continuously increasing rate of erosion and to retain the water *in situ* for enhancing the base flow.

Water Quality

In case surface water passes over salt-containing parent material, it will inevitably carry a certain amount of salts. The salt content of such water may not be so high as to make it unfit for irrigation purposes under a suitable management, but the accumulation of such water in depressions will leave behind salts after evaporation and cause salinity in soils.

Interim surveys and studies of the types of water (Ministry of Energy 1976b) have shown that in the northern part and northwest to southwest of the country, the bicarbonate ion in the groundwater is dominant, having an ECw of 0.25-3.0 dS m^{-1}. These waters, having 180-550 mg L^{-1} of bicarbonate, are usually suitable for irrigation. In the central part towards the north and southeast, waters with various amounts of chloride (1-300 mg L^{-1}) and ECw of 0.80-13.0 dS m^{-1} are common. In a few places in the south, sulfate ion predominates with an ECw ranging from 2.5 dS m^{-1} to 12.0 dS m^{-1}.

Soils

Almost 51 million ha of the land have good to medium suitability for farming. Generally speaking, soils in Iran can be divided into four physiographic zones as related to the river basins given in Fig. 2.

- Plains and valleys (30.5 million ha) with mainly fine or coarse alluvial soil types. About 75% of the total agricultural areas are in the plains, valleys, and plateaus;
- Plateaus (47.0 million ha) with different classes of soils;
- Caspian piedmont (0.35 million ha) where 55% of the total cropped soils are fine-textured alluvial soils and 21% brown forest soils;
- Dissected slopes and mountains (87.15 million ha).

From an agricultural viewpoint, the main limitations of the soils in Iran, in order of importance, are water shortage, salinity, steepness of slopes, coldness, and drought (Anon 1997).

It must be mentioned that agricultural land availability is not a major constraint in the development of Iranian agricultural plans. The major constraint is availability of water for cultivation and development of these lands (Bybordi 1989).

About 23.5 million ha (i.e., 14.2% of the total land) suffer from salinity, sodicity, and waterlogging, or combinations of these problems (Szabolcs 1989). In the arid and semi-arid parts of the country, the main causes of salt accumulation in the soil are poor rainfall, high potential evapotranspiration, topographic conditions creating closed or semiclosed basins, irrigation with low-quality water (surface and groundwater), and inadequate drainage facilities. It may result also from the presence of high amount of salts in the parent material. In areas having such soils, the low amount of yearly precipitation is not effective enough to leach out the salt in the soil profile. As a result, most soils become inherently salty. Another factor that contributes to soil salinization is the low depth of the saline groundwater table. Under these conditions, the capillary rise facilitates the process of salinization if the soil texture is fine, which is predominant in the irrigated projects. In some areas, such as the shores of Orumiyeh, the southern Persian Gulf coastal areas and some parts of the edges of the desert (mainly Dasht-e-Kavir), which formerly were parts of lakes or sea, the soil is initially salty. The removal of salts from these areas by average rainfall is dependent on whether or not the soils are permeable. The causes of waterlogging are seepage and water loss from different sources and irrigation with improper water distribution and management practices.

Management Practices and Research Activities

Irrigation

Iran has a long tradition in irrigation and it is one of the oldest arts practised by Iranians. Archaeologists have found in the earliest records that irrigation in its crudest form was practised in Iran about 3000 BC (Bybordi 1989). The design and execution of modern irrigation projects dates back to the 1950s when the government decided to carry out feasibility studies on constructing dams on the main rivers of the country. Table 3 shows the extent of the irrigated areas downstream of the existing dams. As a part of these projects, some drainage networks have been constructed as well. According to ICID (1977), for an irrigated area of 1.03 million ha, the lengths of the main and secondary irrigation canals were 1352 km and 4287 km, respectively, while the total length of drains was about 6520 km (Ghassemi et al. 1995).

As mentioned earlier, irrigation water is drawn in a variety of ways such as pumps placed directly in or adjacent to the rivers, gravity canals taken directly from the rivers to villages and farms, *Ghanats,* springs, hydroelectric or diversion dams built on rivers, and deep and shallow irrigation wells.

On-farm water application rates are high, but with an irrigation efficiency often below 30% (Bybordi 1989). A major part of the water losses in the agricultural sector is on account of nonlined irrigation canals, but evidence indicates that the most important losses at the farm level occur via evaporation, due to improper irrigation operations (surface irrigation method), and deep percolation to shallow aquifers which leads to waterlogging and salinization. Unfortunately, this trend has been observed in the irrigated areas downstream of almost all the dams in the country. For example, the average annual application rates for major crops are: vegetables 17000 m^3 ha^{-1}, rice 15000 m^3 ha^{-1}, sugar beet 14000 m^3 ha^{-1}, cotton 13000 m^3 ha^{-1}, wheat 5000 m^3 ha^{-1}, and barley 4000 m^3 ha^{-1} (Ghobadian 1990). Bybordi (1989) discussed the inefficiency of irrigation projects and gave some recommendations to improve it. He stated that the main reasons for low irrigation efficiency include improper design of irrigation facilities, poor maintenance, careless operation, negligible water prices, fragmentation of responsibilities among different government agencies, and inadequate knowledge of farmers.

Table 5 presents data on the irrigated and rainfed cultivation area as well as the average yields of different field crops in Iran in the 1991/92 and 1995/96 growing seasons.

Table 5. Total area and average yields of different field crops in the 1991 and 1995 growing seasons.

	1991/92		1995/96	
Cropping pattern	Irrigated	Rainfed	Irrigated	Rainfed
Area ('000 ha)				
Wheat	2317	4321	2264	4063
Barley	693	1392	617	1057
Legumes	269	851	219	1143
Foliage crops	793	129	831	145
Average yield (kg ha^{-1})				
Wheat	2902	800	3038	772
Barley	2460	976	2888	903
Legumes	1160	424	1297	367
Foliage crops	20212	4430	9386	7026

Pressurized Irrigation

Pressurized irrigation (sprinkler or microirrigation) is believed to be the most effective water-saving irrigation method available. It is not so expensive if manufactured locally, but needs higher skill in operation and maintenance. Converting surface irrigation systems into pressurized systems can reduce water use by up to 50%. However, under certain circumstances, switching from surface irrigation to pressurized irrigation implies two important disadvantages: (1) reduced deep percolation (sprinkler) or no noticeable percolation (drip) decreases the amount of water recharging to the aquifer; and (2) salt accumulation (drip irrigation) which in some instances can negatively affect plant growth. Change of technology alone will not guarantee reduction of groundwater use. According to the country's second five-year plan, which started in 1995, the total area under pressurized irrigation by the turn of the century is to be 1.25 million ha. Generally, priority should be given to areas where the annual drop in groundwater level is increasing continuously and where at the same time water shortage limits crop production.

Role of Supplemental Irrigation in Dryland Farming

Considering the type (snow or rainfall), amount, and distribution of precipitation and other climatic factors in dryland areas and their effects on growth of cereals, pulses, oilseeds, and foliage crops, it has been observed that yields of such crops are directly proportional to the amount of precipitation, which indicates a high degree of dependency of yield on precipitation. This underscores the urgent need for application of supplemental irrigation in years of low or limited rainfall. This method has been practised where either surface or groundwater resources are available and easily accessible in spring and summer. Currently, farmers in the medium- to high-rainfall zones use supplemental irrigation for cereals during the growing season but

Table 6. Wheat and barley yields (kg ha^{-1}) under rainfed and supplemental irrigation systems (Siadat 1991).

	Wheat		Barley	
District	Rainfed	Supplemental irrigation	Rainfed	Supplemental irrigation
Maindorood	2500	3500	2750	3500
Agh-ghola	1500	2500	11000	2000
Bola-darband	1800	4000	2000	4000
Mahidasht	1200	1700	1800	2500

not in advance of the production season. From the results of investigations, it is now clear that supplemental irrigation has a significant effect on timely germination and establishment of the crop in autumn and flowering and complete growth of the crop, which could lead to doubling the yield or production in the dryland regions (Keshavarz 1994).

Results of an investigation of the effect of irrigation on rainfed cotton and soybean on the Caspian Sea coast revealed a highly significant response to supplemental irrigation. For soybean, three supplemental irrigations, totaling 95 mm of water, resulted in 80% increase in bean production compared with the yield under rainfed conditions. In the case of cotton, a 145% increase in yield was obtained upon application of 212 mm of water in five supplemental irrigations (Siadat 1991). Table 6 provides the total yield obtained for wheat and barley grown under rainfed and supplemental irrigation systems.

The potential for development and expansion of supplemental irrigation systems cannot be fully realized unless a number of problems are properly dealt with by the authorities. A discussion of the following five problems is needed: (1) economic factors; (2) research and training; (3) fragmentation of land ownership; (4) mechanization factors; and (5) agroecological constraints.

The present low yield of crops under rainfed cultivation and the effectiveness of supplemental irrigation in increasing yields in dryland regions (up to 100% or more), necessitates the strengthening of research and development programs in the dryland areas. In this regard, the main priority should be use of supplemental irrigation by identification, evaluation, and determination of usable water resources, water harvesting, conveyance and storage, suitable methods of irrigation, and utilization of water in the dryland areas.

Watershed Conservation

In most watersheds, the erosion rates have increased due to the fact that the land carrying capacity has been exceeded by about three times. The mandate for watershed conservation is presently allocated to the Ministry of Jihad (MJ). In order to prioritize watershed conservation activities with the aim of sustaining surface water resources used for irrigation purposes, MJ and the Ministry of Agriculture

(MA) must work together much more closely than they have done in the past. The first test of such close cooperation could be the implementation of water harvesting schemes. The MJ would be responsible for the conservation of natural resources within the watersheds of the rivers to be diverted as well as for the conservation of those being part of the alluvial fan, and MA would take part in the development of irrigation schemes. As mentioned before, some activities on soil and water conservation and water harvesting techniques have been designed and executed so far.

Tillage Practices

There is a close integration of livestock raising and arable farming in all parts of Iran. Cereal stubble is used for grazing and in some instances saved for feeding livestock in winter. Grazing of fallow areas for more than two months is common, and for this reason the initial tillage is postponed. Tillage practices in Iran are mechanized. The most common tillage practice in dry farming includes spring plowing of fallow lands with a moldboard plow, followed by discing to break the clods and make a uniform seedbed. Sowing operations consist of estimating the seeding rate and a second discing to cover the seeds. Also, chemical fertilizer is used at the rate of 30 kg N ha^{-1} and 13 kg P ha^{-1} (Shahoei et al.1991).

Phosphorus is used at the time of sowing and a part of N is top-dressed in early spring. Herbicides are not normally used. In recent years, changes in tillage practices during the fallow period have been introduced in farming areas with cold winters, where the primary tillage is done in autumn. When a chisel plow is used, conserving water from snow and early spring rains is the main objective. The land is then harrowed in the spring and again in the following autumn for seedbed preparation. Sowing is carried out with a deep-furrow seed drill.

Rotations

In areas with cool winters and long, hot, and dry summers, the common rotation is wheat-chickpea, and in areas with less than 300 mm rainfall, it is wheat-fallow. In areas with cold winters, the latter is the most common rotation, but in some regions with more precipitation a two-course rotation of wheat-food legume occupies 10-20% of the farms. In regions with cool winters and less extreme summers, like Gorgan in the north, the common rotations are wheat-barley-cotton, wheat-barley-soybean, and wheat-cotton-soybean.

Research and Development Programs and Practices in DARI

The diverse research and development needs of farmers in the dryland regions of Iran are mainly met by the Dryland Agricultural Research Institute (DARI). This institute has 12 research centers in different agroecological regions of the country. Ever since its establishment in 1992, it has concentrated on research activities concerning cereals (wheat, barley), food legumes, and oilseeds. It completed a total of 85 research projects till October 1996. This includes 53 projects on cereals, 23 on pulses, 3 on oilseeds, and 6 on foliage crops. The crop improvement programs of DARI have started yielding good results, and a number of improved varieties of wheat, barley, chickpea, etc. have been released in different regions for general cultivation by farmers. A brief summary of the activities carried out at different research stations of DARI follows.

Cereals

Amongst the various crops grown in the dryland areas, winter cereals wheat (3.14 million t in 1996) and barley (0.95 million t) stand first and second in production. They are cultivated on about 8 million ha under diverse climatic conditions and play a pivotal role in Iranian agriculture. The reported average yield in the dryland areas is low for wheat (772 kg ha^{-1}) and barley (903 kg ha^{-1}) (Table 5). The low yields in rainfed areas are attributed to several biotic (diseases, insects, and weeds), abiotic (thermal, drought, and soil nutrients) and other factors such as improper transfer of research findings and new technologies to farmers, and inadequate number of trained manpower. The following main objectives need to be addressed:

- To develop new varieties/cultivars of wheat and barley with better yield and quality for different dryland regions;
- To investigate the biotic and abiotic stresses depressing the productivity of wheat and barley, and incorporate genetic remittances for the new cultivars;
- To develop an improved package of production practices for adoption by farmers;
- To strengthen the research capability and capacity of researchers in the dryland areas.

Some of the research works already carried out at DARI and its affiliated research stations are: (1) effect of high temperature on the performance of cereals; (2) varietal response of wheat to micronutrients; and (3) growth habit and ecological adaptation of wheat. Research results have shown that yields in farmers' fields can be increased to up to 2-3.5 t ha^{-1} depending on the season (AREEO/ICARDA 1997).

Legumes

Legumes are important in sustainable production of food and feed. Whereas a good deal of research work has been going on for improvement of irrigated food legumes, the work on dryland food legumes has not been as extensive.

Therefore programs have been prepared for development of improved cultivars, and crop production and protection techniques for chickpea, lentil, and important feed legumes in different agroecological conditions. The work plans call for close collaboration among breeders, agronomists, plant production scientists, and those involved in soil and water management. Some of the research topics already carried out at DARI are:

- Introduction of lentil and chickpea germplasm for evaluation under different agroecological conditions;
- Breeding of chickpea and lentil, and cold tolerance for autumn sowing;
- Survey of diseases and insect pests of various chickpea and lentil production areas in the drylands;
- Evaluation of promising annual forage legumes as potential species for fallow replacement in dry areas;
- Determination of suitable dates of sowing, plant densities, and seeding depths in chickpea and lentil for maximum seed yields and different growing conditions; and
- Drought tolerance in chickpea and lentil.

Oilseeds

The per capita consumption of edible oil in Iran is 14 kg and the annual requirement is above 850,000 tons. The consumption demand is rising at the rate of 8-9% annually. The local production is only about 12-15% of the total edible oil consumption. Therefore, a great deal of research work has to be undertaken to raise oilseed production and overcome the financial burden of importing such a huge amount of edible oil from other countries. The total cultivated area under oilseeds in 1995-96 was about 198 000 ha, of which 86% is in irrigated areas and 14% in dryland areas.

The major oilseed crops grown in the dryland areas are sunflower, safflower, and rape seed with sunflower occupying more than 97% of the total area under oilseed cultivation.

The research plan for increasing the production of oilseeds in the dryland areas has the following objectives:

- To develop new sunflower, rape seed, and safflower varieties with better yield and oil content for different dryland regions;
- To investigate the biotic and abiotic stresses influencing the productivity of oilseed crops;
- To develop an improved package of production practices for the farmers.

Following are the titles of some research works already carried out at DARI:

- Development of genetic stock of sunflower for drought-tolerant hybrids and varieties
- The effect of supplemental irrigation and time of irrigation on sunflower seed yield
- Evaluation of sunflower varieties under dry farming conditions
- Yield trial of rape seed with supplemental irrigation for germination.

Conclusions and Recommendations

The water resources of Iran are limited. The average annual rainfall is only 260 mm, whereas the potential evapotranspiration reaches 5 m in some regions. Therefore, sustainable agriculture and food production for the ever-increasing population mainly depends on the efficient use of water. In this regard, the main and long-term strategy of the government is control and regulation of water resources for agriculture, industry, and urban development purposes. As part of this policy, construction of large hydroelectric and diversion dams have been given a high priority in the socioeconomic development plans of the country.

Out of the 87 billion m^3 water available from surface and groundwater sources, about 82 billion m^3 or 94% is allocated to the agricultural sector, which irrigates 7.6 million ha annually. On the other hand, every hectare of irrigated land consumes about 11000 m^3 of irrigation water during the growth season which indicates the ineffectiveness of the on-farm irrigation management practices employed. The main factors that lead to such a low irrigation efficiency include improper design of irrigation facilities, poor maintenance, careless irrigation operations (particularly in surface and traditional irrigation systems), fragmentation of responsibilities among different government agencies, negligible water prices, and inadequate knowledge of farmers. Consequently, the main priority of the Agricultural Research, Education and Extension Organization (AREEO) and related research institutes is to optimize on-farm water-application efficiency.

Out of the 7.6 million ha of irrigated lands in the country, only 2% are under pressurized irrigation systems. Lack of electricity in the agricultural lands, inadequate knowledge of farmers, and the unsuitable quality of irrigation water in most parts of the country have hampered the capability of these systems to optimize irrigation water use. However, widespread research efforts have been initiated in the Iranian Agricultural Engineering Research Institute (IAERI) to examine the possibility of using drip, sprinkler, and pitcher irrigation systems to optimize on-farm water application. Given the fact that about 98% of the irrigated lands are under traditional and surface irrigation systems and that water losses in these methods are basically high, any attempt to improve irrigation water use without considering these systems cannot be successful. Special attention has been given to these methods by the agricultural research authorities.

In Iran, one of the most important approaches to optimizing soil and water use is land leveling and consolidation. In Dez irrigation networks, for example, water-application efficiency is 21% in fragmented blocks, whereas in consolidated lands it reaches about 31%. However, although land consolidation has a high priority in the national agricultural development plans, this idea has encountered serious hurdles. Because the majority of the farmers have less than one hectare of land, land consolidation leads to serious social and cultural problems.

Water quality in several parts of the country, regardless of the origin, is often unsuitable for agricultural purposes. But for thousands of years, crop production has been achieved with salt-affected irrigation water and soil with appropriate management operations. Now in Iran, it is being realized that water is not a commodity for one-time use. Use of waste water and conjunctive use of waters with different qualities is one suitable option to optimize soil and water use in the country.

The total arable land in Iran is estimated to be about 51 million ha, out of which 18.5 million ha is now under cultivation. Therefore, from an agricultural viewpoint, the main restrictive factor on food production is the scarcity of water resources in the country. However, it must be mentioned that human-induced salinization (secondary salinization) as well as water and wind erosion due to overgrazing and deforestation *is* very prevalent. Consequently, sustaining and preserving the productivity of the current agricultural lands is necessary for achieving sustainable agriculture.

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Review of Optimizing Soil Water-Use Research in Jordan

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Abstract

Jordan is dominated by arid climate with 91% of the country receiving less than 200 mm of annual rainfall. Rainfed farming systems depend on a delicate balance between crops, livestock, fruit trees, rangeland, and fallow land. Cultivated rainfed areas cover about 5.5% of the total land (0.5 million ha), and are primarily used for producing field crops (wheat, barley, and summer vegetables). Jordan has suffered from severe water shortage since the 1960s, which limits the development of agricultural production in irrigated and rainfed areas. The rapid population growth (3.4%) exerts great pressure on the limited natural resources; most of these resources are already utilized, and their productivity has started to decline. Agricultural research and extension in the past 45 years has focused on improving the productivity of farming systems in both rainfed and irrigated agricultural lands. To optimize the use of limited rainfall in rainfed agriculture, activities have mainly related to amending crop rotations, tillage practices, fertilizer rates and application, weed control, and to promoting improved varieties, water harvesting techniques, and supplemental irrigation. Past research activities and results in the domain of optimizing soil water use are reviewed, and priority research goals for the future identified.

Resume

he climat dominant en Jordanie est de type aride, avec une pluviometrie annuelle inferieure a 200 mm sur 91% du territoire. Les systemes de production pluviaux sont dependants d'un equilibre delicat entre les cultures, Velevage, la production fruitiere, les paturages et les jacheres. Les zones a cultures pluviales couvrent environ 5.5% du territoire (0.5 millions

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ha), et sont principalement utilises pour la production de grandes cultures (ble, orge et cultures maraxcheres). Depuis les annees soixante, la Jordanie souffre d'un deficit hydrique important qui limite le developpement de la production agricole dans les zones pluviales et irriguees. Une croissance demographique rapide (3.4%) exerce une pression considerable sur les ressources naturelles limitees. La plupart de ces ressources sont deja utilisees, et leur productivite a commence a decroitre. Au cours des 45 dernieres annees, la recherche agronomique et la vulgarisation se sont focalises sur l'amelioration de la productivite des systemes de production dans les zones a cultures pluviales et irriguees. Afin d'optimiser l'utilisation des eaux de pluie en agriculture pluviale, les activites ont principalement ete menees dans le domaine de l'amendement des cultures en rotation, le travail du sol, les doses et modes d'application des engrais, et le contrdle des adventices, ainsi que de la promotion de varietes ameliorees, les techniques de collecte des eaux de ruissellement, et Virrigation d'appoint. Les recherches passees et ses resultats dans le domaine de l'optimisation de l'utilisation de l'eau du sol sont passes en revue, et les objectifs prioritaires de la recherche sont identifies.

Introduction

The total land area of Jordan is about 89,460 km^2, which receives an average rainfall volume of 8.4 billion m^3 annually. Jordan has suffered from severe water shortage since the 1960s, which limits the development of agricultural production in irrigated and rainfed areas. The country's demand for water has grown more rapidly than the development of new sources of water supply. The problem has manifested itself periodically as full-fledged socioeconomic crises when water supply failed to meet the domestic and agricultural demand. Inadequate management and the absence of appropriate water policies have resulted in a failure to generate solutions for water shortages and distribution problems. In addition, water problems have been affected and influenced by hostile natural and external factors. Jordan's water resources have always been scarce, but the most recent growth in demand has led to groundwater extraction beyond replacement and the rationing of municipal and irrigation supplies. Overdrawing of groundwater has resulted in, apart from depletion of a precious source, deterioration of water quality.

The annual deficit of total water resources may increase to nearly 1.2 billion m^3 by the year 2015. Supply increments and severe demand reductions will not be enough to maintain the deficit at its present level. It is imperative to implement a water policy that employs cost-efficient means to narrow the gap between water supply and demand.

Jordan is dominated by an arid climate, with about 91% of the country receiving less than 200 mm of annual rainfall. Approximately 5% of rainwater recharges the groundwater. The predominance of arid conditions coupled with scarce and erratic rainfall are the main factors affecting the availability of water resources.

Cultivated rainfed lands cover about 5.5% of the total area of the country (i.e., 0.5 million ha). These are primarily used for producing wheat, barley, and summer vegetables. The prevailing farming systems have been in practice for more than 2000 years. They are based on a delicate balance between crops, livestock, fruit trees, rangelands, and fallow land. The barley-fallow system dominates the crop production systems in the arid areas, while the wheat-legume and wheat-legume summer crop dominates the farming system in the semi-arid and subhumid regions.

During the last decade, forage legumes were introduced to replace fallow, especially in the semi-arid areas, where fallow covered one-third of the land.

Recent information (WAJ 1996) clearly suggests that the productivity of the natural resources in the semi-arid and arid regions has started to decline. In addition, most of the potential agricultural resources have already been brought under utilization. The rapid population growth (3.4%) exerts enormous pressure on the limited natural resources. These higher demands have caused deterioration of natural resources, and have necessitated the extension of agricultural practices into marginal lands.

Agricultural research and extension activities started in Jordan in 1953. Their main goal is to improve the productivity of farming systems in both rainfed and irrigated agricultural lands. Some of these efforts have succeeded and the results were transferred to farmers. However, tillage practices, new varieties, improved fertilizer rates and application methods, irrigation systems, protected farming system, and Integrated Pest Management have only partially been adopted due to the financial constraints of the farmers and their lack of knowledge because of insufficient extension services.

This paper reviews the past research activities in the domain of optimizing soil water use in Jordan and identifies new research goals for the near future.

Characterization at the National Level

Climate

Jordan's climate is characterized by hot and dry conditions in summer and cool and wet conditions in winter. The rainy season starts in November and extends to the end of March. Maximum rainfall occurs in January and February when evaporation is minimum, resulting in storage of soil moisture during these months. The highest temperature occurs during June, July, and August.

Jordan can be divided into four main agroclimatic regions with distinct rainfall regimes (Table 1). Rainfall varies between 50 mm in the arid regions to about 600 mm in the northwestern mountains. Figure 1 shows the different agroclimatic zones and the rainfall isohyets.

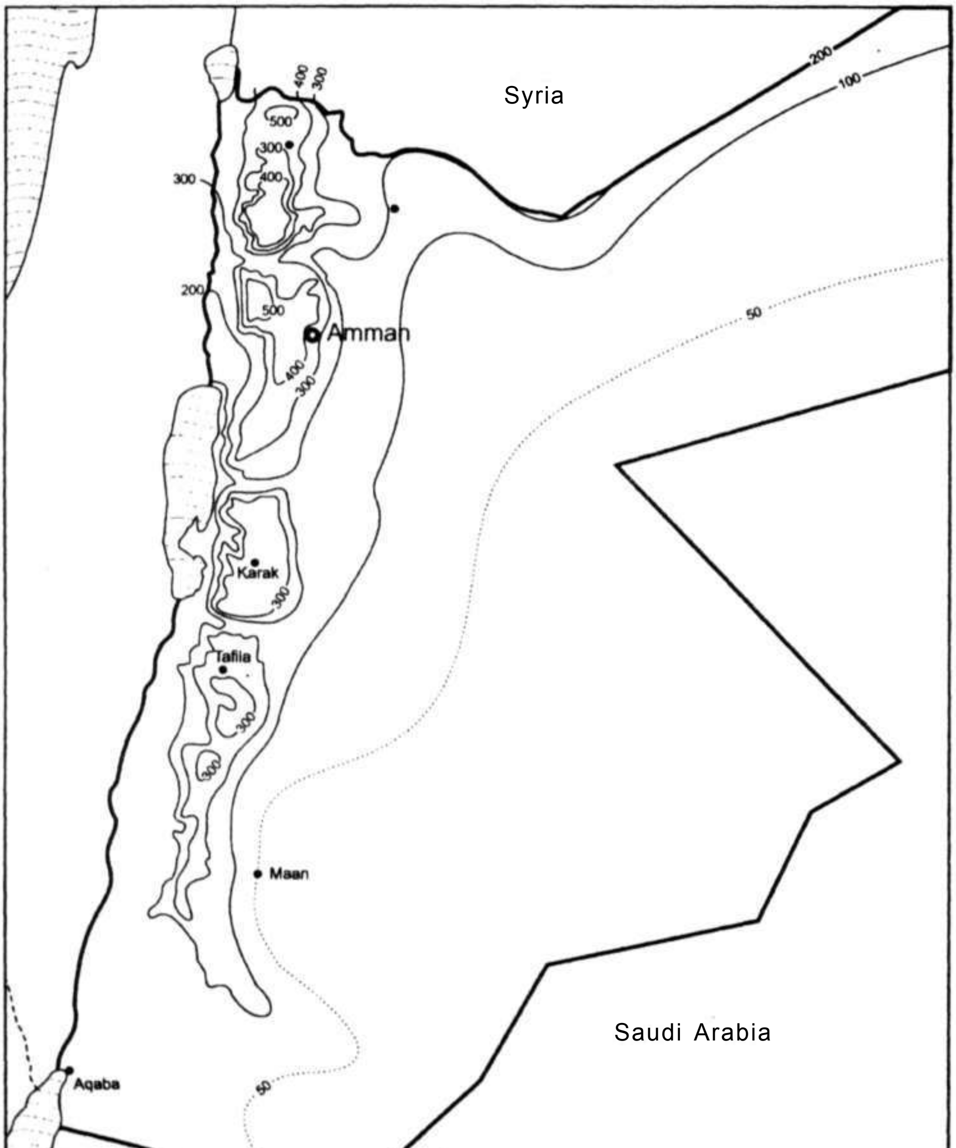

Figure 1. Agroclimatic zones and rainfall isohyets of Jordan.

Table 1. Areas of different climatic regions of Jordan.

Agroclimatic region	Climate	Area (%)	Rainfall (mm)
Jordan Valley	Semi-arid subtropical, arid subtropical	1.1	100-400
Highlands	Mediterranean subhumid, Mediterranean semi-arid	9.0	250-600
Steppe	Mediterranean semi-arid, Mediterranean arid	13.0	100-250
Badia	Arid	76.9	50-100

Water Resources

The average annual rainfall volume in Jordan is 8.4 billion m^3. About 12% of this is available for use from springs, runoff, or as groundwater. The remaining 88% is lost through evaporation or used by crops through transpiration (WAJ 1985). The surface drainage in Jordan is relatively simple and consists of two components: rain falling in the western part of Jordan which drains toward the Jordan Rift Valley, and rain falling in the eastern part of Jordan which drains into desert depressions and the Red Sea. Currently, about 870 million m^3 (MCM) of water are being exploited and utilized by different sectors. Renewable and nonrenewable groundwater resources contribute about 418 MCM, while surface waters contribute about 400 MCM. The remaining 52 MCM come from treated waste water. Figure 2 shows the annual volume of rainfall falling on Jordan from 1987 to 1996.

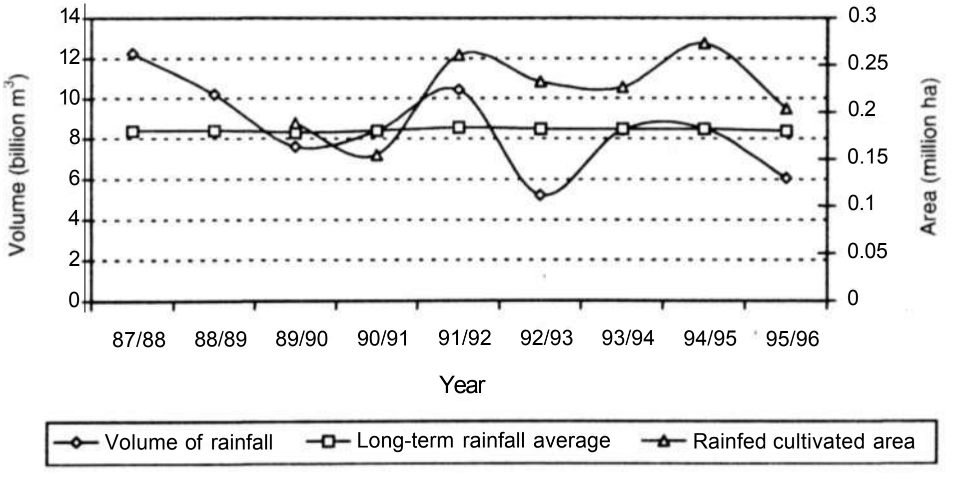

Figure 2. Annual volume of rainfall, long-term average (WAJ 1996), and the rainfed cultivated area (DS 1996).

The permanent water resources available to farmers are distributed over 13 basins. These renewable water resources are estimated at 1.02 billion m^3, divided into (1) groundwater (estimated at 270 MCM and distributed over 13 catchment basins); and (2) surface water (estimated at 750 MCM of which a significant portion comes from outside the country through rivers, e.g. the Yarmouk River coming from Syria).

Currently, the total volume of utilized water is about 920 MCM, about 51% originating from surface water, 29% from renewable groundwater, 14% from nonrenewable groundwater, and 6% from treated wastewater. It is clear that this is not a sustainable situation, and it should be acted upon as soon as possible.

Soil Type

The parent material consists of the following associations of lithological units: Cherty limestone, limestone associated with basalt, marly limestone, dolomitic limestone, sandstone, and granite. These rocks have different mineralogical composition and permeability. Soils that developed from soft marly limestone are calcareous and have a high percentage of coarse rock fragments throughout their profiles. These soils suffer from intensive erosion. Basalt and hard limestone in the high-rainfall zones (northern part of Jordan) produce deep, heavy-textured soils with a moderate to strong structure, and a reddish brown color. In the southern plateau where sandstone and granite are dominanc, soil development is limited and the soils are sandy. In the eastern part of the country, chemical weathering is limited due to low rainfall. The occurrence of subsurface horizons such as calcic, gypsic, and salic is very common (Moorman 1959; NRA 1969).

Land-Use Pattern and Cultivated Area

The cultivated area fluctuates (Fig. 2), but it has in general been increasing in both rainfed and irrigated areas. The area cultivated with cereals, vegetables, and orchards occupied about 67%, 18%, and 15% of the total area, respectively. However, the area cultivated with cereals and vegetables decreased by about 48% and 15%, respectively, during the period from 1980-83 to 1990-93, while the area used for fruit trees increased by 38%.

Rainfed farming systems in Jordan are mainly traditional because of the dominant use of conventional agricultural practices, i.e., heavy reliance on low inputs and fallow crop rotation. Farmers believe that fallow increases soil fertility, reduces weeds, and increases soil moisture storage. Crop rotation is either traditional or improved. The traditional crop rotation consists of 2-3 years of crop rotation after one year of fallow. In the northern region, where the annual rainfall is less than 250 mm, a barley-fallow crop rotation is practised, while in areas with more than 350 mm annual rainfall, cereals and legumes are the primary crops (Table 2). Recently, less area has been sown to legumes because of the nonavailability of suitable combines for harvesting legume crops and the necessity of having to carry out this operation by hand. Examples of a typical traditional crop rotation are wheat-legume (lentil, chickpea, or vetch); fallow-

Table 2. Traditional and recommended crop rotations in different agroclimatic zones.

Climatic zone	Rainfall (mm)	Crop rotation practised by farmers	Recommended rotation
Arid	<200	No crop rotation	No crop rotation
Marginal	250-300	Wheat-fallow, Barley-fallow	Wheat or barley-sown pasture (vetch)
Semi-arid	300-500	Summer crop-wheat, Legume crop-wheat, Fallow-wheat	Wheat-grain legume-summer crop
Semihumid	500-600	Fallow-wheat-summer crop, Legume-wheat-summer crop	Wheat-grain legume-summer crop-horticulture

wheat; and summer crop (summer vegetables, tobacco)-wheat. A three-year crop rotation is practised in areas where the annual rainfall exceeds 400 mm. Examples of such rotations are wheat-legume-summer crop and fallow-wheat-summer crop.

The major factor responsible for the low wheat yield (800 kg ha^{-1}) in the rainfed areas is the lack of an adequate level of available soil moisture for the crop. Total rainfall and its distribution play a major role since other climatic parameters vary slightly from one season to another.

In addition, poor management practices and improper machinery contribute to low productivity. Some of these practices include: (1) poor tillage practices with respect to selection of tillage equipment, plowing times, and operation; (2) poor sowing practices (improper time of sowing and over 90% of the cereal farmers in Jordan still sow by hand broadcasting, the remainder use seed drills); and (3) poor harvesting practices.

Characterization at the Agroclimatic Region Level

Jordan Valley

Climate and Water Resources

Two types of climate dominate this region with the border at Deir Alia. Firstly, north of Deir Alla, the climate is semi-arid subtropical. The annual rainfall varies from 250 mm at Deir Alla to 400 mm in the upper northern part with a hyperthermic temperature regime, while the soil moisture regime is ustic. The rainy season extends from November to March. The mean annual winter and summer temperatures are 14°C and 28°C, respectively.

Secondly, south of Deir Alla, the climate is arid subtropical. The temperature is high in summer and winter with a mean of 17°C and 31°C, respectively. The annual rainfall varies from 250 mm in the upper north to 100 mm near the Dead Sea. The soil temperature regime is hyperthermic where the soil moisture regime is aridic. Frost occurs every few years.

The available water resources of the Jordan Valley in 1996 (314.6 MCM) were composed of 13% groundwater and 87% surface water (WAJ 1996). Due to the lack of information regarding irrigation scheduling available to farmers, excessive water is applied, which reduces the irrigation efficiency.

Soil Types

The distribution of soil types follows the climatic pattern and the dominance of specific sediments. North of Deir Alla, the soils are mainly Inceptisols and Entisols. These recent soils have developed from recent sediments eroded from the surrounding mountains. The soils are very fertile, and their organic content increases toward the north. Soil sediments are low, and higher salinity occurs where transported sediment is mixed with underlying saline lacustrine sediments close to unleveled area.

South of Deir Alla, Entisols with saline phase, Aridisols with saline and gypsic group are the dominant soils. Soils with recent sediments characterized by high gravel content on saline, silty, lacustrine sediment rich with gypsum increase toward the southern part. Fine-textured soils occur only on level topography, which prevails toward the Jordan river. Poor physical and unfavorable chemical properties caused by high salinity and gypsum content characterize the soils of this region (Moorman 1959).

Farming Systems and Management Techniques

Irrigated farming systems are dominant in this agroclimatic zone. The irrigated area is expected to increase from about 32,000 ha in 1995 to 39,000 ha in the year 2000.

Rainfed farming systems comprise less than 13% of the area with the dominant crops being wheat and maize. Supplemental irrigation is practised for most of the rainfed winter crops. The average grain yield for both crops is about 2900 kg ha^{-1}.

Farmers in the irrigated areas use the chisel plow for seedbed preparation or seeding. Sowing is done on furrows in open fields or plastic houses for vegetable production. Fertilizer application through drip irrigation, called fertigation, is widely used. Ammonium sulfate or urea is used as the nitrogen (N) source and di-ammonium phosphate as the source of phosphorus.

Socioeconomic Characteristics

The main socioeconomic problems facing the farmers in the irrigated areas are marketing, small farm sizes, low capital investments, and the low quality of available water, particularly in low-rainfall years.

The Highlands

Climate and Water Resources

This zone has a Mediterranean subhumid and semi-arid climate. Winter (November-March) has cool temperatures, while summer is mild. Relative humidity is high during the winter months, and very low in summer. Minimum relative humidity occurs during June-August. Rainfall varies from 200 mm in the eastern part to 550 mm in the northwestern part (Fig. 1). Thunderstorms or scattered showers occur during March-May. The annual and seasonal variation of rainfall is very high. Occasional frost occurs in the mountainous areas. The temperature regime is thermic, and the moisture regime xeric. Soil moisture storage occurs primarily during January and February, which coincides with minimum evaporation demand.

Ground and surface water are very limited, being estimated at 278.3 MCM and 49.1 MCM in 1996, respectively (WAJ 1996).

Soil Types

This region is dominated by three major soil types, which have in common a major threat of water erosion. Vertisols, very heavy clayey, cracking soils, dominate the flat topography (less than 4% slope) in areas that receive more than 300 mm rainfall. These soils are deep and fertile, but suffer from low organic matter content and unfavorable physical properties. Due to the dominance of flat topography, most of the land is cultivated for crops and orchards. Soil moisture is the primary obstacle to improved management.

Inceptisols occupy areas having slopes of 4-8% and receiving more than 300 mm rainfall, and areas with less steep slopes and 200-300 mm of rainfall. These soils are generally of fine texture, calcareous, deep on level topography, and shallow on steeper slopes. They too are cultivated for crops and orchards. They are low in organic matter and some nutrient deficiencies—mainly of N and P—limit their productivity.

Entisols occupy areas with slopes steeper than 8%. These soils are either shallow to very shallow due to the intensive erosion. They are used for forestry or grazing. Land reclamation through stone clearing in the wetter parts is practised to enable fruit-tree cultivation (Moorman 1959).

Farming Systems and Management Techniques

Two main agricultural farming systems can be found in this region. The irrigated farming system covers about 44,400 ha, i.e., about 15% of the total cultivated area in this zone. The main water source for irrigation is groundwater. The major crops include tomato, watermelon, potato, wheat, and olive and peach trees. The irrigation management efficiency is high (85%) since high-tech irrigation systems (drip and center pivot) are widely used (Jaradat 1988).

The rainfed agricultural farming system covers about 0.2 million ha, but only about 46% of this area has a slope of less than 9% and is suitable for crops and orchards. The

Table 3. Land-use pattern in the rainfed agriculture region of the Jordanian Highlands.

	Area (ha)		Distribution (%)	
Land use	1995	1996	1995	1996
Cereals	176,190	107,380	64.5	52.7
Vegetables	5,260	4,600	1.9	2.3
Fruit trees	91,640	91,740	33.6	45.0
Total	273,090	203,720	100	100

cultivated area mainly depends on the amount and distribution of rainfall, and varies significantly from year to year (Table 3), with associated consequences for production as good or bad weather conditions have been clearly associated with yield variations. Three main commodities are distinguished here: annual crops (wheat, barley, lentil, and chickpea), vegetables (potato, cauliflower, tomatoes, and onion), and fruit trees (olives, grapes, and stone fruits). Annual crops are the most important in terms of area (Table 3). However, the area decreased considerably from 1995 to 1996 (39%). This was caused by (1) The continuous shift in land use from field crops to fruit trees, especially in the highly productive lands, regardless of the rainfall patterns; (2) reduction in the vegetable area due to marketing problems; and (3) the annual fluctuation in the area sown to annual crops according to the seasonal rainfall.

Management techniques in the irrigated farming system in this region are similar to those practised in the Jordan Valley. In rainfed farming systems, six management techniques are used to optimize soil water use: tillage, crop rotation, weed control, fertilizer application, supplemental irrigation, and water harvesting. Except the latter, they will be discussed in detail together with relevant research results in the next section.

Water harvesting techniques (cisterns, hafirs, and earth dams) are mainly related to management of livestock and range improvement. An increasing number of orchard farmers are using such techniques in the rainfed areas (FAO 1995). Water harvesting activities are carried out by the Jordan Highland Development Project. Its objective is to reclaim steep lands suffering from erosion, and to improve the standards of living of farmers by planting fruit trees. Runoff water is used to increase the soil moisture around the trees. Different techniques of soil and water conservation such as rock dams, contour stone lines, trapezoidal lines, and earth contour guidelines have been implemented. The total area covered by such project activities since 1992 is 6,000 ha (FAO 1995).

Socioeconomic Characteristics

Small farms are prevalent in the rainfed areas as the existing laws allow division of land. This reduces the feasibility of using new technologies in these areas, resulting in low productivity of the land. This is considered a major obstacle to the development of rainfed agriculture.

One of the main problems limiting the adoption of new technology in the rainfed areas is the economic status of the farmers. New technology such as tillage, improved seeds, herbicides, fertilizers, and proper machinery have to be available at low cost. The Jordan Cooperative Organization provides farmers with proper machinery, but the scale of its activities is not large enough.

Farmers living in the rainfed area have lower incomes compared with farmers of the irrigated areas due to the fact that the land resources of these areas do not fulfil their biological and economic potential. The farmers' annual average income in the rainfed areas is estimated at 209 JD $person^{-1}$ (300 US$). This is not conducive to saving and investing.

Steppe

Climate and Water Resources

The steppe is characterized by a Mediterranean semi-arid-arid climate with a dry summer. Rainfall occurs during the period from November to March. This zone represents a transition zone between areas with Mediterranean semi-arid and arid climates and receives an average rainfall of 100-250 mm. It occupies about 13% of the total area of Jordan. The moisture and temperature regimes are xeric-aridic and thermic, respectively. Rainfall occurs in sporadic, strong storms which cause intensive erosion. Differences between day and night temperatures are high, and low night temperatures endure for a long time during winter.

Groundwater extraction and water collection behind dams or in cisterns are the only form of water supplies to farmers.

Soil Type

This zone is dominated by fine-textured soils with a high silt content which could reach 40-60% at the surface. The dominant soils are Calcid, Cambids, and Orthids. Calcium carbonate of primary and secondary origin is high in most soils. Soil salinity represents little limitation to plant growth. The soils of this region are highly affected by wind and water erosion and development of surface crusts, which reduces water infiltration and hinders plant emergence. The low nutrient and organic matter content limits soil productivity. In addition, unfavorable physical properties coupled with highly fluctuating climatic conditions foster desertification and other soil degradation processes, negatively affecting the potential for agricultural production.

Farming Systems and Management Techniques

Range management is the dominant farming system in this region. Agricultural development in this area depends on efficient harvesting of rainfall, either directly through on-farm water harvesting or indirectly through watershed harvesting where the water can be used for supplemental irrigation.

Irrigated agriculture expanded rapidly in this region due to the availability of groundwater. The area (about 26,000 ha) is used primarily for cultivation of vegetables and fruit trees, and secondly for forage crops and grazing.

In rainfed agriculture, barley dominates. The area suitable for these rainfed crops is approximately 26,000 ha. A good crop yield is obtained only once every five years.

Management techniques are dependent on the availability of rainfall and moisture storage in the soil profile. In this region, improved agricultural activities can only be carried out by using the harvested water. Different water harvesting techniques, such as cisterns, hafirs, and earth dams have been widely in use for hundreds of years for different purposes.

Future water harvesting schemes should include both on-farm and catchment water harvesting techniques. This should be combined with rangeland development plans to increase the carrying capacity of degraded land. Moreover, water development, control of overgrazing, and combating desertification must be integrated parts of an overall range management plan. In the last decades, five major projects have been carried out in this region related to water harvesting techniques.

- The Zarqa River Basin Project (a part of which is located within the rainfed region) has as its primary objective reduction of the sediment load reaching the King Talal Reservoir, and secondly, conservation of soil by reducing erosion as a mean of improving production. About 3,000 ha have been planted by this project with fruit trees and palatable shrubs (FAO 1995).
- The Balama Project has the objective of harvesting runoff water to improve orchard production. The project has implemented techniques such as contour terraces and ridges used for pasture and range improvement (FAO 1995).
- The Muwaqar Project has a primary objective of improving agricultural production in areas receiving 100-200 mm of annual precipitation and suffering from desertification, through the following activities: (1) development of means to effectively utilize surface water for various agricultural activities; (2) improvement of soil fertility and preservation of soil productivity using local inputs; (3) improvement of natural plant cover by preserving existing species and introducing new varieties adaptable to the local environment; (4) selection and introduction of crops suitable to the local environment; (5) testing of appropriate farming systems for areas suffering from desertification; and (6) determination of the most efficient land use by evaluating the actual potential of agricultural production. The impact zone of the project represents 13% of the total area of Jordan.
- The Project on Improvement of Agriculture Productivity in the Arid and Semi-arid Zone of Jordan aims to contribute to improved use and protection of the steppe and the Badia. The project aims to define criteria for the planning and development of Jordan's arid lands based on the results of trials, surveys, and predictive data. Its activities include (1) modeling of the natural resources of the reference area, particularly of watershed hydrology (runoff forecast, water storage and availability, sedimentation yield, aquifer recharge); (2) rationalizing of water harvesting and transfer; (3) elaboration of appropriate methods of supplementary

irrigation; (4) investigations of soil-climate-plant relationships, soil fertility and soil structure improvement; (5) design of balanced and adequate cropping and grazing systems; (6) introduction of the most valuable range plants and forage crops as well as experimenting with applicable methods for vegetation and grazing to improve forage and subsequently sheep productivity; and (7) application of results in the impact zone of the project by carrying out appropriate demonstrations.

- The Water Harvesting Optimization Modeling Project has the general objective of developing a model to be used in formulating optimal and sustainable strategies for planning, design, layout, and operation of water harvesting schemes in watersheds, and for sustainable use of harvested water to increase crop production and reduce soil erosion. An integrated prediction optimization model for water harvesting, storage, and utilization on the basis of watershed management will integrate the following components: (1) prediction of water runoff over both micro- and macrowatersheds, (2) optimal selection and design of water storage either directly in soil, or in surface reservoirs; and (3) optimal and sustainable utilization and management techniques of stored water.

Socioeconomic Characteristics

This region has been traditionally used for rangeland farming. During the past few decades, its resources were subject to deterioration as well as urban pressure. Due to the fact that local people privately own all land, large-scale range development projects are restricted by property rights issues. Improving the steppe's contribution to the agriculture sector depends on solving the social constraints, and on the introduction of novel water harvesting techniques to overcome the low and erratic distribution of rainfall.

Badia

Climate and Water Resources

This zone is dominated by a Mediterranean arid climate and occupies about 77% of Jordan's area (Table 1). The temperature is high in summer and cool in winter with a high frequency of frost incidence. The relative humidity is very low during summer. Gusty winds blow during all seasons accentuated by the open, flat topography. The annual rainfall is 50-100 mm with extreme annual and seasonal variations. Most of the rainfall occurs as scattered showers. The soil moisture regime is aridic while a thermic temperature regime dominates, except in the low regions where a hyperthermic regime can be found. Vegetation is sparse, with very short grasses and some shrubs along the waterways.

Rainfall is the main water source. Earth dams provide a total storage capacity of 27 MCM. Water is primarily used for livestock consumption. Water wells are abundant and are used for irrigation of orchards. Groundwater basins in this area can be divided into four aquifers with a total storage capacity of 14.730 billion m^3 (WAJ 1996).

Soil Types

Two main soil types occur in this zone. Aridisols occupy a very large area, but suffer from high salt (Salids), calcium carbonate (Calcids), or gypsum (Gypsids), or high silt or gravel content (Haplids). All these soils, except Calcids are problematic and cover large areas.

Entisols occupy steep slopes or mud flats, sandstone-originated soils, or older inactive gravelly and sandy waterways. The last two soils have physical limitations, but are considered promising. Extensive areas are covered with either desert pavement of basalt flow origin on the top of Paleosols, as can be found in the northeastern region, or desert pavement originated from hard cherty limestone, which dominates the middle of the eastern and southern regions. The limestone pavement covers either gypsic or saline or shallow soils. Due to the dominance of aridic conditions and flat topography, wind erosion frequently occurs. Water erosion also occurs, but eroded material is transported and deposited in mud flats, which are small desert playias. Soils of the sandy areas have unstable surfaces. Consequently, they are highly affected by wind activity leading to the formation of local sand dunes threatening agricultural activities (Moorman 1959).

Farming Systems and Management Techniques

Agricultural land suitable for year-round cultivation is limited in this region. Land is primarily used as a range and grazing area. Cultivation of orchards with irrigation from groundwater wells is confined to a limited area. A very small area (waterways having better moisture conditions) is seeded annually with barley for green fodder. Range improvement is only practised by the government within protected reserves.

Water harvesting techniques (cisterns, hafirs, and earth dams) are related to management of livestock and range improvement.

Socioeconomic Characteristics

It is estimated that 200,000 people live in this region, their livelihood depending on livestock. Improvement of range resources could have a positive impact on their lives. Cheap and cost-efficient range development schemes based on various water harvesting techniques should be part of the plans to be implemented in this region.

Evaluation of Research Activities on Rainfed Agriculture

Most of the studies carried out on rainfed agriculture in Jordan have dealt with management techniques to conserve soil moisture and to determine the most appropriate fertilizer rates. Investigations have also been carried out to optimize soil water use and fertilization through optimal agricultural practices, predominantly in the highlands.

In the steppe, most of the research carried out has concentrated on ways to identify the best water harvesting techniques, and to optimize the use of runoff water. A few national projects have dealt with artificial recharge of groundwater. Water harvesting techniques are also used to provide water for animals. Al-Akhras (1996) studied the rainfall-runoff relationship in representative watersheds in the Al-Muwaqar basin. The results suggest that rainfall intensity, crust formation, plant residues, and soil properties are crucial factors in managing the soil in this area (Ziadat 1996). The University of Jordan, through the Muwaqar project, has conducted several studies on application and evaluation of water harvesting techniques under local conditions as well as various means to improve and manage the land.

In the Badia region, most of the efforts have concentrated on (1) rehabilitation of shrubs and fodder plants that serve around 1.2 million sheep and camels; (2) availability of water for animals; and (3) efficiency of water harvesting systems and soil water conservation practices in farmers' fields. Research carried out in the Badia region has been limited due to the scarcity of water resources and the predominance of problematic soils. Activities investigating the use of flood water in range improvement through spreading are currently being undertaken.

Tillage Practices

Two tillage practices are used, i.e., conventional tillage, and conservation and minimum tillage. Moldboard, heavy-disc and chisel plows are among the tools in use since the 1980s. The chisel plow has advantages over the moldboard plow since it requires less draft and leaves more stubble on the soil surface for erosion control.

The conventional tillage practice is characterized by (1) a large number of tillage operations in areas where wheat-fallow rotation is used; farmers feel that more tillage operations and deeper plowing could increase their yield; thus three-four tillage operations during a fallow period of 8-9 months are common in these areas; (2) use of unsuitable tillage equipment such as heavy disc and moldboard plows; and (3) spring plowing for weed control is usually delayed; weeds are often left for grazing by animals until early summer. This tillage system controls weeds effectively, but results in a bare soil surface with few clods, which leaves it highly susceptible to erosion. However, conventional tillage is being gradually replaced by conservation or reduced tillage in the major wheat-growing areas of Jordan.

Conservation and minimum tillage is a system in which the number of field operations is reduced as compared with the number required in a conventional seedbed-preparation system. The advantage of this tillage system in terms of water management is that it enhances soil resistance to wind and water erosion due to high surface roughness, increases the amount of residue and increases water storage (Jaradat 1988).

In both systems, the timing of tillage is very important. Primary tillage is carried out from June to November. Farmers practise fall tillage to disturb and increase the roughness of the soil surface in order to increase infiltration and store more moisture in the soil profile. In areas where farmers do not practice primary tillage, runoff increases by three to four times in comparison with areas where primary tillage is practised (Jaradat 1988).

Table 4. Effect of various fall and spring treatments on moisture-storage efficiency and wheat yield in a wheat-fallow rotation.

Fall treatment	Spring treatment	Moisture-storage efficiency (%)[1]	Wheat yield (kg ha^{-1})
Plowing (October)	Subtillage	25	3090
Subtillage	Subtillage	32	3360

1. Storage efficiency = change in soil moisture content x 100/Total rainfall.

Selection of a spring or fall plowing date depends on a number of factors such as weed control, erosion hazard, soil type, topography, and availability of crop residue. In areas of heavy rainfall, there is a danger of erosion if the soil is loosened by plowing during fall. The crop and the residue on the soil surface may determine the optimum time of plowing. Usually spring tillage, during the fallow period, is performed between March and May. The main purpose is to control weed growth and reduce moisture loss through weed transpiration. The limited available experimental evidence under Jordanian conditions shows that the earlier the tillage, the higher the yield of wheat (Table 4). This yield increase could be attributed to early removal of weeds and lower losses of soil moisture during the summer months. Early postharvest plowing is a common practice in Jordan to control summer weeds and minimize the loss of moisture through cracks, which develop in heavy soils.

Research studies conducted on the use of tillage equipment and crop residue have shown that the chisel plow combined with early or late incorporation of residue retained a significantly higher soil moisture content compared with the moldboard plow combined with early or late incorporation of residue during winter. During the summer, when the soil dries out, the moldboard treatment conserves more water than the chisel (Al-Bakri 1996).

In Vertisols, use of the moldboard plow resulted in significantly higher evapotranspiration and soil moisture depletion than by using the chisel plow (Suleiman 1994). Generally, it was found that tillage operations tend to increase the cracks volume and coefficient of linear extensibility, while decreasing the shrinking characteristics and available moisture. In addition, the chisel with late residue incorporation had significantly lower gravimetric soil surface moisture content and bulk density than the moldboard with immediate residue incorporation. Moreover, there were no significant differences in moisture content between different tillage and residue treatments when the soil was too dry (less than 10%). The initial infiltration rate was significantly lower for the chisel with late residue incorporation (Suifa 1995).

Al-Bakri (1996) showed that the initial infiltration rate was significantly higher under the moldboard plow combined with early incorporation of plant residue than the chisel plow and late incorporation of residue.

Table 5 shows the water-use efficiency for wheat and lentil under different tillage treatments.

Table 5. Water-use efficiency[1] (kg ha^{-1} mm^{-1}) as influenced by different tillage treatments for wheat (Battikhi and Bakri 1996) and lentil (TP 1996) in a wheat/lentil/ melon rotation in Maru, 1996/1997.

Treatment	Wheat	Lentil
Moldboard + Sweep early in the season before rainfall	2.1	0.9
Chisel + Sweep early in the season before rain	2.0	0.9
Sweep late in the season	4.3	0.4

1. WUE = Yield/evapotranspiration.

Crop Rotation

Crop rotation is either traditional or improved. As an improved crop rotation, a wheat-grain legume-summer crop (sweet melon, melon, okra, tobacco, and onion) rotation is recommended (Table 2) to increase soil fertility, and consequently wheat yield, and to decrease soil erosion. Use of a legume phase to replace the fallow period between wheat crops is also recommended. Research has indicated that a short winter fallow is undoubtedly necessary in terms of moisture conservation for the production of a summer crop (Jaradat 1988). However, it is questionable whether a summer fallow would help to conserve soil moisture through the summer for the benefit of the following winter crop.

Results have shown that duckfoot fallow and chemical fallow treatment stored 6.3 cm and 4.1 cm water, respectively, more than continuous wheat. The calculated fallow efficiencies (i.e., the ratio of the difference in soil water content from harvest to sowing time to rainfall received in that period) for duckfoot and chemical fallow were 13.4% and 8.7%, respectively; this difference is due to the effectiveness of each fallow treatment to control weeds (Al-Turshan 1991). Figure 3 shows the water-use efficiency for wheat crops in three different crop rotations and under different tillage treatments.

Ghariba (1981) reported that fallow increased soil water in a 60 cm soil depth by 26 mm compared with barley-barley, resulting in increased grain and straw production of 28% and 27%, respectively. In addition, deep tillage increased the stored soil moisture by 7 mm compared with surface tillage for the rotation with no fallow treatment, while soil moisture increased by 9 mm for the rotation with fallow treatment.

Other results showed that moisture conservation by fallow is most efficient under treatments with tillage at 8-10 cm depth and fertilizer rate of 100 kg ha^{-1} and 150 kg ha^{-1} of di-ammonium phosphate (DAP) for barley and wheat, respectively. These practices improve production sustainability in comparison with fields where no practices were used.

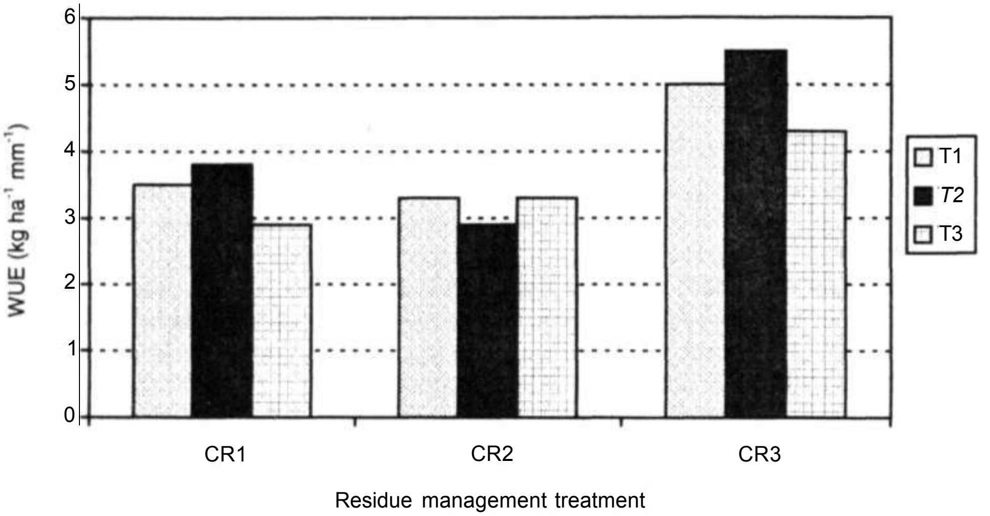

Figure 3. Water-use efficiency (kg ha^{-1} mm^{-1}) as affected by different tillage treatments for wheat under three different crop rotations in Mushaqar (322 mm annual rainfall) for season 1996/1997 (TP 1996; Al-Bakri 1996). CR1=heat/lentil rotation, CR2=Wheat/ vetch rotation, CR3= Wheat/lentil/melon rotation; where the tillage treatments are Tl=Moldboard + Sweep early in the season before rainfall, T2 = Chisel + Sweep early in the season before rain, and T3 = Sweep late in the season.

Fertilizer Application

Information indicates that only about 10% of the DAP sold in Jordan is used in the rainfed areas. Research has indicated that nitrogen and phosphorus are the most critical nutrients in the rainfed areas. Sulfur is not considered to be a limiting nutrient until N and P were added at high rates. The potassium content of most soils in the rainfed areas seems adequate. Fertilizer consumption per hectare of arable land in Jordan is the lowest among countries in the Near East region, being 11 kg ha^{-1} for N and 6 kg ha^{-1} for P. It is estimated that only 8% of the farmers apply nitrogen and 5% phosphate to their fields.

Nitrogen fertilizer application increased significantly the water-use efficiency (Table 6), but the type of fertilizer seems of less importance (Table 7). Al-Shrouf (1993) concluded that the seasonal effective rainfall (the portion of rainfall received

Table 6. Water-use efficiency (kg ha^{-1} mm^{-1}) for wheat under different nitrogen rates at Mushaqqar, 1991/92 (Al-Shrouf 1993).

N application (kg ha^{-1})	Grain	Total dry matter
0	0.64	1.95
50	0.8.	2.24
100	0.85	2.57
150	0.86	2.73

Table 7. Water-use efficiency (kg ha^{-1} mm^{-1}) for wheat under different sources of nitrogen (Ankeer 1996).

Fertilizer type	1990/91	1991/92
Urea	0.51	1.1
Ammonium sulfate	0.45	1
Potassium nitrate	0.53	1.03

during the growing period of a crop and being available to meet consumptive water requirements) for high rates of N fertilizer (100 kg ha^{-1}) was significantly higher than for low rates of N fertilizer.

Despite this advantage, N fertilizer application is widely obstructed by the low and erratic rainfall distribution. A very limited number of farmers (about 5%) apply N fertilizer to their wheat crop. Farmers are thus prepared to accept lower but consistent yield in preference to occasionally higher but more variable yields.

With respect to timing of fertilizer applications, almost no information is available. Nevertheless, a higher number of split applications of N fertilizer is recommended with one half applied at sowing and the remainder side-dressed just prior to the tiller stage. However, research results have indicated that there was little difference in wheat yield whether the entire N dose was applied at sowing or split into a number of applications.

Water-use efficiency for wheat with one dose of N (1.43 kg ha^{-1} mm^{-1}) was no different from two doses (1.41 kg ha^{-1} mm^{-1}). Three doses resulted in an even lower value (1.30 kg ha^{-1} mm^{-1}; Al-Turshan 1991).

With respect to placement of nitrogenous fertilizer, ammonium sulfate is commonly drilled or broadcast with the cereal seed. If split application is practised, one half of the N is usually broadcast at tillering. There is little information on the effect of the application method and placement of N fertilizer on N-use efficiency and crop yield. Phosphorus is usually broadcast prior to sowing of wheat. However, some research has indicated that P should be banded near the seed at the time of sowing since broadcasting may not give the desired response. This suggestion has not been verified under Jordanian conditions. Water-use efficiency for wheat did not show significant differences under these two methods of fertilizer application, although a ear effect was noticed (0.50 kg ha^{-1} mm^{-1} versus 1.05 kg ha^{-1} mm^{-1}; Ankeer 1996).

Table 8. Water-use efficiency (kg ha^{-1} mm^{-1}) for wheat under different crop rotations (used for weed control) and tillage methods at Mushaqqar, 1991/92 (Ankeer 1996).

Treatment	Chisel plow	Moldboard plow
Duckfoot during fallow-wheat	1.19	1.00
Chemical treatment during fallow-wheat	1.01	0.86
Wheat-wheat	1.09	1.02

Weed Control

Weed control, either manually, mechanically or chemically, increases water-use efficiency of the crop. Experiments on weed control for wheat showed that WUE increased by 11% for the manual and chemical weed control treatments compared with the nonweed control treatment (Jaradat 1988). Another experiment studied the effect of three crop rotations, duckfoot during fallow wheat, and chemical treatment (Gramaxon 3 mL L^{-1}) to control weed on water-use efficiency (Table 8). However, in spite of the benefits of proper weed control, the adoption of herbicide use is very low.

Supplemental Irrigation

Wheat and barley are the principal field crops in Jordan. However, due to erratic rainfall, the yields are low and highly variable. In the last decade, research studies on supplementary irrigation of wheat and barley, using traditional water resources, have indicated that supplementary irrigation can lead to a sustainable yield increase. The results indicated that supplementary irrigation has a significant effect on (1) yield improvement; (2) stabilization of production (reduction of spatial and temporal yield variability); and (3) higher technology inputs, irrespective of seasonal rainfall. Rainfed wheat yields increased from 1.07 t ha^{-1} to over 3.05 t ha^{-1} using supplementary irrigation (Zeidan 1988). Rainfed barley yields increased from 1.7 t ha^{1} to 3.2 t ha^{-1} using supplemental water (Fardous and Mazahreh 1996). Supplemental irrigation during the presowing and flowering stages increased grain yield of wheat and barley crops by 2.3-4.2 kg m^{-3} of supplemental water during dry seasons. The maximum yield of barley (4260 kg ha^{-1}) was obtained from a treatment applying 736 $m^3 ha^{-1}$ at 60 kg N ha^{-1} (Fardous et al. 1995).

Results showed that the WUE of rainfall for wheat (at Mushaqqar with about 300 mm annual rainfall) is 0.33 kg ha^{-1} mm^{-1}, but when 1 m^3 of rainfall is combined with 0.5 m^3 of supplemental irrigation, the overall WUE is increased to 3.0 kg ha^{-1} mm^{-1}. The WUE of the applied water varies, however, as a function of the amount of water applied (Table 9).

Covering the soil surface partially with mulch, and under similar conditions, applying supplemental water at 50% Management Allowable Depletion (MAD) is recommended. Fardous et al. (1995) recommended amounts of supplemental

Table 9. Supplemental water-use efficiency (kg ha^{-1} mm^{-1}) for wheat (ACSAD 65) and lentil (Jordan 1) under different irrigation amounts as determined by distance from the sprinkler at Mushaqqar (RPIWMI 1996).

Distance (m)	Wheat	Lentil
0-3	0.32	0.06
3-6	0.3	0.06
6-9	0.19	0.09
9-12	0.26	0.1

irrigation for some wheat (ACSAD 65 and Deir Alla 6) and barley (ACSAD 176 and Deir Alla 106) varieties.

Supplemental irrigation experiments carried out by the National Center for Agricultural Research and Technology Transfer (NCARTT) resulted in the following recommendations: (1) tobacco requires supplemental irrigation five times at a rate of 5 L $plant^{-1}$; (2) no supplemental irrigation for wheat and barley in the three-year crop rotation during years of high rainfall and good distribution; (3) supplemental irrigation at the rate of 75% and 50% of the pan evaporation readings for onion and garlic, respectively; (4) supplemental irrigation should be about 75% of the pan evaporation for wheat during the flowering stage; and (5) supplemental irrigation of olive, peach, and grapes during the summer season should be 100% of the pan evaporation (RPSIWMI 1996) .

Research Using Modeling Techniques

During the last two decades a great diversity of models have been developed and used. However, many of the models should be tested (calibrated and validated) under different field conditions. Locally, research should focus on the operational use of these models. Research is needed with respect to parameter estimation for different crops and soils. Modeling concerning water-use efficiency needs further work.

Introduction of simultaneous heat and water flow models under rainfed conditions in Jordan is highly needed. Some models dealing with watershed management have been adopted and verified under Jordanian conditions. The results indicate that these models can be used successfully in watershed management.

Linear programming models were developed to determine the water-use efficiency for different crops. Future models should deal with the whole system through the following techniques: (1) crop type: by sowing crops tolerant to droughts; (2) agricultural practices (tillage, crop residue, soil type, fertilizer application methods and rates); (3) use of supplemental irrigation; (4) crop rotation; and (5) water harvesting techniques.

Two major activities are being conducted in the steppe region: Modeling techniques aimed at optimum land utilization using either on-farm or catchment water harvesting, and on-farm water or catchment storage. A holistic developmental approach is employed in both projects.

Priority Issues for Further Research to Optimize Soil Water Use

According to the National Agricultural Research Strategy, the aims of research activities in the area of irrigated agriculture are to achieve efficient and economic production, diversification and marketing of crops for domestic and export markets. Accordingly, activities should focus on the following issues: (1) optimum use of water and land resources; (2) optimum utilization of inputs; (3) minimizing the negative environmental impact; and (4) reduction of postharvest losses.

The activities given high priorities include the following research thrusts: (1) monitoring and controlling soil parameters related to soil, and environmental impacts; (2) evaluation and enhancement of soil productivity, fertilization, irrigation and fertigation management; (3) soil conservation and sustainability of agricultural production; (4) nutrition imbalance in irrigated soils; and (5) monitoring and controlling water quality.

Priorities with regard to resources are (1) soil and land resources including soil fertility, conservation, salinity and drainage, and land-holdings, and (2) water resources including water-use optimization, optimum irrigation management, and use of nontraditional water for irrigation, fertigation, water harvesting, supplementary irrigation, and moisture conservation.

The goal of rainfed agricultural research (NCARTT 1994) is to optimize the use of rainfall in efficient and economic production. The strategy for achieving this goal is to be accomplished through the following: (1) optimize the use of water and land resources including nontraditional water resources with minimal environmental degradation, and water harvesting and supplementary irrigation; (2) optimize the utilization of inputs through optimizing the agricultural practices and IPM programs; (3) improve yield and its quality of rainfed crops by introducing drought-tolerant cultivars and new management practices; (4) introduce new crops with domestic and export potential; (5) minimize environmental degradation through proper use of production inputs and land utilization and using appropriate agricultural practices to conserve land and soil resources; and (5) reduce postharvest and storage losses by developing appropriate technologies.

In future, less water will be available for agriculture. Therefore, ways must be found to improve water-use efficiency and maintain water quality. Strategies include the use of more water-efficient crops, reduction of losses in transmission and distribution, and employment of farm management methods including all factors which will result in optimum water-use efficiency.

It is widely acknowledged that water harvesting provides a principal alternative to sustain agricultural activities without mining groundwater resources. The potential for water harvesting, especially in areas that receive an average annual rainfall of less than 200 mm, is promising. The existing ecological systems of this region are fragile and prone to degradation. They are vulnerable to further degradation unless new systems are introduced which allow sustainable development, preservation of the natural equilibrium and prevent further desertification. Various types of degradation processes, especially desertification, affect the land. However, it possesses a reasonable potential for agricultural production if it was utilized properly at the proper time. Further research on water harvesting is essential for development in arid and semi-arid areas. Priority issues include: (1) rainfall distribution; (2) efficiency of the collecting systems; (3) the potential of water harvesting for artificial groundwater recharge; (4) agricultural development strategies using water harvesting techniques; (5) property rights issues of shared water and land resources; (6) economic returns using water harvesting technology; and (7) identification of appropriate water harvesting techniques and their integration with range improvement.

The major challenge for farmers relating to adoption of the technology of supplemental irrigation is the availability and cost of traditional water resources. Treated waste water represents a promising new water resource in Jordan, which will become one of the main sources of irrigation water in the future. It is expected that treated waste water will be the source for more than 20% of the irrigation water used in Jordan. The impact of supplemental irrigation with treated waste water on the physical productivity of rainfed wheat-based and barley-based farming systems will have to be investigated to develop a package of technical recommendations that provide safe and high efficiency of waste water use for agricultural production.

Interpretation and Conclusions

Water loss in the rainfed region occurs through evaporation and runoff. The major challenges are how to decrease evaporation and runoff and to increase infiltration. The main causes of high evaporation in the rainfed areas are light showers, bare soil, high temperature, and poor water storage of shallow soil. Runoff is mainly caused by low infiltration rates, formation of a surface crust, high rainfall intensity, poor surface roughness, plowing against the contour, and low organic matter content. To reduce such losses, the infiltration rate must be increased to maximize moisture storage and to enhance crop coverage.

Very limited research has been carried out in Jordan on the relationship of agroclimatic conditions and crop calendars. The R index (ratio between actual evapotranspiration and potential evapotranspiration) reflects the water supply and demands for crops in the areas under study. It was calculated for different locations: for arid, semi-arid, and semihumid locations it was 44.5, 61.0, and 82.2, respectively (Jaradat 1988), indicating the scope for improvement. This index might be used at a regional or national level to determine crop alternatives or to estimate crop production under certain rainfall and soil moisture conditions.

Arid and semi-arid areas occupy a large part of Jordan. A considerable amount of rainfall is lost to evaporation and surface runoff. Proper management of this land through novel water harvesting schemes could improve the agricultural productivity of a substantial area. Activities could include crop cultivation and improving range production. Water harvesting can also be employed to recharge groundwater to enhance water supplies. Range improvement should also be integrated with water harvesting, thus improving the efficiency of water harvesting systems. Social and economic issues related to water harvesting such as economic return, adoption, and property rights are important constraints.

Implementing water harvesting schemes could make about 400 million m^3 of water available. Storage of this water in appropriate reservoirs could contribute substantially to agricultural and domestic use. Recharge of groundwater aquifers as a means of enhancing water supplies and restoring already-depleted aquifers is very promising. Development of range resources in areas with good soil and suitable for water harvesting could improve the livelihood of local inhabitants.

Suggested Research Projects

- Agroclimatic characterization for improving rainfall efficiencies. These studies will help in designing cropping patterns and rotations, and in implementing appropriate supplementary irrigation as well as water harvesting.
- Watershed management as an integrated approach for arid and semi-arid region development.
- Optimizing soil water use by adopting tillage practices, crop rotation, and mulching.
- Introduction of drought-tolerant crops.
- Improving rainfall effectiveness through different agricultural practices.

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Optimizing Soil Water Use in the Semi-Arid Areas of Kenya

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Abstract

The paper describes the salient features of the crop production systems in the semi-arid areas of Kenya in relation to the climate, water resources, soils, crops and their management practices, and socioeconomic conditions. The paper also summarizes past research findings on factors affecting the efficiency of soil water-use, such as rainwater capture and infiltration, soil evaporation, weed transpiration, plant spacing and population, time of sowing, and application of fertilizers and manure. These findings are then interpreted and conclusions drawn on the major forms of water loss, the wide differences between actual and potential yields, the farming systems and socioeconomic factors affecting the efficiency of soil water-use, and the adoption of improved techniques. The paper concludes with a list of priority issues for further research.

Resume

Ce chapitre presente les aspects saillants des systemes de production agricole dans les zones semi-arides du Kenya, en fonction du climat, des ressources en eau, des cultures et de leur mode de gestion, et des conditions socioeconomiques. he chapitre resume egalement les resultats de la recherche concernant les facteurs influencent Vefficience de l'utilisation de l'eau, tels que la retention de Veau de pluie et l'infiltration, l'evaporation, la transpiration par les adventices, la densite, la geometrie et la periode de semis des cultures, et l'application d'engrais inorganiques et de fumier. Ces resultats sont ensuite interpretes et des conclusions sont tirees concernant les principales sources de pertes en eau, l'existence d'un grand ecart entre les rendements actuels et potentiels, et sur les systemes de production agricoles et les facteurs socioeconomiques qui affectent Vefficience de l'utilisation de

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l'eau du sol et Vadoption de techniques ameliorees. he chapitre se termine avec une liste de themes de recherche prioritaires pour Vavenir.

Introduction

Kenya lies astride the equator between longitudes 34°E and 42°E and between latitudes 4°30' S and 4°30' N, and has an area of 583 000 km^2. Agriculture is the mainstay of the economy and accounts for 30% of the gross domestic product. The sector as a whole employs 75% of the working population and provides all the national food requirements and raw materials for the agroindustrial sector. On the basis of the annual rainfall, the country is divided into seven agroclimatic zones (Fig. 1). Agriculturally, agroclimatic zones I to III are categorized as having high potential while agroclimatic zones IV to VII are categorized as having marginal or low potential. Currently, the per capita arable land is estimated at 0.4 ha. Small-holders occupy about 85% of the land, with their holdings ranging from 0.1 to 10 ha. The remainder is occupied by large farms, ranging in size from 10 to over 10,000 ha (F.N. Muchena and C.M. Njihia, KARI, personal communication). In the recent past, population pressure has increased in the arid and semi-arid lands (zone IV partly, and zones *V,* VI, and VII) due to a high (3.3%) annual growth rate (RK 1994a) and influx of people migrating from the densely populated high potential areas.

Crop and livestock production are the two main agricultural enterprises in the semi-arid areas (zone IV partly, and zone V) while livestock production is the main enterprise in the arid zones. Crop production in the semi-arid areas takes place against a background of inadequate soil water, and crop failures are a common feature. On an average, there is a crop failure in two out of five seasons (Stewart and Faught 1984). According to the National Development Plans and National Food Policies (RK 1989; 1994a, b), the top-ranking policy objective of the agricultural sector is to attain self-sufficiency in basic food. Therefore, increasing crop production through techniques that optimize the use of soil water is imperative.

Characteristics of Semi-Arid Crop Production Systems

Climate

Climate is greatly influenced by relief and altitude. Agroclimatic zone IV has mainly low to medium altitudes, ranging from 1300 to 1800 m above sea level. The mean annual temperature here ranges from 18 to 21 °C. Agroclimatic zone V falls within 800-1300 m above sea level, and the mean annual temperature ranges from 21 to 24°C.

The annual rainfall ranges from 500 to 800 mm per annum, and is erratic in amount and distribution. It is bimodal in the areas along the coastal hinterland and in the areas around the eastern slopes of the central highlands, and unimodal in the areas to the west of the central highlands. In the areas where it is bimodal, it is almost evenly distributed between the two seasons, i.e., the 'long' rains (March-May) with a peak in

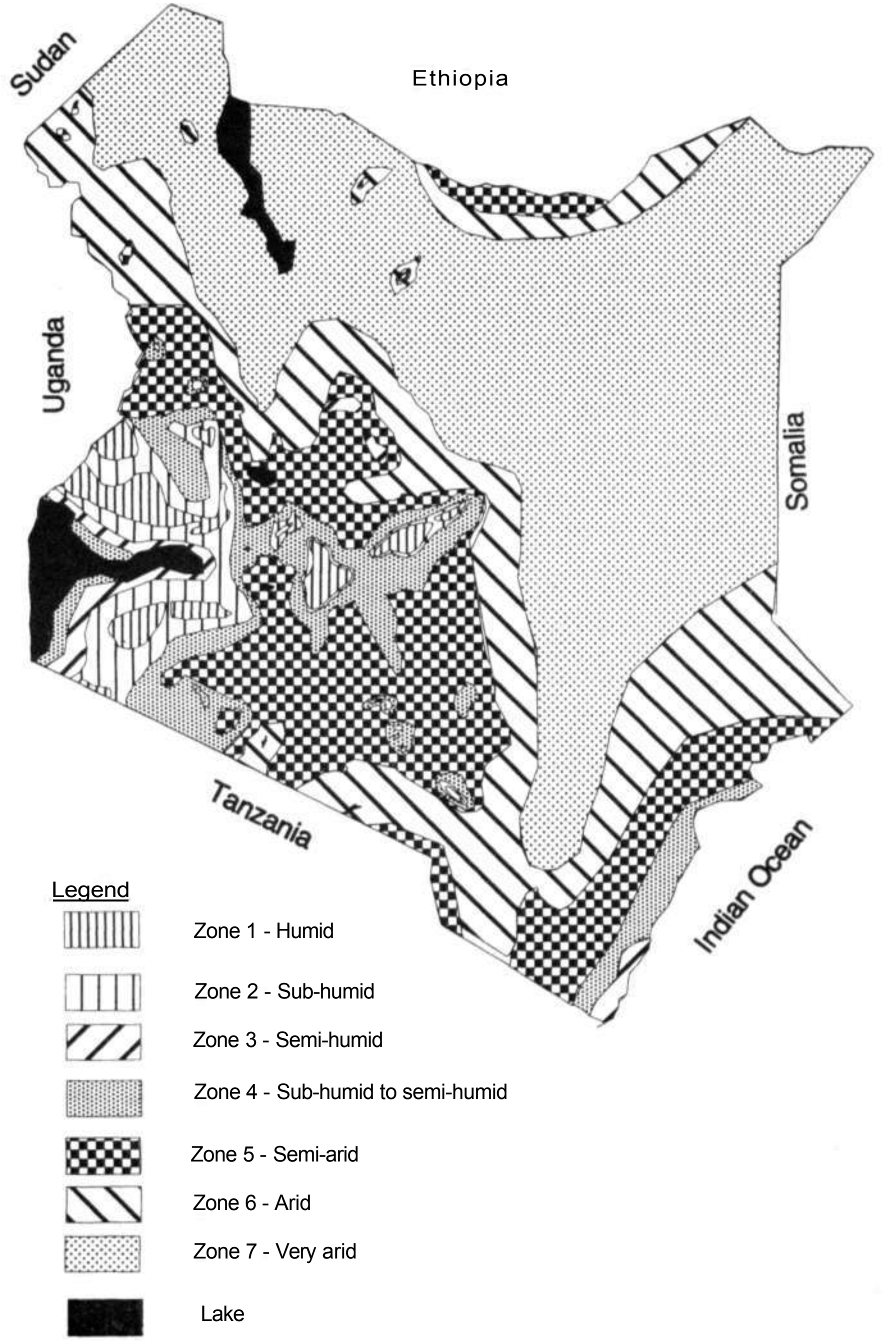

Figure 1. Agroclimatic zones of Kenya (adapted from Sombroek et al. 1982).

April, and the 'short' rains (October-December) with a peak in November.

The rates of evaporation are generally high due to the high daytime temperatures. Rates of up to 8.2 mm day^{-1} have been recorded at Katumani, which lies in agroclimatic zone IV (Stewart and Hash 1982).

Water Resources

The semi-arid lands of Kenya are poorly endowed with surface water resources. There are only a few perennial rivers draining these areas. The most notable ones are the Tana, Athi, Kerio, and Turkwell. Most of the other rivers in these areas are seasonal and hence cannot supply water when it is most needed. A number of lakes occur in the semi-arid areas of the Rift Valley, such as the Turkana, Natron, Baringo, Naivasha, Elementaita, Nakuru, Magadi, and Bogoria. However, among these, the only fresh water lakes are Naivasha and Baringo, the others being saline. Other surface water resources include earth dams, water pans, rock and roof catchments.

The groundwater resources are not abundant and, with some exceptions, the local geology is not favorable for substantial retrieval of groundwater through boreholes. The average yield of boreholes for which data are available is 117 L min^{-1}; about half of them produce less than 80 L min^{-1}. Moreover, in many places, the water produced is saline. Generally, groundwater in the semi-arid lands is slightly exploited, except in a few areas. Current abstraction levels for the majority of the subbasins are less than 1% of the available recharge.

Soils

The predominant soil types are Luvisols, Acrisols, and Vertisols. Numerous other soil types occur, but they are of less significance in terms of the agricultural area they occupy. The dominant clays of Luvisols and Acrisols are kaolinitic (1:1) clays, although 2:1 clays may occur in the vertic groups, e.g., Vertic Luvisols (D.N. Mungai, W.N. Wamicha, KARI, personal communication). Their texture ranges from sandy loam to loamy sand with a tendency to harden when dry, but are friable when wet. They are deep and well-drained in the wetter areas but tend to be shallow in the drier areas due to the presence of petroplinthite (murrum) horizons. They have low organic matter content, mainly due to the poor growth of the natural and human-modified vegetation and the removal of crop residues for livestock feed. They have a low water-holding capacity; are generally acidic (pH 5.0 to 6.5) in the surface horizons; have a poor nutrient status; and, due to poor structural development, are highly erodible and prone to surface sealing and capping through the energies of high-intensity rainfall and solar radiation (Muchena 1975; Mbuvi and van de Weg 1975). Vertisols tend to occur in the plains and depressions. Their texture is clayey throughout the profile, and the clay minerals are predominantly of the montmorilonitic type (2:1 clays). They are moderately deep to deep, and have a better nutrient status. However, they are more difficult to manage because they do not drain easily, are heavy and sticky when wet and extremely hard when dry. They have low infiltration rates owing to swelling when wet

(Mbuvi and van de Weg 1975). Where subsoils are shallow and gravelly, wear and tear of tillage equipment is usually high.

Crops and Management Practices

Crop production in the semi-arid areas is mainly for subsistence. A wide range of crops are grown. The major cereals include maize, sorghum, and millet. Beans, pigeonpea, and cowpea are the main grain legumes. The main horticultural crops include citrus, mangoes, pawpaws, kales, and tomatoes. Cereals and grain legumes are grown almost entirely in mixtures. In semi-arid Eastern Kenya, three main cropping systems have been identified: maize/bean which is, predominant in areas higher than 1300 m above sea level; maize/pigeonpea/cowpea, predominant in areas between 900 and 1300 m above sea level; and sorghum/bulrush millet, predominant in areas below 900 m above sea level (Bakhtri et al. 1984).

Methods of land preparation, sowing, and weeding vary from one area to another, depending on the type of tools/implements available. Where farmers own oxen and plows, and grow their crops in rows, these three operations are performed with plows while where farmers do not own plows, these are done using hand tools. Where farmers use animal-drawn implements for land preparation and weeding, the furrows formed during these operations act as water conservation structures. Almost every farmer is aware of the importance of early land preparation, early sowing, and timely weed control, but for various reasons, most farmers are not able to carry out these operations on time, resulting in substantial yield reduction.

Limited supplementary irrigation, with water from permanent rivers, seasonal streams, and dams, is used for the production of horticultural crops, which are important in the cash economy of these areas. A few farmers, especially in semi-arid Eastern Kenya, harvest water from roads, homestead compounds, and grazing lands for the production of both grain and horticultural crops.

Farmyard manure is the principal source of nutrients for crop production (Rukandema 1984; Muhammad and Parton 1992; NSWMRP-ASALC 1993). However, the quality of this manure is low and the quantities produced are not adequate for the whole cropped area (Probert et al. 1992; NSWMRP-ASALC 1993). Use of inorganic fertilizers is very low, mainly due to the lack of cash (Muhammad and Parton 1992). Crop rotation is almost nonexistent as almost all farmers grow their crops in mixtures. Crop residues are an important livestock feed and hence are not retained on croplands. The limited mulching that is practised is restricted to kitchen gardens.

Use of pesticides is minimal as most farmers lack knowledge of control measures. Appropriate pesticides are not always available at the village level. Most pesticides require the use of water which is often very scarce, and there is a lack of sprayers (Bakhtri et al. 1984). Lack of cash to purchase pesticides and sprayers is the other major factor contributing to the scant use of pesticides.

Socioeconomic Conditions

The major production inputs are land and family labor. The average family size ranges from 7 to 9 persons, with the number available for farm work ranging from 2 to 5 (Rukandema 1984). The labor force is thus characterized by a high dependency ratio, with women being the major source of labor due to emigration of males seeking paid employment. The mean farm size is about 7 ha, with about 2.5 ha developed for crop production and the rest occupied by the homestead and grazing area (Muhammad 1996). More than 70% of the farm output is retained for domestic consumption and family incomes are generally very low. A socioeconomic study conducted in semi-arid Eastern Kenya (Rukandema 1984) showed that the average annual family income ranged from 27 to 62 US$. This situation has worsened following a steady increase in inflation that has affected all sectors of the Kenyan economy.

Past Research Findings

The concept of efficient soil water use is based on the principle of minimizing the loss of rain or irrigation water from the moment it reaches the soil surface and ensuring that its utilization by crops is as efficient as possible. Under rainfed conditions, the amount of water available for utilization by a crop may be expressed by the equation:

$$T_{crop} = P - R - D - E - T_{weeds} - \Delta s$$

Where, T is transpiration, P is precipitation, R is runoff, D is drainage, E is evaporation from the soil surface, and Δs is change in soil water stored within the root zone.

This equation clearly demonstrates that in order to optimize soil water use, it is essential to increase T_{crop} relative to the pathways of losses, i.e., R, D, E, and T_{weeds}.

The effects of a wide range of soil and water management techniques on soil water-use have been studied in the dryland farming areas of Kenya. The findings of these studies are reviewed in the following sections.

Rainwater Capture and Infiltration

Tillage and Mulching

The objectives of tilling the soil include seedbed preparation, soil and water conservation, erosion prevention, loosening compacted soil (hard pans), and weed control. Tillage has various physical, chemical, and biological effects on the soil, both beneficial and degrading, depending on the appropriateness or otherwise of the methods used. The physical effects on parameters such" as aggregate stability, infiltration rate, and soil and water conservation have a direct influence on soil productivity and sustainability. Mulches include materials such as crop residues, plastic films, petroleum-based products, gravel, and soil itself. The beneficial effects of mulching include protection of the soil surface against raindrop impact, decrease in flow velocity by imparting roughness, reduction of soil evaporation, weed control, and improved infiltration capacity. Mulching also enhances the burrowing activity of some species of earthworms (Lal 1976) which improves transmission of water through the soil profile (Aina 1984) and reduces surface crusting and runoff, thereby improving soil moisture storage in the root zone. Mulching is particularly valuable where a satisfactory plant cover cannot be established at the time of the year when erosion risk is greatest.

Tillage and mulch management research in semi-arid Kenya began in the early 1950s, and has the effects of tillage and mulch management on soil and water conservation and their subsequent effects on crop yields as its principal objective. In the last four and a half decades, a number of workers have attempted to investigate the effects of various tillage and mulch management techniques on crop production.

M'Arimi (1978) reported from a tillage study on an alfisol (Chromic Luvisol, FAO/UNESCO classification) in semi-arid Eastern Kenya, that at the end of the rainy season soil water content was highest under tied ridging (Table 1), and that significantly higher dry matter and grain yields of maize were obtained from the tied-ridged plots (Table 2).

Njihia (1979), working on the same Alfisol in the same region, investigated the effects of tied ridges, conventional tillage, crop residue mulch, and farmyard manure on soil and water conservation. He found that maize stover effectively controlled runoff through increased surface storage, which in turn increased infiltration opportunity. Maize stover also minimized evaporation, surface sealing and crusting.

Table 1. Effect of tillage methods on soil moisture content at the end of the short rains period, 1976/1977 (M'Arimi 1978).

	Soil moisture content (% volume)				
Soil depth (cm)	Minimum tillage	Conventional tillage	Tied ridging	SE[1]	PWP[2]
0-30	15.7	16.1	17.9	±0.52	19.0
30-60	19.7	19.4	21.9	±0.55	20.3
6-100	19.6	19.0	21.1	±0.36	20.6
100-150	16.3	16.5	16.7	±0.21	19.9

1.SE = Standard error; 2. PWP = Permanent wilting point (% volume).

Table 2. Effect of tillage methods on crop biomass (M'Arimi 1978).

		Crop yield (kg ha^{-1})			
Period	Crop	Minimum tillage	Conventional tillage	Tied ridging	SE[1]
Long rains	Maize (total dry matter)	1068	1047	1105	±63
Short rains	Maize (total dry matter)	2040	1920	1760	±0.09
	Maize (grain)	337	221	513	±51

1. SE = Standard error.

Table 3. Soil moisture and runoff arising from 122.1 mm rainfall (Njihia 1979).

Treatment	Soil moisture storage (mm)	Runoff (%)
Stover mulching	128.0	
Tied ridging	86.0	13.7
Conventional tillage, with manure	69.0	38.0
Conventional tillage, without manure	65.8	42.7

Table 4. Mulching effect on maize yield (kg ha^{-1}) expressed as the means of four replications in two different rainy seasons (Ulsaker and Kilewe 1984).

Treatment	Short rains 1982	Long rains 1983
No mulching	4810*	270 NS
Mulching	3750	350

*Significant at 0.05% probability level.

Tied ridges also effectively controlled runoff even from a large storm of 70 mm day^{-1}. Conventional tillage with or without farmyard manure resulted in about 40% runoff loss (Table 3). A crop of maize was realized from tied-ridged and maize-stover mulch plots in a season with 171 mm, whereas no yield was obtained from the conventional tillage plots with or without farmyard manure. However, Ulsaker and Kilewe (1984), working with maize in the same region, reported no beneficial effect of residue mulch for the entire period of the experiment (Table 4). In a semi-arid highland area of Kenya (Kalalu, Laikipia district), Gicheru (1990), working on a clay soil (Ferric Acrisols), showed that crop residue mulching conserved more water than tied-ridging.

In another study in semi-arid Eastern Kenya, Kilewe and Ulsaker (1984) showed that conventional contour furrows, wide furrows, and mini benches retained all the runoff and resulted in a significantly higher water-storage capacity than flat tillage; this resulted in increased yields of maize and water-use efficiency. Wide-furrow tillage produced significantly greater yields than all the other treatments (Table 5).

In a study to evaluate the effects of three tillage methods (conventional tillage, strip tillage, and minimum tillage) on the performance and yield of maize in a medium-

Table 5. Effects of tillage methods on water use, grain yield, and water-use efficiency of maize (Kilewe and Ulsaker 1984).

	Total water use (mm)		Maize yield (kg ha^{-1})		Water-use efficiency (kg ha^{-1} mm^{-1})	
Treatment	Short rains	Long rains	Short rains	Long rains	Short rains	Long rains
Flat	521.2	359.3	3722	256	7.1	0.7
Conventional furrows	506.2	368.8	5242	725	10.4	2.0
Wide furrows	509.2	351.4	5458	844	10.7	2.4
Mini bench	524.2	370.1	4680	643	8.9	1.7

Table 6. Effect of tillage methods on maize grain yield (kg ha^{-1}; Ngugi and Michieka 1986).

Tillage method	Short rains	LSD[1] (.05)	Long rains	LSD (.05)
Conventional tillage	3380	1.00	6060	1.09
Strip tillage	3330	1.00	5790	1.09
Spot tillage	3340	1.00	4650	1.09
SE (treatment means)	±0.118		±0.114	

1. LSD = Least significant difference.

rainfall area of Kenya, where the soils are brown clays (Eutric Nitisols) with a low organic matter content, Ngugi and Michieka (1986) showed that conventional tillage gave the highest yields in the two seasons of experimentation (Table 6).

Kilewe and Mbuvi (1988) studied the effects of crop cover and residue management on runoff and soil loss. They reported that maize with minimum tillage reduced runoff by 0.8% and 39.2% during the two seasons of experimentation, while application of 3 t ha^{-1} of maize residue reduced runoff by 58.7% and 78.6% as compared with that produced on bare fallow (Table 7). During the following two seasons of experimentation, maize with conventional tillage reduced runoff on an average by 23%, beans alone by 35%, and maize intercropped with beans in alternate rows by 36% (Table 8).

In a study to assess the effect of agronomic and biological management strategies on soil and water conservation, Okwach et al. (1992) showed that mulching increased the runoff initiation time and the ponded infiltration rate (Table 9) and reduced soil loss and runoff significantly, which in turn resulted in increased yields (Table 10).

Itabari and coworkers (J.K. Itabari, KARI, unpublished data) compared the effects of tillage methods and fertilizer on yield and water-use efficiency of sorghum in a semi-arid area of Eastern Kenya. They found that tied ridging, Zai pitting, and fertilizer increased grain yields and WUE (Table 11).

Table 7. Effect of bare fallow, maize with minimum tillage, and maize with 3 t ha^{-1} of maize residue on runoff at Katumani during the long and short rain seasons in 1983 (Kilewe and Mbuvi 1988).

Season	Bare fallow (mm)	Maize with minimum tillage (mm)	Maize with minimum tillage (% of bare fallow)	Maize with 3 t ha^{-1} of maize residue (mm)	Maize with 3 t ha^{-1} of maize residue (% of bare fallow)
Long rains	24.7a[1]	24.5a	99.2	10.2	41.3
Short rains	52.8	32.1	60.8	11.3	21.4

1. Values followed by the same letter in each season were not significantly (P<0.05) different.

Table 8. Effect of bare fallow, maize with conventional tillage, beans alone, and maize intercropped with beans in alternate rows on runoff at Katumani during 1984 short rain and 1985 long rain seasons (Kilewe and Mbuvi 1988).

Year and season	Bare fallow (mm)	Maize with minimum tillage		Beans alone		Maize intercropped with beans	
		(mm)	(% of bare fallow)	(mm)	(% of bare fallow)	(mm)	(%of bare fallow)
1984 short rain	91.0	72.7	79.9	53.6 a[1]	58.9	52.8a	58.0
1985 long rain	99.6	74.6b	74.9	70.0b	70.3b	70.5	70.8

1. Values followed by the same letter in each season were not significantly (P <0.05) different

Table 9. Surface hydrology for rainfall event of 9 April 1990: total rainfall = 40.6 mm; peak rainfall rate (15 minute intensity) = 30 mm/hr (Okwach et al. 1992).

Treatment	Total runoff (mm)	Runoff initiation time (min)	Ponded infiltration rate (mm hr^{-1})
Bare fallow	26.3	5	9.0
Traditional	26.5	4	11.1
Reduced tillage	25.2	5	15.2
Full mulch	23.4	9	22.3

Table 10. Crop yields, runoff, and soil erosion during the 1990 long rains (Okwach etal.1992).

Treatment	Crop yields (t ha^{-1})		Runoff (mm)	Soil loss (t ha^{-1})
	Maize	Beans		
Bare fallow	-	-	77[1]	42
Traditional	1.4	-	99	47
Intercrop	2.0	0.4	86	14
+ mulch	2.0	-	73	15
+ mulch + N	3.5	-	74	15
Reduced tillage + N	3.2	-	67	19
Full mulch + N	3.4	-	55	7

1. Incomplete season figure.

Table 11. Effects of tillage and fertilizer on grain yield and water-use efficiency (WUE) of sorghum at Masinga during the 1995 short and long rains. (Itabari et al. unpublished).

Treatment	Grain yield (kg ha^{-1})	ET (mm)	WUE (kg ha^{-1} mm^{-1})
A. Short rains			
Flat cultivation-fertilizer	190b[1]	299.0	0.64
Flat cultivation + fertilizer	380b	299.2	1.27
Tied ridging-fertilizer	360b	297.8	1.21
Tied ridging+fertilizer	820a	300.5	2.73
Zai pitting -fertilizer	850a	297.9	2.85
Zai pitting + fertilizer	1010a	298.8	3.38
B. Long rains			
Flat cultivation - fertilizer	80 c	276.09	0.29
Flat cultivation + fertilizer	350 abc	276.86	1.26
Tied ridging - fertilizer	310 bc	275.53	1.13
Tied ridging + fertilizer	1030 a	276.97	3.75
Zai pitting - fertilizer	900 ab	275.10	3.27
Zai pitting + fertilizer	780 ab	275.99	2.83

1. Values followed by the same letter are not significantly different at the $P \leq 0.05$ level.

Water Harvesting

Water harvesting may be defined as the collection and concentration of runoff for the production of crops, pasture, or trees, for livestock or domestic water supply, or for other productive purposes. All water harvesting systems comprise a catchment area and a storage component. Catchments (sources of water) include natural slopes or sealed catchments, rocks, roofs, roads, and flood water from seasonal rivers. Storage can be either short-term or long-term. Short-term storage is storage in or just above the soil profile whereas long-term storage is deep ponding of water. Short-term storage techniques are usually for crop, fodder, pasture, and tree production whereas long-term storage techniques are for domestic and livestock water supplies.

Recently, a number of initiatives have been undertaken to explore the potential of water/runoff harvesting for crop production in the semi-arid areas of Kenya. In Baringo district, the Baringo-Pilot Semi-Arid Area Project (BPSAAP) has tried various techniques of runoff harvesting. In one experiment, runoff harvesting using an external catchment technique significantly increased the yield of sorghum, and the effectiveness of this technique increased when the catchment: cultivated area ratio was increased (Table 12). In a second experiment, designed to compare four runoff harvesting techniques with a control (deep tillage alone), it was shown that all runoff harvesting techniques were superior to deep tillage alone (Table 13). In a third experiment, using sorghum and bulrush millet, the superiority of runoff harvesting over conventional tillage was again demonstrated as the latter had no yield (Table 14).

In Kitui district, the former Ministry of Agriculture and Livestock Development, through the ASAL Development Project, initiated three off-farm trials to test two

Table 12. Yield of sorghum from BPSAAP trial plots using external catchment systems (Imbira 1989).

Plot	Year	Catchment: cultivated area ratio	Experimental plot yield (kg ha^{-1})	Control plot yield (kg ha^{-1})
Katiorin	1982	2:1	775	135
Marigat	1983	1:1	540	10

Table 13. Yields (kg ha^{-1}) from a runoff harvesting trial at Katiorin in 1981 (Imbira 1989).

Treatment	Sorghum		
	First harvest	Ratoon harvest	Cowpea
Impounded plot, deep tillage	420	595	70
Impounded plot, zero tillage	120	N/A	N/A
3 m contour ridges Hoop, zero tillage	410	900	130
Control plot, deep tillage	60	325	20

Table 14. Yields (kg ha^{-1}) from Katiorin water-harvesting plots, 1985 (Imbira 1989).

System	Sorghum	Bulrush millet	Cowpea	Tepary beans	Green grams
Macrocatchment	867	107	115	107	132
Microcatchment	1,456	469	29	N/A	85
Control plot		N/A	N/A	N/A	N/A

runoff harvesting techniques, contour ridge and external catchment, which had proved successful in Baringo district. These trials were conducted for three seasons at Ukai and Kyuso, for two seasons at Zombe, and for one season at Waita, between October 1984 and February 1986, using cereals (maize, sorghum, and bulrush millet) intercropped with legumes (cowpea, tepary, and beans). The four treatments were: contour ridges, external catchment, *fanya juu,* and control (conventional tillage) (Table 15). *Fanya juu* is a Kiswahili phrase for 'make-up slope'. *A fanya juu* terrace is a variant of a conventional bench terrace. It is called *fanya juu* because the soil is thrown up-slope to make an embankment which forms a runoff barrier, leaving a trench which may be graded to drain excess runoff in the more humid areas or to retain runoff in the semi-arid areas.

During the first season, when rainfall was above average, none of the runoff harvesting techniques affected crop yields at any site. During the second season, runoff harvesting increased the yield of sorghum at Ukai. Runoff harvesting also increased the yield of bulrush millet at Zombe. During the third season, runoff harvesting increased the yield of cereals at Ukai except maize in the external catchment system. Subsequent on-farm trials, utilizing the contour ridge technique showed a positive response.

Table 15. Crop yields (kg ha^{-1}) under different water harvesting techniques (Critchley 1989).

	Contour ridges	External catchment	Fanya juu	Control	Contour ridges	External catchment	Fanya juu	Control	Contour ridges	External catchment	Fanya juu	Control
Oct/Nov rains '84		Ukai				Zombe				Kyuso		
Maize (i/c)*	1780	1875	1845	1610	1145	1205	n/a	925	795	775	820	745
Tepary	85	135	135	120	75	190	n/a	320	175	235	135	n/a
Sorghum (i/c)	710	860	1850	1225	1630	740	n/a	840	480	430	755	n/a
Cowpea	370	390	310	400	500	220	n/a	440	555	425	160	n/a
Mar/Apr rains '85		Ukai				Zombe				Kyuso		
B. Millet	285	280	245	455	735	690	n/a	505	155	655	545	260
Tepary**	60	30	140	50	55	170	n/a	65	115	195	85	100
Sorghum (i/c)	590	525	385	425	235	235	n/a	255	0	0	25	30
Cowpea	35	45	10	45	565	405	n/a	225	205	205	320	595
Oct/Nov rains '85		Ukai				Waita				Kyuso		
Sorghum	775	405	305	n/a	155	n/a	100	n/a	335	455	125	120
Cowpea	160	560	380	n/a	205	n/a	255	n/a	245	270	125	90
Maize (i/c)	725	510	550	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Beans	100	300	505	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Soil Evaporation

In a study to assess the possibilities of improving rainwater use through various conservation measures (traditional or local, ridging, mulching, and agroforestry), Liniger (H.P. Liniger, Laikipia Research Project, unpublished data) reported that water loss through soil evaporation was higher under ridging and lowest under mulching. Mulching increased maize yields to 4.4 times that of the local method (Table 16). Using a crop model (CERES-Maize; Jones and Kiniry 1986), water loss through evaporation at the experimental site was estimated to be about 60% of the season's total rainfall.

In a study to determine the potential of alley cropping in semi-arid Eastern Kenya, Kinama (1996) monitored the effects of mulching, hedgerows, and grass strips on the water balance of plots cropped with maize or cowpea. The control treatment was conventional tillage alone. Mulching at rates of 1.2 t ha^{-1} to 2.4 t ha^{-1} reduced soil evaporation by 4% to 9% during the period of experimentation (Table 17). During the study period, water loss via soil evaporation from the control plots ranged from 49% to 66% of the season's total rainfall.

In the same area, soil evaporation from plots cropped with maize and cowpea has been estimated, using modelling, at between 42% and 58% of the total estimated evapotranspiration (McIntyre et al. 1996). Soil water measurements throughout the study period indicated no losses due to deep percolation.

Weed Transpiration

Weeds compete with crops for water, resulting in lower water use by the crops and hence lower yields. Under conditions of adequate soil water supply or irrigation, some

Table 16. Average annual maize yield (t ha^{-1}) at Matanya (four growing seasons, 1986 and 1987) (Liniger, unpublished data).

Method	Maize	Beans
Local	0.95	1.21
Ridging	1.35	1.34
Mulching	4.20	1.58
Agroforestry	3.45	0.94

Table 17. Effect of mulching, hedgerows, and grass strips on soil evaporation (percentage of total rainfall) (Kinama 1996).

Season	Control	Mulch	Hedgerows+mulch	Hedgerows	Grass strips
1994	66.3	57.5	56.5	62.6	64.3
1994/95	50.0	46.0	45.5	48.5	49.5
1995	49.0	43.0	42.5	46.0	46.5

Table 18. Effects of weeds on maize yields (kg ha^{-1}) at two locations in the short rainy season (SR) of 1969/70 and the long rainy season (LR) of 1970 (Makatiani 1970a).

	Kampi ya Mawe		Katumani	
Treatment	SR 1969/70	LR 1970	SR 1969/70	LR 1970
Control (no weeding)	130	1960	20	1170
Clean weeding for the first 3 weeks	740	2960	1990	3870
Clean weeding after the first 3 weeks	560	2900	1600	3400
Clean weeding throughout	619	2870	2330	4240

weeds may be tolerated without loss of economic yield. However, as soil water becomes more limited, weed control becomes more critical (Bolton 1981). Makatiani (1970a) reported maize yield losses due to weeds of 79% at Kampi ya Mawe and 99% at Katumani, during a season with below-average rainfall. During a season with above-average rainfall, yield losses at the two sites were 32% and 72%, respectively (Table 18).

In another weed control study, Kimotho et al. (1997) found that late weeding was more deleterious to the maize crop in the drier (zone IV) than in the wetter (zone HI) lower midlands of semi-arid Eastern Kenya, indicating the importance of weed control as rainfall becomes more marginal.

Plant Spacing and Population

The optimum number of plants per unit area required for maximization of yield and water-use efficiency depends, other factors held constant, on soil water conditions. Under well-watered conditions, plant population density above a certain minimum number seems to have little or no effect on the subsequent yield (Donald 1963). However, in areas of limited soil water supply, plant population and distribution can exhibit a substantial influence on the water-use efficiency and the subsequent grain yield (Harper, cited in Bolton 1981). Under the unreliable rainfall conditions of semi-arid Eastern Kenya, Nadar (1984) found that sowing maize at 75 cm row spacing would optimize maize yields under almost all rainfall conditions tested. The optimum population to be sown under favorable rainfall conditions was around 70,000 plants ha^{-1}. Under less-than-favorable conditions, 20,000 plants ha^{-1} or less would produce the highest yields.

Time of Sowing

In dryland crop production, the time of sowing may have a significant effect on the optimization of soil water use by ensuring that the growth of the crop is adjusted to the available soil water. Early-sown crops have the advantage of a longer growing season than later-sown crops, though the latter are sown under more favorable conditions of soil water supply. A longer growing season reduces the risk of water stress during grain filling. Early sowing also takes advantage of the flush of nitrates produced at the onset of the rains. Makatiani (1970b) showed that delaying sowing for three weeks after the onset of the rains reduced maize yields by 76% during a season in which rainfall was below average and by 21% during a season in which rainfall was above average.

Application of Fertilizer and Manure

A balanced nutrient supply enables a crop to utilize the available soil water more efficiently. The principal effect of applying fertilizer and/or manure is to allow more rapid growth of the canopy which shades the soil surface, thereby reducing the proportion of the total water use that is evaporated (Gregory et al. 1984; Cooper et al. 1987).

Besides inadequate soil water supply nutrient deficiencies, particularly of N and P, are a major constraint to crop production in the semi-arid areas of Kenya. Studies carried out by Okalebo (1987) at several locations in Eastern Kenya have shown that application of fertilizer increases maize yields. In a study to quantify the effects of fertilizer on growth, yield, and water-use efficiency of maize, Itabari (1991) found that application of fertilizer increased grain yield and water-use efficiency of maize (Table 19).

Yield increases following application of fertilizers have also been reported by other investigators (Ikombo 1984; Nadar and Faught 1984; Kilewe 1987; Probert and Okalebo 1992). Application of farmyard manure has also been used to increase crop yields (Ikombo 1984; Kilewe 1987; Itabari et al. 1994).

Table 19. Effect of fertilizer on grain yield and water-use efficiency of maize (Itabari 1991).

Treatment	Yield ($kg\ ha^{-1}$)	WUE* ($kg\ ha^{-1}\ mm^{-1}$)
0 kg N + 0 kg P_2O_5	4030	14.3
20 kg N + 20 kg P_2O_5	4970	17.6
40 kg N + 40 kg P_2O_5	4700	16.7
60 kg N + 60 kg P_2O_5	5360	19.0
LSD (P=.0.05)	984.5	3.5
SE	±237.2	±0.8
CV(%)	10.4	10.5

* Water-use efficiency was determined using the total season's rainfall (282 mm).

Interpretation of Findings and Conclusions

Major Forms of Water Loss

Optimization of soil water use for increased crop production in dryland agriculture is dependent on agronomic practices that result in an increase in the amount of water stored in the soil and efficient utilization of the stored water. The two major pathways of water loss are evaporation from the soil surface and runoff. Losses due to evaporation from the soil surface can be as high as 66% of the season's rainfall (Kinama 1996). These losses are particularly severe during the first month after sowing due to the sparse vegetation cover on cropped lands. The first month after sowing is also the time when the heaviest rains usually occur and radiant energy is high. Due to low infiltration rates and low water-storage capacities of the soils, runoff losses are high, and can be of the order of 43% of the season's rainfall (Njihia 1979). As with losses due to evaporation from the soil surface, runoff losses are higher during the first month after sowing. These losses are especially severe on sloping land that lacks effective conservation measures and on terraces that are incorrectly laid out, poorly constructed, or not stabilized with grass.

Occurrence of Wide Differences Between Actual and Potential Yields

Wide gaps between actual and potential yields are widespread. For instance, the potential yield of Katumani composite B, a maize variety suited to dryland farming conditions, is over 8000 kg ha^{-1} (Keating et al. 1992), while data from smallholdings have shown that yields during a good season (>400 mm), an average season (250 - 400 mm) and a poor season (<250 mm) are 997, 628 and 278 kg ha^{-1}, respectively (Bakhtri et al. 1984). The main causes of these differences are lower-than-optimum sowing densities, plant nutrient deficiencies, late sowing and inadequate or untimely weed control. Currently, an interrow spacing of 90 cm and an intrarow spacing of 30 cm, which is equivalent to a sowing density of 3.7 plants m^{-2}, is recommended. However, farmers do not achieve this recommended density. Typical sowing densities observed at farm level are of the order of 2 plants m^{-2} (Nadar 1984) and 1.2 to 2.2 plants m^{-2} (Ockwell et al. cited by Muhammad 1996).

Despite the widespread occurrence of N and P deficiencies in the soils, use of chemical fertilizers is very limited. A recent study conducted in the semi-arid areas of Machakos district, in the Eastern Province of Kenya, showed that on an average 22% of households use chemical fertilizers. However, the rates of application are much lower than recommended, e.g., the rate of N application in maize was found to be one-fourth of the recommended rate (J.M. Omiti et al. KARI, Katumani, unpublished data). Availability of farmyard manure is declining mainly due to decreasing livestock populations. Farmyard manure produced on smallholdings is also low in N content and its use involves high labor requirements (J.M. Omiti et al. KARI, Katumani, unpublished data).

The current sowing time recommendation is that at least a part of the cropland should be dry-sown, and that sowing should be completed within one week of the onset pf the rains (Weir 1985). Most farmers are aware of this recommendation. However, a recent study in semi-arid Eastern Kenya showed that 44% of the farmers in the sample were not complying with it (Muhammad and Parton 1992).

Although all farmers are aware of the adverse effects of weeds on crop yields, studies conducted in semi-arid Eastern Kenya showed that 90% of the farmers weed most of their fields late (Rukandema et al. 1983a, b).

Farming System and Socioeconomic Factors Affecting the Efficiency of Soil Water Use and the Adoption of Improved Techniques

The farming system in the semi-arid lands of Kenya is typically mixed farming, i.e., farmers grow crops and keep livestock. There is a strong interaction between livestock and cropping activities. Livestock provide manure and draught power for land preparation, weeding, and transportation of manure to the fields while cropping activities provide crop residues for livestock feed. However, there is a significant conflict between livestock and activities that enhance soil water use, e.g., crop residues and maize stover which could be returned to the field to reduce runoff and provide nutrients for future crops are used as livestock feed.

The main socioeconomic factors affecting the efficiency of soil water use and the adoption of improved soil water management techniques are household income, technical knowledge, labor availability, and land tenure. The overwhelming majority of farm families are poor and hence cannot afford to purchase yield-increasing modern inputs such as chemical fertilizers, pesticides, and farming implements. Lack of cash also hinders installation of soil and water conservation structures such as terraces, which are labor-intensive. Lack of knowledge of designing soil and water conservation measures is frequently cited by farmers as reasons for nonadoption of these techniques. Labor supply for the various field operations is inadequate. A recent study (NSWMRP-ASALC 1994) showed that 78% of the farmers experienced labor shortages during peak periods. And 72% of them cited shortage of labor as a major constraint to the adoption of improved soil and water management techniques. Most of the farmers rely solely on family labor. Hiring of labor is rare, and is restricted to the most arduous field operations. On an average only 10-20% of the farmers have reported hiring labor in semi-arid Eastern Kenya (Rukandema 1984). In most of semi-arid lands of Kenya, land is communally owned. Communal ownership militates against adoption of permanent conservation measures. On the other hand, increased subdivision of land parcels makes it difficult to undertake optimal soil and water conservation layouts, enforce proper land use, or obtain convenient water ways.

Priority Issues for Further Research

Research Needs

- Further investigations into the viability of the various water harvesting techniques available locally and in other areas of the semi-arid tropics should be undertaken. Further research on annual and perennial crops suitable for runoff farming should also be undertaken.
- Further evaluation of biological soil and water conservation measures should be undertaken to provide an alternative to the expensive physical structures wherever possible.
- Kenya's Ministry of Agriculture has adopted a catchment approach to soil and water conservation. The effect of this approach on catchment hydrological processes and nutrient balances needs to be quantified.
- Agroforestry systems involving fruit trees and food crops are widely practised in the semi-arid lands of Kenya. These systems have, however, not taken into consideration the competition between trees and annual crops for the essentials of growth and development. This inevitably leads to a reduction in the yields of the food crops due to their lesser ability to compete. Appropriate agroforestry systems need to be developed.
- Strategies for improving the quality of farmyard manure produced on smallholdings should be developed. Improving the quality of this resource will reduce the rate of application, thereby increasing the area of cropped land supplied with manure.
- The relationship between El Nino Southern Oscillation (ENSO) and the prevailing local climate conditions should be established. It is hoped that the establishment of this relationship will improve the predictability of rains, and using a suitable crop model be able to predict crop yields under selected soil and water management strategies.

Ongoing National Research Activities and Linkages

- Development of improved integrated soil fertility and water management techniques.
- Assessment and monitoring of nutrient flows and stocks to develop appropriate nutrient management strategies. This activity is carried out in collaboration with Wageningen Agricultural University of the Netherlands.
- Viability of increasing yields using small-scale irrigation techniques.
- Evaluation of socioeconomic viability of existing water management techniques.
- On-station research and simulation of runoff, erosion, and nutrient losses under different land management practices. Collaborating institutions are the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Agricultural Production Systems Research Unit (APSRU), Australia. Data

generated in this activity will be used for parameterising, calibrating, validating, and testing the APSIM Model developed in Australia.

- Assessment of the potential of water harvesting (runoff/runon) for maize production in semi-arid Eastern Kenya using a modelling approach (PARCH Model). The model was calibrated for the maize cultivar (Katumani Composite B) recommended for semi-arid areas in collaboration with Silsoe University in the United Kingdom.

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Optimizing Soil Water Use in Mali: A Review

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Abstract

Soil constraints to crop production in Mali are predominantly water- and nutrient-related. Mali receives an annual rainfall ranging from less than 200 to 1,300 mm in addition to the water sources of the Niger and Senegal rivers. About 36% of the soils are affected by serious nutrient limitations while 84% have water-related constraints. The traditional practices and improved technologies that are available to alleviate these constraints and to optimize soil water use include better soil surface management through tillage, water capture, and infiltration techniques, addition to soil amendments, and use of cropping strategies such as species combinations and varietal choices. The effort to increase production and obtain sustainable cropping systems is handicapped by the absence of a mechanism for transfer and adoption of available technologies to optimize soil water use. A second critical gap is the limitation on efficient use of soil water by nutrient stress, especially P deficiency. Two research priorities are identified. First, to define technologies to "reroute" via transpiration the amount of rainfall (at least 30%) lost through evaporation from the soil. Second, to find ways to relate the optimization of soil water use to economic growth, environmental issues, health and population growth, and poverty alleviation.

Resume

Au Mali, les contraintes pour la production agricole liees au sol sont dominees par les contraintes liees a l'eau et aux elements nutritifs. La pluviometrie annuelle au Mali varie de moins de 200 mm a 1300 mm, en plus de Veau exploitable a partir des fleuves Niger et Senegal. En general, 36% des sols sont affectes par de fortes limitations en elements nutritifs alors que 84% des sols sont affectes par des contraintes liees a l'eau. L'amelioration de la gestion de la surface par le travail du sol, les techniques

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de capture et d'infiltration de l'eau, l'apport d'amendements organiques, et l''utilisation de strategies de culture tel que la culture associee et le choix des varietes font parties des pratiques traditionnelles et des technologies ameliorees disponibles pour reduire ces contraintes et optimiser l'utilisation de l'eau du sol. L'absence de transfert et d'adoption de technologies dans le domaine de l'optimisation de l'utilisation de l'eau du sol constitue un frein majeur pour accroitre la production et aboutir a des systemes de production durables. La faible efficience de l'utilisation de l'eau due aux deficiences en elements nutritifs, principalement le phosphore, constitue un second manquement critique. Deux domaines de recherche prioritaires ont ete identifies. Tout d'abord, il s'agit de detourner vers la transpiration une partie de l'eau (au moins 30%) actuellement perdue par evaporation du sol. Deuxiemement, il convient de trouver des voies pour lier l'optimisation de l'utilisation de l'eau du sol a la croissance economique, aux problemes environnementaux, a la sante et la croissance demographique, et a la reduction de la pauvrete.

Introduction

Water has long been recognized as the main factor limiting agricultural production in Mali as well as in many other countries of Sub-Saharan Africa (SSA) and West Asia and North Africa (WANA). It is therefore essential to optimize the use of every raindrop falling in these regions. In other words, efficient soil water use is the key to sustainable and profitable crop production.

Optimizing soil water use involves two key components. The first is to achieve maximum infiltration of rainwater. The second is to make optimum use of the water infiltrated into the soil. These components can be achieved through sets of technologies, which will be discussed in this review paper.

Research has been conducted for the past 30 years by the Institut d'Economie Rurale (IER) and its collaborative partners on aspects related to the two components referred to above. Some of the technologies developed have been transferred and are being used to some extent by farmers. The gaps in the transfer and adoption of these technologies as well as additional research needs will be dealt with in this review paper.

Characterization at the National Level

Climate

The annual average rainfall ranges from less than 200 mm to 1300 mm across Mali, creating five ecological zones (Nasi and Sabatier 1988):

Saharan Zone. A part of the Sahara desert, this zone receives about 150 mm annually. It covers 632,000 km^2, about 53% of the total land area of the country. The potential evapotranspiration (PET) in this zone exceeds 2000 mm per annum.

Sahelian Zone. This zone covers 281,000 km^2, and could be subdivided into a northern part (with 200-350 mm annual rainfall) and a southern part called the Sahelo-Sudanian zone (350-600 mm). The rainy season is short: from June to September (3-4 months). The PET exceeds 2000 mm per annum.

Sudanian Zone. This zone covers 215,000 km^2, and receives 600-800 mm. The rainy season lasts five months and agriculture is a sedentary activity. The PET reaches 2000 mm annually.

North-Guinean or Sudano-Guinean Zone. This zone covers 75,000 km^2, and receives 800-1300 mm. The PET reaches 1700 mm annually.

Internal Delta. This zone includes both the Central Delta of the Niger river and the lacustrine area. Most of it falls in the Sahel and covers 29,200 km^2. The mean annual rainfall is about 250 mm in the north and 800 mm in the south. The PET exceeds 2000 mm annually.

In general, the maximum average temperature is 35°C (from May to June), while the average minimum temperature is 22°C (from December to January).

Soil Types

According to the French soil classification, seven major soil types exist in Mali, of which three dominant types cover most of the arable land (Table 1):

Sols Ferralitiques. These cover about 20,000 km^2 of the Guinean zone in the southern part of the country. The moderate fertility of these soils is compensated by their depth.

Sols Ferrugineux Tropicaux. These cover most of the Sudanian zone and about two-thirds of the Sahelian zone for a total of about 173,000 km^2. These soils are fertile, tut moderately susceptible to erosion.

Vertisols and Sols Hydromorphes. These cover the Internal Delta and the alluvial valleys.

Soils have also been characterized according to the "PIRT" classification (PIRT

Table 1. Distribution of soils of Mali according to the French soil taxonomy (Spencer et aL 1995).

French taxonomical group	Area (km^2)
Sols Ferralitiques	20,010
Sols Ferrugineux Tropicaux	171,310
Sols Peu Evolues	422,330
Sols Bruns Sub-Arides	311,190
Sols Bruns Eutrophes	6,060
Vertisols	10,600
Sols Hydromorphes	51,510

1986) on the basis of geomorphology, parent materials, morphological, physical, and chemical properties. The soils classified according to PIRT are located south of the Sahara desert, and cover 47% of the total area of Mali (Table 2).

Soil constraints to crop production are dominated by water- and nutrient-related constraints. About 36% of the soils of Mali are affected by serious nutrient limitations while 84% have water-related constraints. Soil constraints to crop production are summarized in Table 3.

Table 2. Distribution of soils of Mali according to the PIRT soil taxonomy (Spencer et al. 1995).

PIRT taxonomical group		Area (km^2)	Soil property
D	Dunes Sableuses	100,378	Deep, good drainage
DA	Dunes Sableuses Erodees et Aplanies	58,089	Deep, good drainage
PA	Plaines a Materiau Argileux	12,656	Deep, + or - drained
PL	Plaines a Materiau Limoneux	92,140	Deep, good drainage
PS	Plaines a Materiau Limoneux-Sableux	21,410	Deep, acid
TC	Terrains de Cuirasses Lateritiques	123,854	Shallow, gravelly
TH	Terrains Hydromorphes +/- Inondes	19,657	Deep, poor drainage
TI	Terrains Inondes de Facon Saisonniere	26,203	Deep
TR	Terrains Rocheux	43,912	Shallow
X	Terrains Speciaux	34,259	Degraded, bare

Table 3. Soil constraints to crop productivity according to the Fertility Capability Classification (Spencer et al. 1995).

Soil limitation	Area (km^2)	Country soils (%)
Steep slopes (8-30%)	432,286	34.6
Low moisture holding	245,483	19.6
Basic reaction	222,582	17.8
Dry	217,739	17.4
Shallow	207,779	16.6
Low CEC	162,086	13.0
Acidic	160,363	12.8
Erosion-prone	139,756	11.2
Gley	65,463	5.2
Very steep slopes(>30%)	62,526	5.0
Low K reserves	26,303	2.1
Salinity	20,378	1.6
Vertisols	15,028	1.2
Aluminum toxicity	7,027	0.6
Natric	171	0.1

Water Resources

The water resources of Mali include (1) rainfall ranging from less than 200 mm to 1300 mm per annum; (2) the Niger river; and (3) the Senegal river.

The Niger river runs from the west to the east of Mali and has a total length of about 1700 km. It holds the dams of Sansanding (near Segou) and Selingue (near Bamako). In addition, this river provides for 17 lakes and many permanent ponds. The Senegal river runs west of Mali and has a total length of about 900 km, and holds the dam of Manantali.

The above water resources provide a potential for irrigating 565,000 ha. However, only 190,000 ha are cropped under full irrigation (Spencer et al. 1995).

Production Systems and Management Practices

The most important cash crops grown in Mali are cotton, peanut, sugarcane, and tobacco. However, only cotton "pays" the cost of recommended inputs. The most important food crops are millet, sorghum, rice, maize, cowpea, fonio, wheat, yam, and sweet potato. These major crops and their production areas and levels are indicated in Table 4. Crops in most cases are grown in association with trees such as Sapotaceae (*Vitellaria paradoxa)* and Mimosaceae *(Faidherbia albida* and *Parkia biglobosa).*

Soil, water, and nutrient management techniques used by farmers depend on the ecological conditions, the cropping system, and the socioeconomic conditions (at the household, village, and regional levels). Cereal-based cropping systems are either continuous millet (intercropped with either cowpea or peanut) or a cereal in rotation with cotton or peanut. Currently, the following practices are followed:

Land preparation. The operations include Zai construction, zero tillage, plowing, and ridging, depending upon the soil type, the land configuration, the time of the season, and the level of farmers' equipment.

Fertilizer application. Inorganic fertilizer application is limited to cotton, irrigated rice, and to a lesser extent maize (Kieft et al. 1994). Today, most of the efforts are

Table 4. Major crops grown in Mali and their production levels (kg ha^{-1}; IER 1993).

Crop	Actual yield (1993)	Target yield (2005)	Production area
Millet	930	1200	South
Millet	735	825	Central Mali
Sorghum	600	750	North
Maize	2000	2750	South
Maize	1300	1735	Southwest
Irrigated rice	4500	6000	Anywhere
Lowland rice	1400	2500	Anywhere
Cowpea	50	1500	Anywhere
Peanut	890	1480	Anywhere
Cotton	1250	1500	South

directed toward production and use of organic amendments. However, crop residues are generally removed (van der Pol 1992).

Sowing. Manual or mechanized (animal-drawn equipment) sowing is done early, upon the arrival of the first rains. However, insufficient rainfall usually leads to resowing until the desired plant population is obtained.

Weeding. For most farmers in Mali, weeding is the major constraint to crop production. A major necessity for managing this operation is the ownership of mechanical weeding equipment.

In addition, fallow periods are shorter (Hoefsloot et al. 1993), marginal lands are cropped, forests are being cleared for firewood, and pasturelands are overgrazed (van der Pol 1992; Kieft et al. 1994).

Socioeconomic Characteristics

The population of Mali is about 9.23 million, with a density of 7.2 persons km^{-2} and a growth rate of 3.1% (Spencer et al. 1995). Most of the population (75%) lives in the rural areas and the schooling rate is about 32.5%. Access to quality drinking water is limited to 46% of the people in the urban areas and to only 10% in the rural areas.

The economy is essentially agricultural, with cotton making up about 50% of the exports (Cretenet et al. 1994). The per capita GNP was US$ 310 in 1992, with a growth rate of 3.4% (Spencer et al.1995).

Land is technically owned by the government, and farmers are only land "users". Diffusion of technologies to farmers is done by the extension services (governmental organizations) and nongovernmental organizations. Farmers are locally organized in several types of farmers associations which have specific mandates.

In terms of gender, women are involved at every level of agricultural production, but rural Mali still remains a "man's world", implying that women are in most cases not involved in decision-making processes.

The government of Mali has been planning to encourage cereal-based farming by increasing the area under irrigated rice production, building a fertilizer factory (based on Tilemsi phosphate rock), and creating markets for corn, millet, sorghum, etc.

Research on Component Technologies to Optimize Soil Water Use

Component technologies to optimize soil water use in agroecological systems are achieved through managing the system's soil water balance. Depending upon the scale of interest, systems can be defined in terms of small experimental plots, farmers' fields, farming or household systems, watersheds, river basins, or entire geographic regions. The soil water balance, which is based upon the physical principle of conservation of mass, simply states that any change in the amount of water stored within the soil (S) is equal to the difference between water inputs and outputs.

Neglecting special cases, inputs are generally limited to rainfall (P) and runon (RJ. Outputs include drainage from the root zone (D), evaporation from the soil surface (E), runoff (R_{off}), and plant transpiration (T). The water balance of an agroecological system can therefore be defined by the following equation (Jones et al. 1998):

$$S = (P + R_{on}) - (D + E + R_{off} + T)$$

Since man cannot directly control the weather (P), optimizing soil water use requires that (1) S and R_{on} be managed so that there is sufficient water for crops to complete their growing cycle; and (2) all other outputs of water (D, E, and R_{off}) be minimized in order to maximize T, which is linearly related to yield. Recent evidence suggests that the slope of this relation can in some cases be increased to further optimize soil water use.

The best way to optimize soil water use in an agroecosystem necessarily depends upon a number of biophysical variables associated within the system, such as physical and chemical properties, vegetation, slope, weather conditions, water table, and landscape position. It also depends upon the level of organization of the system, e.g., whether one wishes to optimize soil water use for an individual field, a particular farming system, or an entire watershed. An often overlooked factor is that optimization of soil water use can be very dependent upon social and economic factors, such as available inputs, local market considerations, availability of government subsidies or credit, social organization within the system (tribal status, land tenure, etc.), and local income levels. Component technologies studied in Mali for managing the water balance are discussed next.

Water Capture and Infiltration

Water capture and infiltration depend most on rainfall, soil properties, and soil management. These factors are mainly managed through water harvesting, tillage or residue management to reduce R_{off} and perhaps E.

Water harvesting techniques have been used in Mali either when the infiltration rates are too low due to the presence of laterite, crusts, or high clay content, or when the risk of poor yield is high due to low or erratic rainfall. However, much of the work on water harvesting in Mali constitutes part of the "gray" literature such as development project reports of limited circulation (Wennink and Fane 1995). Several water harvesting techniques are being used to reduce runoff and increase infiltration. Examples include digging of "demi-lune" or half-moon catchments, Zai' and tied ridges, constructing "diguettes filtrantes" or stone lines, "petits barrages" used for supplemental irrigation, and other traditional systems for rainfall harvesting (Dunham 1983; Kouyate and Wendt 1991; Wennink and Fane 1995). Stone lines are commonly used on sloping land in almost every ecological zone, but more in the cotton-cereal based cropping system of the Sudanian and Northern Guinean zones (Wennink and Fane 1995). These stone lines are implemented on a community basis, in most cases through the support of a donor. They are often located on the upper parts of the landscape or toposequence (summit, shoulder, or backslope) to reduce runoff and soil erosion (Wennink and Fane 1995). Half-moons are more used in the Saharan zone, whereas the Zai' is found in the Sahel. Both techniques are mainly used when crusting or hardpans significantly reduce water infiltration. Tied ridges prevail in the Sahelo-Sudanian zone (Roose 1981; Kieft et al. 1994; INSAH 1997).

The importance of tillage in optimizing soil water use is often determined by the importance of R_{off} which in turn is a function of soil physical properties, vegetation, slope, and rainfall intensity. In several coarse sandy soils of Mali, R_{off} is not so much a concern as is deep drainage (Stroosnijder and Hoogmoed 1984; Hoogmoed et al. 1991), even on relatively steep slopes. On other soils, such as the more silty soils of Mali, soil crusting poses serious runoff problems, necessitating techniques such as the Zai or half-moons to reduce runoff and increase infiltration (Roose 1981; Kieft et al. 1994; Wennink and Fane 1995; INSAH 1997). Even the finer sandy soils can form at least temporal crusts when they are degraded due to erosion or lack of cover (Casenave and Valentin 1991). Tillage operations can be useful for optimizing soil water use even in coarse sandy soils, but not necessarily due to reduction of R_{off}. Presowing tillage led to better seedling establishment due to protection from dust storms, thereby improving soil water use (Stroosnijder and Hoogmoed 1984), and shallow cultivation by hoe on sandy soils immediately after rainfall has also been shown to reduce E such that cumulative seasonal soil water conservation was increased by up to 70 mm in a 2.4 m profile, due to changes in the surface energy and water balance (Payne 1992).

Tillage along contour lines has been tested in on-farm activities, and was proven effective in cotton-cereal cropping systems in the Sudano-Guinean Zone (Gigou et al. 1997). The main effects of this technique are reduced R_{off} and increased crop growth and yield. At sites located in the Sudano-Guinean Zone, R_{off} was reduced by 200 to 300 mm. In addition, results show a yield increase of 227 kg ha^{-1} of grain sorghum with contour ridging (increased water infiltration). When soil amendments are added to contour ridging, the increase in yield is 553 kg ha^{-1} (increased infiltration and nutrient-use efficiency). According to farmers, tillage along contour lines reduces R_{off}, soil erosion, and washing off manure and applied fertilizers. Thus, the technique is being widely adopted, and farmers are even paying to get it implemented in their fields.

In addition to reducing soil E, crop residues may have other indirect effects which help in optimizing soil water use. On degenerated, lateritic soils, they attract termites, which then form stable soil macropores, thereby dramatically increasing infiltration rates and reducing R_{off} (Chase and Boudouresque 1991).

Drainage Losses Versus Groundwater Recharge

Nonproductive losses of soil water include surface runoff, deep drainage, evaporation from soil surface and deep cracks, and transpiration by weeds. However, drainage is a key factor to groundwater recharge. Water losses through deep drainage can be important due to the relative importance of sandy soils in Mali. In the Sahelian Zone, drainage losses increased with available soil water (Kone et al. 1998). Drainage losses were 115 mm, 170 mm, and 465 mm for available soil water levels of 460 mm, 535 mm, and 670 mm, respectively. About 76% of the country is occupied by soils with sandy textures (Spencer et al. 1995). Hence, a high portion of the limited rainfall is recharging the groundwater. However, little information is available to quantify this.

This situation contrasts with the conditions in WANA where it is generally assumed that there is no loss of water through deep percolation (Cooper et al. 1987). Similarly, the deep and uniformly fine sand of the Kalahari desert is known to hold all water against deep drainage, thereby supporting a fairly dense natural flora of perennial woody species.

Evaporation and Transpiration

The available literature on soil water use provides little evidence on evaporation and transpiration characterization in Mali. The reason may be that the focus of most research programs is on applied and adaptive research.

Soil water balance studies in the Sudano-Sahelian Zone provide evidence that the amount of dry matter produced by crops is directly proportional to the amount of water transpired (Penning de Vries and Djiteye 1982). However, the vegetation uses only 10% to 15% of the rainwater; the remaining 85% to 90% is lost through evaporation, runoff, and drainage. If nutrients were not limiting, only 50% of the rainwater would be lost (Penning de Vries and Djiteye 1982). Similarly, Breman et al. (1998) reported that the vegetation uses only 10% to 20% of the rainwater. They demonstrated that about 60% of that water is lost through evaporation and 25% through runoff.

In many arid and semi-arid regions, evaporation from the soil surface is a substantial component of the total crop water use (evapotranspiration), and yield and water use are frequently unrelated (Gregory 1991). On sandy soils in Niger, Wallace (1991) estimated that 30-36% of the seasonal rainfall is evaporated from sparse fields of rainfed millet. The similarity between the climatic conditions and cropping systems of the Sahel in Mali and Niger (Sivakumar et al. 1984) suggests that similar quantities of rainfall may be lost from direct evaporation from soils of the Sahel in Mali.

The implications of the results discussed in this paper are that component technology to optimize soil water use has to focus on maximizing transpiration and minimizing evaporation. Considering that at least 30% of the total rainfall is lost from the soil through evaporation, the question is whether there is scope for "rerouting" some of this wasted water via plants to improve productivity. Furthermore, the same strategy may provide a means of sustaining productivity under a lower rainfall regime (Sivakumar et al. 1984; Sivakumar and Wallace 1991). A key factor is to involve management practices which do not require any more water in total, but which make more efficient use of the limited rainfall by ,minimizing evaporation (Sivakumar and Wallace 1991). Management practices to maximize transpiration and minimize evaporation would include soil amendment, species combinations, and varietal choices. Such management practices are described next.

Soil Amendments

Addition of soil amendments increases S and T, while it reduces E, D, and hopefully R_{off} However, it has become generally recognized that soil nutrient supply trends to be more limiting to crop production than water supply in Mali. This has been demonstrated by several studies, and is particularly true for low-input fields (Stroosnijder 1981; Penning de Vries and Djiteye 1982; Doumbia et al. 1993 and 1998; Breman et al. 1998). These studies have found, for all but the driest sites, that substantial quantities of unused, plant-available water remained within and below root zones at the end of the growing season. The results have shown that (1) 20% of the plant-available water was left in the soil by native vegetation at the end of the growing season because of nutrient deficiencies; (2) if nutrients were not limiting, plants would use about 50% of the plant-available water; and (3) sorghum seedlings affected by P deficiency and Al toxicity died even when rainfall distribution was satisfactory. This does not imply that there is more than enough rainfall in West Africa. It, however, demonstrates that water use is far from being optimized (Dancette 1983; van Keulen and Breman 1990; Payne et al. 1990; Klaij and Vachaud 1992). There are many reasons for which soil water use is far below optimum in West Africa, but by far the most important is poor soil fertility (Stroosnijder 1981; Day and Aillery 1989). Water-conserving practices that increase available water by reducing runoff, increasing infiltration, and reducing evaporation can become (economically) feasible only when nutrient deficiencies are corrected (Onken and Wendt 1989; Payne et al. 1991). Improving soil chemical properties is the most important factor to increase and sustain crop production (Penning de Vries and Djiteye 1982; Onken and Wendt 1989; Joly 1989).

Of the plant-essential elements, soil P tends to be extremely low (IRAT 1975; Manu et al 1991; Doumbia et al. 1993, 1998). Phosphorus availability is closely related to water availability, use, and WUE because of its effects upon root and leaf growth (Payne et al. 1990). It is perhaps ironic that P availability is the primary constraint to optimizing soil water use in Mali and many other parts of West Africa, because these regions are relatively rich in rock phosphate ore (Pieri 1989).

Soils of Mali are also deficient in most other essential nutrients (van Duivenbooden and Gosseye 1990; van der Pol 1992). The nutrient balance was found negative for the following essential nutrients in the Sudano-Sahelian Zone of Mali: N (-40 kg ha^{-1}), P (-2 kg ha^{-1}), K (-33 kg ha^{-1}), Ca (-8 kg ha^{-1}), Mg (-10 kg ha^{-1}), and $CaCO_3$ (-16 kg ha^{-1}) (van der Pol 1992).

Crop Residue Application

The value of crop residues for water conservation depends upon several factors, such as quantity and type of residues, climate and soil characteristics, and tillage practices. In areas of high PET in West Africa, and particularly on sandy soils, residues may actually provide only little direct reduction of soil E (Nicou and Chopart 1976). In addition, it is very doubtful that the amounts (typically 10,000 kg ha^{-1}) of residue required to achieve a significant reduction in E would be available in many farming systems of SSA, since the demand for crop residues is high, particularly during the long dry season. In Mali, crop residues are (1) incorporated in the soil to increase soil organic matter content; (2) mulched to reduce erosion and evaporation and to increase soil organic matter content; (3) burned on the field; (4) transported home for use as feed; (5) used as bedding material in the stable; and (6) pastured by animals in the field (van Duivenbooden and Gosseye 1990; Quak et al. 1998). However, even in relatively small amounts, residues can trap sediments and seeds, protect soil seedlings from burial, and provide badly needed nutrients to depleted soil reserves for crop growth (van Duivenbooden 1992). These nutrient inputs contribute to further optimizing soil water use.

Combining Crop Species

To optimize soil water use, cropping strategies must take advantage of temporal and spatial patterns of S such that crop competition is minimized to reduce risk, and other outputs (E, D, and $R_{off.}$) are minimized in favor of maximizing T. A classical example is the traditional millet/cowpea intercropping system, which increased millet grain yield by 15% to 103% (Hulet and Gosseye 1986). The photoperiod response of the determinate local varieties assures that the length of the vegetative stage adapts to sowing date, and that drought is least probable during flowering. This assures minimal food supply for the following year. As millet leaf area declines after flowering due to senescence, its water requirements decline. It is then that the local indeterminate, photoperiod-sensitive cowpea reaches full foliage, and continues to flower until residual soil water reserves are exhausted.

Photoperiod sensitivity is advantageous in many situations, e.g. if: (1) the length of the growing period is unpredictable; (2) simultaneous flowering of two intercrops needs to be avoided to minimize competition for water; (3) adaptation to risky climatic conditions is required; (4) more flexibility in the choice of the sowing date is needed; and (5) drought periods during the maturation phase have to be avoided (Niangado et al. 1996; Ouattara et al. 1997; Kouressy et al. 1998). Vaksmann (1991) found that the knowledge of the phenological development of a crop is significant when it comes to making a varietal choice in terms of climatic risks. Most of the photoperiodic sorghum varieties of Mali mature around September 20, but some mature later, particularly in the higher rainfall zones of the country. This behavior allows plants to avoid diseases, but water consumption needs are not satisfied during grain filling and maturity duration is therefore reduced. In addition, photoperiod sensitivity strongly modifies the length of the period from sowing to flowering, leaf area, and number. The flexibility in the sowing time available to farmers can contribute to limiting excess water if flowering is too early or water stress when it is too late (Vaksmann 1991). Niangado et al. (1996) indicated that photoperiod sensitivity is an adaptation characteristic to seasonal phenomena. In fact, it allows a synchronization of flowering at the end of the rainy season. In low-intensity conditions, one of the main qualities of local sorghum and millet cultivars is their adaptation to climatic variations, the valorization of the total rainfall, and the optimization of grain maturation conditions (Ouattara et al. 1997; Kouressy et al. 1998).

Choosing the Right Crop Variety

Farmers' strategies for handling drought include adaptation of sowing dates to rainfall patterns, choice of crop/variety, moving to valleys, intercropping, and tillage practices for hetter soil water management (Coulibaly 1997).

For millet, historically there has been no consistent drought screening to facilitate development of drought-resistant material. IER has relied instead upon multisite trials, hoping that at least one site would experience drought. Since it is often difficult to separate water stress from high-temperature stress (both may occur in most semi-arid zones at the beginning of the rainy season), the technique developed by Sullivan (1974) was used to screen sorghum and millet genotypes for drought and high-temperature resistance at seedling stage. These crops have three major mechanisms in response to drought: (1) drought escape, *(2)* drought avoidance, and (3) drought resistance or tolerance. Less work has been done on breeding for drought resistance (Coulibaly 1997).

In general, breeders have created genotypes before testing them for drought resistance. Often, these genotypes were obtained by using criteria other than morphological and physiological drought resistance. Drought-resistant germplasm is being developed within and between national programs in Mali, through collaborative efforts between IER and international organizations (e.g., ICRISAT). Most of the breeding programs in Mali have focussed on breeding early-maturing varieties which can escape drought (Coulibaly 1997).

Much work needs, however, to be undertaken and the breeding approaches must be carried out with some low-input agricultural practices such as crop residue management, ridges, etc. (Coulibaly 1997). A better understanding of the physiological mechanisms that command crop adaptation to water deficit is essential to renew varietal improvement strategies.

Gaps in Technology Transfer and Research

As indicated earlier, soil surface management, water harvesting, soil amendment, and cropping strategies have been identified as technologies to optimize soil water use. Research activities conducted by IER and its collaborative partners have covered and generated numerous data on these four technologies. Several of these results have been proposed for transfer to farmers. Unfortunately, adoption of these technologies by farmers is very limited. This has various reasons.

First, transfer of the technologies available represents a major shortcoming to optimize soil water use. There is obviously a need for a socioeconomic analysis to explain the very poor transfer and adoption of selected key technologies.

One of these technologies relates to the inefficient use of soil water caused by nutrient stress, especially P deficiency. This gap is very ironic as Mali owns the most reactive phosphate rock (PR) in West Africa. Future research needs to supplement the socioeconomic analysis by Kamara et al. (1994) by defining technologies which are agronomically sound, economically feasible, and socially acceptable to alleviate the major two constraints to the use of Tilemsi PR: dustiness and slow reactivity.

The use of crop residues to improve soil and water management will remain limited until alternatives are developed to substitute their immediate use (feed, fences, fuel, etc.). In addition, much more quantitative information is required on the biophysical effects upon optimization of soil water use that can be expected from application of socially realistic amounts of residues. These include quantification of increased infiltration rates on degraded soils, amounts and timing of nutrient availability from decomposing residues, and effects on soil surface resistance.

Considering that at least 30% of the total rainfall is lost from the soil through evaporation (Sivakumar and Wallace 1991), there is a research need for "rerouting" some of this wasted water via transpiration. Furthermore, under conditions of decreasing rainfall, there is a research need to provide a means of sustaining productivity under a lower rainfall regime. The key is to involve management practices which do not require any more water in total, but which make more efficient use of the limited rainfall by minimizing evaporation.

Most of the review data have been collected on either a small experimental plot or farmers' fields. In a few cases (water harvesting techniques), a watershed level was considered. One of the challenges of the OSWU Consortium is to apply its work to different scales: small experimental plots, farmers' fields, communities, and watersheds.

The activities of the OSWU Consortium will overlap, supplement, or complete other research/development activities on soil, water, and nutrient management in Mali. The Consortium will need to identify its mandate, objectives, activities, target agroecological zones, etc. together with the following organizations and institutions, and seek collaboration with them: (1) national agricultural research services, (2) national agricultural extension services, (3) nongovernmental organizations working in agriculture, (4) major farmer organizations, (5) desert margins program, (6) Consortium for Sustainable Use of Inland Valleys, (7) soil fertility initiative, (8) "Pole Gestion des Ressources Naturelles /Systemes de Production," and (9) collaborative research support programs (IntSorMil, SM-CRSP, Inter-CRSP, IPM-CRSP).

Conclusions

Most Malians (75%) live in the rural areas, and make about $310 per year. Mali receives an annual rainfall ranging from less than 200 up to 1300 mm, in addition to the water resources of the Niger and Senegal rivers. Soil constraints to crop production in Mali are dominated by water and nutrient deficiencies. In general, 36% of the soils of Mali are affected by serious nutrient limitations while 84% have water-related constraints. However, the rate of transfer and adoption of the traditional practices and modern technologies that are available to alleviate these constraints and to optimize soil water use (better soil surface management through tillage, water capture and infiltration techniques, addition of soil amendments, and use of cropping strategies such as species combinations and varietal choices) is very limited. Research priorities need to include the following:

- Socioeconomic analysis to explain the very poor transfer and adoption of selected, key technologies.

- Supplemention of the socioeconomic analysis on phosphate rock to define technologies which are agronomically sound, economically feasible, and socially acceptable to alleviate the major two constraints to the use of Tilemsi PR: dustiness and slow reactivity.
- Quantification of the biophysical effects of crop residues applied at socially realistic amounts upon optimization of soil water use.
- Identification of technologies to "reroute" via transpiration the amount of rainfall (at least 30%) lost by evaporation from the soil.
- Development of management practices which do not require any more water in total, but sustain productivity under a lower rainfall regime.
- Understanding of the physiological mechanisms that command crop adaptation to water deficit to renew varietal improvement strategies.
- Quantification of the effects of optimizing soil water use strategies at different scales: small experimental plots, farmers' fields, and watersheds.

Finally, Mali needs to find ways to relate its work on optimizing soil water use to economic growth, environmental issues, health and population growth, and poverty alleviation.

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Optimizing Soil Water Use Research in Deficient Water Environments of Morocco

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Abstract

The arid and semi-arid regions of Morocco face severe water deficits. The average annual rainfall is limited and highly erratic in amount as well as in distribution. The traditional dry farming techniques used are not well-adapted. They usually cause wastage of scarce soil water and make crop production risky. Research has been conducted to address production constraints and improve production and soil water use. Different sources of information were used to assess research findings regarding the optimization of soil water use in dryland agriculture. The technologies that have been developed are related to crop, soil, and nutrient management, and supplemental irrigation. These technologies have shown the potential of improving soil water use under the deficient conditions of Morocco, but some issues are still to be investigated. This paper discusses past and current research and illustrates some of the prospects and future research.

Resume

Les regions arides et semi arides du Maroc connaissent des deficits hydriques graves. La pluviometrie moyenne annuelle est faible et tres aleatoire aussi bien en quantite que dans sa distribution. Les techniques traditionnelles de l'agriculture pluviale ne sont pas bien adaptees. Elles causent generalement des pertes d'eau du sol et rendent la production des cultures risquee dans ces regions. Des recherches ont ete conduites pour degager les contraintes a la production et ameliorer l'utilisation de l'eau du sol et les rendements. Differentes sources d'information ont ete utilisees pour evaluer les resultats de la recherche relatifs a l'optimisation de l'utilisation de l'eau du sol en agriculture pluviale. Les technologies ainsi developpees sont relatives a la gestion des cultures, du sol et des nutriments, et a l'irrigation d'appoint. Ces technologies font apparaitre le potentiel pour

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ameliorer l'utilisation de l'eau du sol sous les conditions defavorables au Maroc, mais d'autres aspects restent encore a prospecter. Cet article discute des recherches passees et actuelles et illustre certaines perspectives et recherches futures.

Introduction

The arid and semi-arid regions of Morocco have Mediterranean type of climate with winter rainfall and mild temperatures and a dry, hot summer lasting 5-6 months (Ionesco 1965). These areas lie in the northeast (high plateau and Moulouya valley), the central-west region (Casablanca-Beni Mellal-Marrakech-Essaouira), and in the southwest in the Souss region. They cover 27% of the whole country and 80% of the arable land. They comprise 60% of the cereal acreage and produce 55% of the cereal production. In addition, they account for 56% of the sheep, 45% of the cattle, and 51% of the goat populations (ElMourid and Sefrioui 1991).

Biophysical Challenges

The arid and semi-arid regions of Morocco face severe water deficits. The average annual rainfall distribution in time and space is limited (ElMourid and Watts 1993). These regions are characterized by a high risk of drought.

In the last 50 years, Morocco has experienced four cycles or 11 years of drought (Lahlou 1986), the most drastic being from 1980 to 1985. During these five years, the average rainfall deficit varied from 20% to 51% depending on the region, with extremes of 85% in the 1982-83 and 1983-84 cropping seasons (Belkheir et al. 1987). Morocco experienced another two-year drought in 1991/92-1992/93 when the absence of rainfall lasted 120 days, an occurrence never before seen in the country. This drought has been well-documented (Benaouda 1993; Bendaoud 1993; Derkaoui et al. 1992; Herzenni 1992). Nicholson and Wigley (1984) showed that when droughts occur in Morocco, (1) they tend to affect quite large areas; (2) there is a long period of drought during summer with no rain from the end of May to October; and (3) it is during the last part of the growing season (March-April), and erratically at the beginning of the cropping season (November to January). Moreover, short-term seasonal lack of moisture is common (ElMourid and Watts 1993). High temperatures during cereal grain filling (Mekni and ElMourid 1991), combined with high evaporative demand and shallow and eroded calcareous soils (more than 80%) aggravate the lack of soil moisture (Eloumri 1999). Furthermore, foliar diseases (rusts, septoria, etc.) and insects (hessian fly, green bug, sowfly, etc.) are widespread and affect crop yields. There is also large spatial variability of other climatic conditions, soils, and land resources. This biophysical variability is associated with contrasts in land use, agronomic practices, and economic potential, often even over short distances.

Given these environmental characteristics, crop and livestock productions are very low and highly irregular, and years of marginal crop production quite common. In fact, in the 1994-1995 season (under harsh conditions) the total production of cereals was as low as 1.7 million tons, whereas in the 1995-1996 season (under favorable conditions) it was as high as 9.7 million tons.

Socioeconomic Challenges

Agriculture is an old tradition in Morocco's arid and semi-arid regions. The farming systems are complex and heterogeneous (Moore et al. 1993). The increase in the human population and changes in the nomadic or seminomadic ways have resulted in greater use of marginal lands that hitherto were essentially reserved for grazing. Cereal monoculture is increasing along with a tendency to abolish fallow (Benaouda et al. 1993), and farmers are tending to cultivate marginal lands and overgraze natural pastures. Furthermore, land tenure, size of holding, as well as the complex ownership pattern limit the adoption of improved technologies. Cropping is integrated with livestock production, primarily sheep and goats, which plays an important role as an insurance policy and a bank for the farmer. After harvest, the straw is stored for the winter, and the stubble is grazed by livestock through the dry summer. Some barley is grazed during early growth. Mechanization that is well adapted for the more favorable rainfall areas is frequently inappropriate for semi-arid dryland conditions, because it wastes scarce moisture. The offset disk plow is the commonly used implement for seedbed preparation and sowing.

Dry farming techniques of growing cereal crops such as barley, wheat, and maize have been developed and practised for centuries. Cereals constitute the main crop in Morocco and are grown in rotation with fallow and food legumes. When used in the rotation, fallow plots are normally grazed up to springtime. Barley dominates in areas receiving less than 300 mm (Gibbon 1981). Techniques for producing cereal crops consist of waiting for the first rain before sowing in order to destroy the weeds. Seed is broadcast and covered by an offset disk plow (often custom-hired) so that seed is distributed at various depths. Rates of seeding range from 150 kg ha^{-1} to 250 kg ha^{-1} for both barley and wheat. Fertilizers are not generally used and most applications are inadequate for the crop needs. In many cases weeds are left to grow, then hand pulled and fed to livestock.

The lack of adequate and appropriate infrastructure for credit, and for seed, fertilizer, pesticides, farm equipment, and spare parts distribution, and for storing the excess production during the good years indicates the underinvestment in these harsh environments. Moreover, many farmers are isolated in their villages and cannot market their produce under favorable conditions and have no access to social facilities (schools, hospitals, etc.).

The traditional extension approaches have been unsuccessful in convincing farmers to adopt innovations. Farmers have not been involved in decision-making and farmers' organizations (professional associations, chambers of agriculture) are just emerging. Illiteracy rates in the rural areas are still high (exceeding 70% in some areas). In this context, agricultural research scientists are obliged to develop and test technology over a longer period of time than is required in the more favorable areas, in order to be assured that the recommended practices will be both productive and economically viable.

Research

In response to these challenges, the Institut National de la Recherche Agronomique (INRA) created a dryland agriculture research center (Centre Aridoculture, Settat) in 1982. The Aridoculture Center has addressed research problems from a systems perspective. Systems-approach research was implemented comprising three major interrelated components: (1) research agenda development; (2) research process; and (3) monitoring and impact assessment with feedback. This approach considers technology development and technology transfer as a continuum. It is conceived on the basis of concomitant interactions between research scientists, extension workers, farmers, and policy-makers. In addition, the systems perspective provides opportunities for focusing research priorities and addressing farmers' needs through the study of their production systems, i.e., household consumption system, crop/ livestock system, and marketing system. Using this approach, the following thrusts were developed:

- Basic research on improved understanding of the biophysical and socioeconomic environment to more effectively target development initiatives and disseminate new or improved technologies;
- Adaptive research on wheat, barley/livestock, and rangeland cropping systems;
- Conservation of natural resources (soil, water, genetic resources), improvement of their management, and optimization of their uses;
- Development of more productive and less costly technologies, and identification of alternative crops and technologies that ensure flexibility within the farming systems and enhance the sustainability of Morocco's arid and semi-arid areas;
- Development of an information dissemination system to enhance, measure, and monitor the impact of new technologies; and
- Development of a sustainable "aridoculture" training structure which enables transfer of embodied knowledge methods and technologies.

In 15 years, this institute has regenerated knowledge, and developed methods and technologies relevant to the constraints of the fragile dryland farming systems and natural resources of Morocco. This paper reviews past and current research on soil water-use efficiency and ways to improve it in low-rainfall dryland production systems. It also identifies priority research areas in this field.

Research Results

Agroecological Characterization

As indicated earlier, in the semi-arid environments of Morocco, erratic rainfall sequences within and between years and unpredictable occurrences of extreme temperatures lead to great uncertainty in rainfed crop production for individual farmers as well as at the national level. This uncertainty complicates the planning, conduct, and interpretation of agricultural research, the transfer of innovations, and the formulation of effective agricultural policies to optimize allocation of scarce resources. To alleviate these problems, scientists at the Aridoculture Center used agroecological characterization, including a farming-systems typology (Moore et al. 1993) and simulation methods which make it possible to quantify and model climatic variability over time and space and its effects on crop growth and production (Lamine et al. 1993; Elouali et al. 1999; Balaghi and ElMourid 1999). Use of simulation modelling helped in delimiting four agroecological zones in the central-west semi-arid regions of Morocco (ElMourid and Watts 1993; Eloumri 1999). However, the other parts of these regions need to be characterized.

Soil and Crop Management

Soils of the semi-arid regions are characterized by a low content of nitrogen and in some cases of phosphorus and in most cases a good status of calcium and magnesium. They are in general well-provided by potassium, often have a high content of unweathered reserves of mineral nutrients and a high pH. On the other hand, they have a low content of humus and in most cases they are deficient in nitrogen and occasionally in iron and zinc due to fixation. It must, however, be stated that under these conditions the high calcium content and the corresponding slightly alkaline reaction may impair the availability of iron and manganese whilst molybdenum availability is improved (Ryan et al. 1990).

Several soil water conservation practices, cropping systems management, and weed control techniques have been investigated over many years (Kacemi et al. 1994; El Mejahed 1993). They involved different fallow types and tillage systems at different periods in biennial rotation of fallow/wheat, continuous wheat, wheat/maize, wheat/food legumes, wheat/forages, as well as weed management.

Conservation tillage techniques (no till, minimum till, chemical fallow) and weed control generated higher wheat grain yields owing to greater water storage and water-use efficiency. It was also found that clean fallow-wheat rotation was best in conserving water (80-100 mm) and stabilizing crop yields (Kacemi et al. 1994). Finally, improved cropping systems management practices such as seeding date, seeding rate, and adapted genotypes, could result in even sharper differences among conservation tillage systems for conserving soil and water, and increasing and stabilizing crop yields.

Studies on the effect of date of seeding showed that under Hessian fly- and weed-free conditions the optimum time for seeding wheat for maximum yield was early

Table 1. Effect of early seeding date on water-use efficiency (kg ha^{-1} mm^{-1}) (Bouchoutrouch 1994).

Seeding date	1984/85	1985/86	1986/87
Early	11.1	12.6	14.8
Intermediate	7.6	10.9	14.0
Late	6.4	9.2	6.5

November (Bouchoutrouch 1994). Grain and straw yield, spike number, kernel weight, and plant height were reduced and maturity delayed when wheat was seeded after the optimum time. Soil water use by wheat was confined to the upper 1 m soil depth, and water-use efficiency was consistently highest for earlier sowings (Table 1).

Studies on water use by weeds (Tanji and Karrou 1992; Tanji 1994) showed that competition for water between wheat and weeds is high from the stem-elongation stage to maturity of wheat. Weeding during that period can save up to 50 mm of soil water and increase yield by 35%.

Crops and Varieties

One way of increasing soil water use efficiency in rainfed agriculture is the selection of adapted species and varieties. In fact, many of the varieties currently used by farmers are not well-adapted to dryland conditions. Although they produce a lot of dry matter and hence are appreciated because of their high straw yield, they have the disadvantage of depleting the soil moisture early in the season which normally affects their grain yields. Moreover, being late, they are exposed to late drought and high temperatures. To provide better material to farmers, scientists have been developing improved varieties and testing species and alternative crops under different soil moisture conditions.

The mechanisms involved in drought resistance and WUE have been studied. In most experiments the line-source system of irrigation was used to create different soil moisture regimes. The parameters measured were those related to growth and development of plants such as dry-matter accumulation and partitioning, leaf area index and duration, root growth, and grain-filling rate and duration. Water use, water-use efficiency, plant water relations, leaf gas exchange, nitrogen-use efficiency and (Malonylamino) cyclopropane-1-Carboxylic Acid (MACC) accumulation were also investigated. Here only the results on soil water use, water-use efficiency and some important physiological criteria will be presented.

Comparison of Crops

The main crops studied were bread and durum wheat, barley, triticale, maize, and chickpea. The performances of these crops under wet (400-450 mm of rain and irrigation water) and dry conditions (less than 300 mm of rainwater) in different experiments have been summarized in Table 2. The data presented are averages of

Table 2. Water-use efficiency (WUE, kg ha^{-1} mm^{-1}), water use (WU, mm) and grain yield (kg ha^{-1}) of different species under wet and dry conditions (Karrou and ElMourid 1996).

		Wet			Dry		
Crop	Variety	WUE	WU	Yield	WUE	WU	Yield
Durum wheat	Coccorit (early)	10.3	382	3938	5.8	244	1416
	Keyperounda (late)	6.6	375	2473	2.5	237	592
	Mean	8.5	379	3206	4.2	241	1004
Bread wheat	Potam (early)	10.5	363	3807	6.5	248	1614
	Florelle (late)	6.5	394	2558	2.2	242	533
	Mean	8.5	378	3183	4.4	245	1074
Barley	Acsad 60 (early)	10.6	379	4013	6.1	242	1177
	Arig 8 (late)	11.8	375	4424	2.9	249	808
	Mean	11.2	377	4219	4.5	245	993
Triticale	Juanillo	14.1	390	5500	11.6	232	2750
Maize	Pioneer 3969 (early)	17.6	150	2650	5.1	126	643
	TX 21 (late)	14.5	172	2250	1.5	144	216
	Mean	16.1	161	2450	3.3	135	430
Chickpea		3.2	188	602	1.2	97	116

varieties that belong to the same type of duration (early or late). Under both soil moisture regimes, bread and durum wheat used similar amounts of water, and their grain yields and water-use efficiency indices were equivalent. However, WUE under wet conditions was higher than under dry conditions. Barley showed a similar trend, and under the more favorable conditions it had higher grain yield and water-use efficiency than durum and bread wheat. Triticale turned out to be the most best-adapted crop to different soil moisture conditions since it used water more efficiently than wheat and barley under the wet and dry regimes. Although its actual evapotranspiration values were not very different than those of the other cereals, its grain yields were significantly higher. Among the spring crops, maize yielded better and used water more efficiently than chickpea.

Experiments with alternative crops, such as sorghum, which were thought to be more adapted because of their tolerance to drought showed that sorghum did not fit the conditions of this environment (Karrou 1986). If sown as early as maize (first week of February), it suffered cold stress with poor germination and loss of vigor of seedlings. Hence grain yield was negatively affected. However, when sorghum was sown later (March or April), stand establishment was frequently very low because of the soil moisture deficit.

Comparison of Varieties

In general, although the total amounts of water used were not significantly different between early and late varieties, early cultivars yielded better and used water more efficiently (Table 2). Late and old durum (Kyperounda) and bread (Florelle) wheat and barley (Arig 8) did not perform as well as the earlier cultivars Cocorit, Potam, and Acsad 60, respectively. Samir (1993) confirmed this result when she compared relatively early durum wheat (Marzak) with the relatively late cultivars Karim and Oum Rabia. For maize (Table 3), early and medium varieties produced more grains and used water better than late varieties under dry conditions (1986). If both grains and straw (feed) are targeted, it is better to use medium varieties. Under wet conditions (1985), late (HT 308) and early (Pioneer 3969) cultivars had higher yields and WUE. Cultivar differences have been reported in chickpea too (Dahan 1993). Flip 84-182C exhibited significantly higher seed WUE than Flip 84-92C, Flip 83-48C, and PC-46. As was mentioned for maize, WUE of chickpea was more related to grain yield than to the amount of water used.

Different strategies are used by varieties to tolerate drought. Among them is earliness as mentioned above. Early varieties have the advantage of escaping terminal drought and maintain longer their leaf water potential high, and hence their stomata are kept open (Karrou and ElMourid 1993). Consequently, photosynthesis and most of the components of yield are less affected by late drought. The early vigor of Merchouch 8 and its high CO_2-assimilation efficiency and CO_2 exchange rate (Karrou and Maranville 1993a) offer the possibility of early root growth and development, and hence better use of water during the wet season. The early seedling establishment characteristic gives this cultivar more time for seed-set, and more seeds per spike are formed (Karrou and ElMourid 1993).

Early soil shading is a second variety characteristic that can reduce evaporation, save soil water for later growth stages, and increase transpiration. This mechanism was verified in experiments with reduced row spacing. Karrou (1997) showed that reducing row spacing in wheat from 25 to 12 cm significantly increased grain yield without affecting significantly the amount of water evapotranspired. Consequently,

Table 3. Water-use efficiency (WUE, kg ha^{-1} mm^{-1}), water use (WU, mm) and grain yield (kg ha^{-1}) of different hybrids of maize at the Sidi El Aidi (SEA) and Jamaa Shaim (JS) experiment stations (Karrou et al. 1992).

	SEA (1985)			SEA (1986)			JS (1986)		
Hybrid	WUE	WU	Yield	WUE	WU	Yield	WUE	WU	Yield
DRA 400 (late)	16.1	156	2520	2.02	143	290	-		430
TX 21 (late)	14.5	172	2250	1.50	144	220	5.46	175	950
HT 308 (late)	16.5	164	2690	2.44	133	330	3.22	172	580
Funks 4065 (intermediate)	16.0	149	2340	4.06	154	640	5.91	182	1070
Pioneer 3969 (early)	17.6	150	2650	5.13	126	650	6.31	172	1090
Pioneer 3994 (early)	15.8	153	2420	4.37	143	630	7.52	171	1230

soil water was used more efficiently. However, further research on varieties is still needed to identify varieties that have the capacity of shading the soil early in the season.

The third mechanism to tolerate drought is the combination of osmotic adjustment capacity, low stomatal sensitivity and turgor maintenance characteristics under water deficit conditions as observed in durum wheat Marzak and Oum Rabia (Samir 1993) and chickpea PC 46 (Dahan 1993). Consequently, this mechanism helps plants maintain leaf transpiration under dry conditions and hence a low leaf and canopy temperature. The difference between the canopy and air temperatures was found to be very well-correlated to yield in the dryland areas (ElMourid 1988; Karrou et al. 1992; Samir 1993).

Karrou and ElMourid (1993) reported that early senescence of parts of leaves and tillers (e.g. bread wheat Nesma) and grain-filling rate increase, and seed-size maintenance (e.g. barley Acsad 60) under drought are the other strategic uses of cereal genotypes to tolerate late water and heat stresses. Benichou et al. (1993) found that solutes (MACC) accumulation under drought might play an important role in genotype adaptation to drought and in the improvement of water use and water-use efficiency.

Water and Nitrogen-Use Efficiency

The possibility of fertilizer-use in dryland agriculture is limited by nature. The efficiency of fertilizer application depends to a large extent on the distribution and amount of rainfall, and the way of fertilizer application. Since rainfall is unpredictable, effects of fertilizer application under such climatic conditions are a matter of luck. Under deficit rainfall conditions fertilizer use may be ineffective or even detrimental if growth during the early stage had been promoted by fertilizer and no reserves of soil moisture were left to the plant for grain formation. On the other hand, omission of fertilizer application might impair vegetative growth to such an extent that even the small amount of available soil moisture is not utilized efficiently by the plant. Many experiments in the arid and semi-arid regions have shown that adequate fertilizer supply increases yield and improves water-use efficiency (Moustapha, Gandah et al. in these proceedings).

Nitrogen-use efficiency in rainfed agriculture has not been explicitly described and has been shown to vary from year to year and from one field to another. The factors that most affect N-use efficiency are in general related to climatic conditions, soil chemical and physical characteristics, plant characteristics, and cropping systems.

It is generally accepted that N-use efficiency in wet years is higher than in dry years. Soil characteristics such as depth, N mineralization potential, and initial mineral N content also affect the efficiency of N-use by plants. Crops are less efficient in terms of N-use at high levels of N application (Karrou and Maranville 1993b). Varieties with a high yielding capacity use N more efficiently than those with low yield potential.

Results of experiments on fertilizer N-use efficiency (kg yield kg^{-1} applied N) show a large variability, i.e. from 25% to 50% in rainfed agriculture, and from 40% to 75% in irrigated areas. Soltanpour et al. (1989) reported values of apparent fertilizer N recovery of 50% in a wet year and 34% in a drier one. However, Abdel Momen et al. (1990) in a study on dryland wheat response to N and P reported values of 28% and lower depending on the soil type and previous crop. Nitrogen-use efficiency for barley and triticale was found to follow the same trend, low in the dry years and high in the wetter ones (Ryan et al. 1991). El Mejahed (1993), using isotopic methods (^{15}N) found that real N recovery values for wheat ranged from 25% to 35% depending on climatic conditions and cropping systems. Karrou and Maranville (1994, 1995) have reported that the effect of N on N content of the above-ground parts of the plant was masked by severe water stress, and that of underground parts was not affected. In fact, the N content of the underground parts increased with N application. However, the results were not the same for all the cereal varieties studied. On the other hand, Agbani and Badraoui (1994) studied the effect of water stress on maize root capacity to absorb nitrogen and potassium, and found a close relationship between soil water availability and N and K uptake. They also reported that N and K absorption capacity of maize could satisfy the plant's needs for these nutrients even under high soil water osmotic pressure (-1 Mpa).

Research on water- and nitrogen-use efficiency per se has not been well-studied in Morocco with the exception of few studies mainly conducted in greenhouses by INRA (Karrou et al. 1994, 1995) and IAV Hassan II (Agbani and Badraoui 1994). The relationship between water- and N-use efficiency has still not been understood and requires more attention. This fact should be considered while making fertilizer recommendations. At present, fertilizer N recommendations take into consideration mainly the yield goal, soil N available before sowing, soil type, and the previous crop. It is advisable to consider the water availability in the soil and determine the relationship between this parameter, fertilizer application, and yield.

Supplemental Irrigation

Supplemental irrigation is an efficient means of overcoming, or at least reducing the effect of water stress on crop production. In Morocco, supplemental irrigation studies have mainly been conducted in large agricultural perimeters, notably Chaouia, Abda, Doukkala, Saiss, Gharb, and Tadla (Handoufe et al. 1987; Belbsir 1990; Chaouch 1990; Boutfirass 1990, 1997; Boutfirass et al. 1992, 1994; Ouattar et al. 1992). These works mainly dealt with cereals, particularly wheat. Other researchers used this technique in other crops such as sunflower (El Asri 1990), sugar beet (Chati 1996), and winter chickpea (Boutfirass 1997).

In cereals, the beneficial effect of supplemental irrigation on production and water-use efficiency was found to be significant. In most of the studies mentioned above, supplemental irrigation was applied at critical stages of development of wheat: tillering, booting, and grain-filling. Crop watering was done during one or the other of these stages, but the effect in terms of yield increase varied considerably. In the case of a single irrigation, water supply during the preanthesis stage increased the yield more than during the postanthesis stage. This difference in yield increase is explained both by the production of a minimum biomass threshold at anthesis that is needed for grain production and estimated at 6000 kg ha^{-1} (ElMourid 1988) and by the fact that the two most important grain-yield components (number of spikes and number of grains) are elaborated early in the cycle of wheat development and benefit from the early irrigation. Postanthesis irrigation can help only in the increase of kernel weight.

If we consider the preanthesis phase with its two stages of tillering and booting, differences in response to supplemental irrigation can be explained by:

- differences in the soil water storage capacity of different soil types;
- differences in soil profile recharge that can vary with (1) the crop life cycle positioning in relation to the rainfed season (seeding date, thermal amplitude, and evaporative demand during the vegetative phase); and (2) the rainfall intensity and number of rainy days during the vegetative phase; and
- differences in the soil water depletion rate, depending on: (1) the use of different cultural practices (seeding rate, sowing depth, seedbed preparation); (2) weather conditions (evaporative demand); (3) the crop type and varieties used; and (4) the plant cover early in the season.

Boutfirass (1997) showed the positive effect of a tillering-stage supplemental irrigation on water-use efficiency under two different rainfall conditions (Table 4). The WUE increase varied from 30% in a high-rainfall season (1990-91) to 96% in a low-rainfall season (1991-92).

For a better integration of most of these variables, a simulation of the effect of supplemental irrigation at different growth stages was carried out using a wheat growth model, SIMTAG (ElMourid et al. 1992). In this simulation, the authors used a climatic data series of more than 20 years in two contrasting regions. In each region, the simulation was made for two soil types (deep and shallow soils) and three bread wheat varieties (early, semiearly, and late cultivars). Results showed that the effect of supplemental irrigation varied with the soil type and wheat variety. In the deep soil, supplemental irrigation at the tillering stage gave the best yield increase, whereas in the shallow soil, irrigation at booting stage did better. The same results were also obtained in terms of probabilities. Early- and semiearly-maturing varieties were found to be the best-adapted varieties for the simulated conditions of the arid and semi-arid zones. Late-maturing varieties should be avoided under similar conditions.

Table 4. Water-use efficiency (kg ha^{-1} mm^{-1}) in wheat under supplemental irrigation (60 mm of water) at various development stages. (Adapted from Boutfirass 1997).

Water source	1990-1991	1991-1992
Rainfall (mm)	342	247
Rainfed	11.82	4.99
Supplemental irrigation at tillering	15.25	9.78
Supplemental irrigation at booting	12.85	6.28
Supplemental irrigation at grain-filling	12.26	3.93

Yield variability over years is greater for shallow soils with low water storage capacity. The best yield stability was obtained for deep soils irrigated at the tillering stage. In terms of water-use efficiency, the same trends as for grain yield were obtained. These results confirmed those obtained by Boutfirass (1997) in a field experiment conducted during two contrasting years (with rainfall of 342 mm and 247 mm in a deep soil). The latter author concluded that in the semi-arid regions where the soil is deep, it is better to apply supplemental irrigation early in the growth season.

For other crops too, preliminary results have shown the importance of supplemental irrigation in yield improvement and stabilization. The yield increases obtained for some crops and irrigation water saving achieved for others show that this technique is promising. Indeed, in the case of sugar beet, Chati (1996) concluded that as long as the crop is well-watered at the seedling stage the crop would be suitable to supplemental irrigation. He also found that the number of irrigation events is not as important as the period of irrigation.

For winter chickpea, a single irrigation of 60 mm water at the pod elaboration stage helped the crop maintain a green-area duration of more than 45 days as compared to the rainfed plot (Boutfirass 1997). This green area duration contributed to an important increase in grain yield.

For sunflower, supplemental irrigation during the most sensitive stages of the crop (floral bud, flowering) increased considerably the yield (El Asri 1990). The highest grain yield was obtained with one irrigation at the floral bud stage. However, the oil content of the grain was negatively affected due to the fact that the total oil production remained similar for different grain yields.

To sum up, supplemental irrigation is an efficient means of improving and stabilizing yield of cereals. In the case of a single irrigation, it would be more efficient to apply it early in the crop life cycle (at the tillering stage), particularly when the soil has a large water storage capacity. In the case of more than one irrigation, it is necessary to target the three most sensitive stages of the crop to water stress. In the case of wheat, these stages are tillering, booting, and grain filling. However, most of the studies mentioned later were conducted with cultural techniques that are normally recommended for rainfed agriculture. This supposes that possibilities of improving yields under supplemental irrigation remain to be exploited while adopting cultural practices adapted to irrigated agriculture (such as seeding date and rate, seedbed preparation, fertilization, pest control, etc.). Attempts have been made (Handoufe et al. 1992; Bahaja 1994), but are inadequate at this stage to draw practical recommendations.

As long as supplemental irrigation requires an investment for the equipment, the economical profitability factor should be considered. Therefore, relative profitability studies using supplemental irrigation in different conditions and with different irrigation systems were undertaken. Different approaches were used in these studies, but in all of them the bank interest rate taken into account was 14 to 15%.

Ouattar et al. (1992) presented a case study using a mobile ramp irrigation system. In their calculations they considered outputs under the preanthesis supplemental irrigation and found that this technique was economically justified when the minimum area exceeded 10 ha. Moreover, when they increased the bank interest rate from 14% to 28% the technique was profitable at a minimum of 13 ha of equipped and irrigated area.

Lamrani et al. (1992) attempted to evaluate the financial profitability of supplemental irrigation through an analysis of "farm models" in which they considered three typical farms of 5 ha, 30 ha, and 50 ha. The first farm was equipped with the classic sprinkler system, the second with a self-propelled ramp, and the third with a center pivot system. Simulation of output gains was run for over 30 years. Results showed that in order to make the technique profitable, the upper limit of investment is 2250 US$ ha^{-1} for an output of 6000 kg ha^{-1}, and 1740 US$ ha^{-1} for an output of 5000 kg ha^{-1} and 1230 US$ ha^{-1} for an output of 4000 kg ha^{-1}. This last alternative was possible only with a self-propelled ramp. Nevertheless, it would be necessary to notice that subsidies granted by the government in this area were deducted from these investments.

Conclusion

Rainfed agriculture in the arid and semi-arid regions of Morocco is prone to different challenges. In spite of these challenges, crop production has continued for many centuries. In the dryland areas, crop yields have increased substantially over the last twenty years, mainly due to the development and adoption of new technologies. However, the production potential of these areas has not been realized yet. It has been shown that crop yield in these regions could be increased by more than 60% only by adopting the available new technologies developed at the Aridoculture Center. However, efforts still have to be made especially in terms of soil water-use optimization in order to achieve higher yields and attain agricultural sustainability in these areas, which represent 80% of the total arable land in the country.

Prospects and Future Areas of Research

Strategies for agricultural production in the arid and semi-arid regions of Morocco should be based on productivity, stability, and sustainability. The challenge is to have a balance of all three qualities. Productivity is usually expressed per unit of area, per person, per unit of energy input, or per unit of capital investment. Stability is the reliability or consistency of farm production. Sustainability is defined as the ability of an agroecosystem to maintain productivity when subjected to a major disturbing force (salinity, erosion, declining market, etc.). Sustainability is achieved when a given level of productivity is maintained over time.

The crop-production objectives in these drought-prone regions are to improve, stabilize and sustain yields through selection of species, cultivars, and cultural practices that will reduce yield fluctuations and permit stable production. The emphasis should be on the interrelationships of the environmental, soil, and crop management factors with crop productivity. These are limited not only by low and uncertain rainfall, but also by extreme temperatures and shallow soils. The best means of reducing these stresses are the application of sound agronomic practices as well as selection of appropriate cultivars. These means mainly involve:

- evaluation of the genotype-environment interactions;
- soil and water conservation through appropriate soil and crop management systems;
- water use and water-use efficiency;
- nitrogen-use efficiency through modeling N fertilizer recommendations based on nitrogen spatial variability, and N, crop, soil, and climate interactions and their impact on the environment quality; and
- better understanding of yield processes and determination in relation to phenological stages, agronomic practices, and environment. The concentration of rainfall in the cooler half of the year, during winter, when evaporative demand is low offers advantages for improving water-use efficiency and increasing biomass. Moreover, deep soils (Vertisols) can store water that can be used later in the season.

Hence, all breeding programs and improved agronomic practices should aim at efficient use of the limiting resource, water, by avoiding its waste, by improving the soil water storage capacity, by choosing crops which are best adapted to these conditions, and by adopting agrotechnical practices that lead towards increased soil moisture availability. In other words, the task is to devise very efficient water-use cultural practices and highly efficient crops and cultivars. Using the available water more efficiently may mean fewer crop failures and thereby stable yields.

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Optimizing Soil Water Use in Niger: Research, Development, and Perspectives

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Abstract

Research on optimal water use in Niger has been carried out since the seventies on various themes, including physical and hydrodynamic soil characterization, crop water use, water conservation techniques, and water-use efficiency improvement. The results indicate that soils used for rainfed crop production have in general low water -holding capacity and are therefore subject to deep drainage beyond the rooting depth in years of adequate rainfall (P > ~300 mm). Runoff and water erosion are common as a result of high rainfall intensity and there is an occasional occurrence of a thin surface crust. Soil evaporation is a major component of the water balance due to low sowing densities (sparse canopy). Water storage in the sandy soils during the 8-9 month-long dry season is inefficient, and therefore technology development has been geared toward, a more efficient use of soil moisture during the growing season. Technical options for improving water-use efficiency include the use of short-cycle varieties, improved residue and surface management practices, intercropping, and soil fertility improvement.

Resume

Les recherches menees au Niger sur l'utilisation optimale de l'eau ont demarri dans les annees soixante-dix sur plusieurs themes. Les principaux themes de recherche ont porte sur la caracterisation physique et hydrodynamique des sols, l'utilisation de l'eau par les plantes, les techniques de conservation de l'eau et l'amelioration de l'efficience d'utilisation de l'eau. Les resultats indiquent que les sols utilises pour l'agriculture pluviale ont en general une faible capacite de retention de l'eau et sont donc susceptibles de presenter des pertes en eau par drainage

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profond au-dela de la zone racinaire lorsque la pluviometrie depasse les 300 mm environ. De meme, le ruissellement et l'erosion kydrique sont friquents du fait de l'agressivite des pluies et de la presence occasionnelle d'une fine croute superficielle. L'evaporation du sol est une composante majeure du bilan hydrique suite a la faible densite de semis des cultures (canopee eparse). La conservation de l'humidite du sol au cours des 8 a 9 mois de la saison seche est inefficace et le developpement des technologies a donc ete oriente plutot vers une utilisation plus efficiente de l'eau au cours de la saison de culture. Les options technologiques pour l'amilioration de l'efficience d'utilisation de l'eau comprennent entre autre l'utilisation de varietes a cycle court, la gestion des residus de culture et le travail du sol, les cultures associees et l'amilioration de la fertilite des sols.

Introduction

Efficient use of water, particularly rainwater, is a necessity for sustainable agricultural production in semi-arid Niger. Niger is a landlocked country located between 11°37'N and 23°33'N, and between 0° and 15°E with an area of 1,267,000 km^2 (Fig. 1), of which 62% is desert or subdesert (FAO 1993). The country has limited surface water resources and therefore agriculture relies predominantly on rainfall. The need for efficient water use is becoming even more pressing with the observed decline in rainfall over the last 30 years (Sivakumar et al. 1993). As exploiting groundwater resources is costly, rational use of rainwater is a high priority and the sole practical means of improving food security for the rural population.

Research and development activities on water-use efficiency have been carried out in Niger since the 1970s. This paper summarizes the results of that work, with emphasis on rainfed crops, followed by a discussion of the strengths and weaknesses of the research, future research orientation in the framework of OSWU, and opportunities for its implementation.

Characterization at the National Level

Climate

The climate of Niger is predominantly Sahelian (Fig. 1), dependent on the movements of the intertropical convergence zone. The rainfall is unimodal and falls between the months of May/June and September/October with large spatial and temporal variability. Annual rainfall varies from 800-900 mm in the southwest to less than 100 mm in the north (Sivakumar et al. 1993), with an average rainfall decrease of 1 mm km^{-1} latitude. A similar phenomenon occurs from west to east, creating an isohyet curvature towards the southeast, such that between Zinder and N'Guigmi the rainfall decreases by 0.6 mm km^{-1}. The temporal coefficient of variation for annual rainfall (1931-1990) increases from south to north: 17% in Gaya, 22% in Niamey, 27% in Tahoua, and 35% in Agadez.

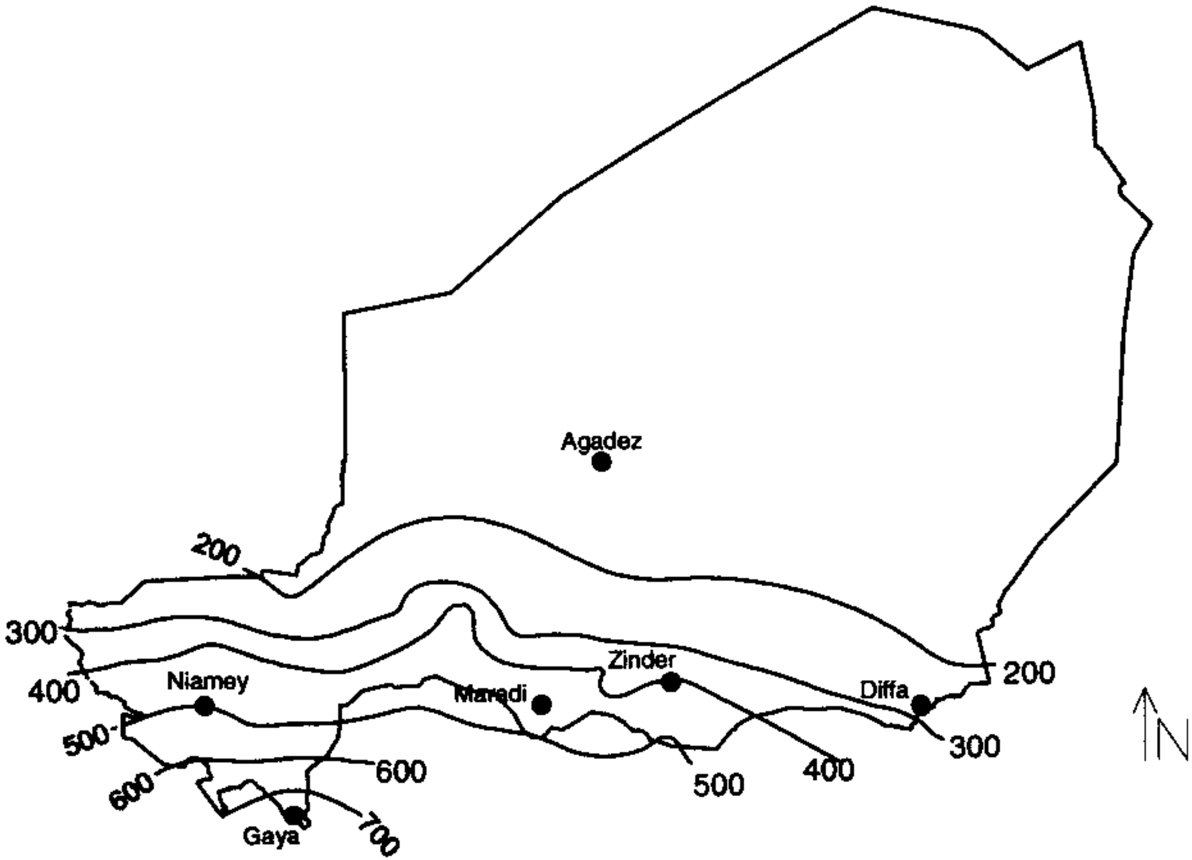

Figure 1. Map of isohyets in Niger (average 1968-1997).

An analysis of the rainfall time series since the beginning of the century shows three distinct periods (Sidikou 1998):

- until the 1940s, average rainfall conditions with substantial interannual rainfall variability; drought periods (1911-1914, 1941-1942, 1947-1949) never exceeded two years;
- from 1940 to 1968, a period of excess rain that diminished slightly between 1950 and 1967;
- from 1968 till the present, rainfall below the long-term average. Two drought periods in particular mark this period: 1972-73 and 1983-84. The aridification of the climate during this period has resulted in a shift of the isohyets towards the south (Caruci 1990; Sivakumar 1990).

The additional factors that characterize the semi-arid climatic conditions are: (1) low variability in hours of sunshine throughout the course of the year (from 8 to 10 h d^{-1} on average); (2) high air temperatures (T_{min}: 11-27°C; T_{max}: 28-41°C); (3) low average daily relative humidity (13% to 66%); (4) the alternating wind systems: the 'Harmattan', hot and dry northeastern continental wind, and the 'mousson', humid southwestern maritime wind; and (5) high annual evapotranspiration (2000-2800 mm). On the basis of these factors, Niger can be divided into three agroclimatic zones (Table 1).

Table 1. Selected characteristics of the main agroclimatological zones in Niger (FAO 1993).

Zone	Rainfall ($mm\ yr^{-1}$)	LGP[1]	Area (%)	Potential use
Desert and semidesert	<200	<15	62	Nil or very extensive livestock (except for oases)
Sahel	200-600	15-100	29	Agropastoral systems in the north, cropping in the south
Sudanian zone	600-800	100-120	9	Cropping and livestock[2]

1. Length of the growing period.
2. In the zones where drinking water supply is limited.

Soils

Soils in Niger have been classified into six major categories: Mineral soils ('sols mineraux bruts'), weakly developed soils ('sols peu evolues'), subarid soils ('sols subarides'), ferruginous tropical soils ('sols ferrugineux tropicaux'), hydromorphic soils ('sols hydromorphes'), and Vertisols (INRAN/ FAO 1997). The major soil types used for agriculture are the ferruginous tropical soils and hydromorphic soils.

The ferruginous tropical soils (FTS) have a sandy texture which makes them easy to till and suitable for the less-demanding crops like millet and sorghum, but they are very susceptible to wind erosion and, when affected by surface crusting, to water erosion. In the Niger river valley and in the Dallols (dry fossil riverbeds), FTS are found on the terraces which results in a certain hydromorphy and halomorphy that is often apparent on recent alluvium.

The FTS have physical and chemical characteristics that are very limiting to good plant (crops and pasture) production. The inherent chemical fertility is very low, especially in terms of nitrogen and phosphorus. In the absence of surface crusts, the water infiltration rate is high ($7\ 10^{-5}$ m s^{-1}), but the water-retention capacity (0.12-0.16 m^3 m^{-3} at -5 kPa) and the plant-available water (1% to 5%) are very low (Payne et al., 1991a). Despite the intrinsic high permeability of FTS, runoff is often observed during rainstorms. This results from the high rainfall intensity (> 100 mm h^{-1}; e.g. 30 mm in 6 min; Hoogmoed et al. 1991) and the susceptibility of these soils to surface crusting which reduces their infiltration rate to 5-20 mm h^{-1} (Casenave and Valentin 1991).

Hydromorphic soils are found along waterways, in Dallols, and in sediment deposits. They are commonly clayey in texture. Because of the presence of a shallow water table and depending on the water quality, these soils are sometimes affected by a salinization or alkalinization process, which negatively impacts their crop production potential.

Water Resources

Niger possesses a large groundwater potential, which is, however, poorly managed, insufficiently exploited, and serves only a very small area. The major source of surface water comes mostly from outside the country and is exploited within the country only to irrigate a limited number of projects where rice is the main crop. There are seven hydrological units including the Komadougou Yobe and the Niger river, the latter being the only permanent water source. In addition, there are 200 permanent and semipermanent lakes that reinforce the potential surface water supply, but their use depends highly on the erratic annual rainfall.

Underground water resources are more abundant and better distributed in space, but their exploitation is highly dependent on drilling and pumping costs depending on the depth of the water table. Renewable water resources represent 2,500 million m^3 and fossil water resources are of the order of 2,000 billion m^3 (Anonymous 1992).

The area of lands suitable for irrigation is estimated at 300,000 ha, of which 47% are located in the Niger river valley. Around 15,000 ha are presently cultivated using modern irrigation methods (11,000 ha in controlled hydroagricultural irrigation schemes) and 67,000 ha using traditional management.

Agricultural Production Systems

Three main rainfed production systems can be distinguished on the basis of climatic and agroecological conditions: pastoral, agropastoral, and crops (Sidikou 1998). The dominant crops are millet *(Pennisetum typhoides),* sorghum *(Sorghum bicolor),* cowpea (*Vigna unguiculata),* and groundnut (*Arachis hypogaea).* Rainfed crops are often intercropped: e.g., millet/cowpea, millet/sorghum, and millet/groundnut. Relay cropping is not widely practised because of the short duration of the rainy season. In the agropastoral and crop production systems, traditional water management is practised in the following ways:

- early sowing, or even dry sowing, to exploit as best as possible the full length of the rainy season. On sandy soils (>90% sand) land preparation is not common and sowing is usually done after the first rain exceeding 15-20 mm. On heavier soils, plowing or hoeing precedes the first sowing. Soil preparation is done manually or using animal traction. On these soils, sowing is usually delayed until the second half of June or early July in order to ensure sufficient soil water storage prior to sowing;
- sowing of the main crop (cereal) in hills at low densities (3,000-6,000 hills ha^{-1} with three plants per hill) to increase the relative availability of water and nutrients;
- growing of an intercrop: The sowing of the intercrop (usually a legume) is delayed as determined by the evolution of the rainy season;
- frequent weeding (2-3 times per season); and
- in some cases, use of traditional or improved soil and water conservation technologies such as the 'Zai', contour stone bunds, or 'demi-lunes' to retain or even harvest runoff water and improve water infiltration.

Millet (on 5 million ha) and sorghum (on 0.8 million ha) represent 75% and 20% of the total cereal production of Niger, respectively. The amount of land cultivated with food crops is increasing each year at the expense of fallow, cash crops, forests, and marginal lands. The average grain yield in Niger is 300-400 kg ha^{-1} for millet and 500 kg ha^{-1} for sorghum (Sidikou 1998). However, the potential grain yield of cereal crops is of the order of 2,000-3,000 kg ha^{-1}.

Rice constitutes the main irrigated crop in Niger, with two crop harvests per year and yields of up to 4-5 t ha^{-1} per season. This is possible along the Niger river with a year-round water supply. Other irrigation systems can only be practised for a few months each year and are based on gravity irrigation using dams, on the pumping of water from temporary lakes or on the sowing of crops (sugarcane, manioc, sorghum, calabash, and squash) as the surface water recedes (recession agriculture). Finally, underground water resources are sometimes exploited, especially when the water table is shallow such as in the Dallols (e.g. the Tarka valley), or in temporary streams. The main constraint in this case is the cost of water lifting. Irrigation is usually used for cash crops, including rice, vegetables, and fruits.

Population and Socioeconomic Aspects

In 1997, the population in Niger was about 9.2 million inhabitants, of which 83% was living in a 100-150 km wide belt in the south of the country. Given the current growth rate of 3.7%, one of the highest in the world, the population is expected to reach 18 million by 2025 (Anonymous 1994), which means an increase in food needs. The population density varies from region to region and sometimes exceeds 100 inhabitants km^{-2} (Sidikou 1998).

In many ways, socioeconomic factors limit the development and adoption of technologies by farmers. For instance, adoption of antierosion measures and runoff water management on a larger scale than privately owned fields is difficult in the traditional production systems, because it requires a communal approach. In addition, the labor and financial requirements to implement these technologies often exceed household capacity, and the organizational structure is often inadequate. Other factors include low purchasing power, absence of credit, and lack of markets. Modernization of the agricultural sector remains very limited due to the lack of a long-term national policy.

Animal husbandry, the second pillar of agricultural development, contributes about 18% to the BNP, and directly involves nearly 20% of the population (Sidikou 1998). Socioeconomic and climatic changes affect this sector too. In particular, one observes a change in the current timing of migration and grazing patterns, resulting in reduced fertilization of the land by manure and, therefore, a reduction in crop yields and water-use efficiencies.

Research on Rainwater Management

Water management research started in the 1970s with a study on water erosion and on the water needs of various crops in the Tillabery, Lossa-Sona, and Maradi regions. In the 1980s, research intensified due to the installation of various research institutes (INRAN, ICRISAT, IRD (formerly ORSTOM), University of Niamey, AGRHYMET) and many projects involving scientists from Europe and USA. The subjects researched have included water-balance modeling and improvement of water-use efficiency using conservation techniques. A summary of the main results follows.

Water Collection, Infiltration, and Erosion

Land morphology, surface microtopography, and surface characteristics (crusting, litter, etc.) determine the partitioning of water between infiltration and runoff. Research on erosion was started by Delwaulle (1973) in the village Allokoto. In the Hamdallaye watershed, approximately 40 km east of Niamey, Manu et al. (1994) estimated erosion at 1.8 t ha^{-1} during a one-hour simulated rainfall event at a rainfall intensity of 150 mm h^{-1} and an infiltration rate of 40-45 mm h^{-1} in the bare areas between plateau bushes (Table 2).

Although runoff can be viewed locally as a loss of water, the redistribution of water due to runoff often does not extend beyond a few hundred meters, frequently less. Seguieri et al. (1994) have shown that redistribution of water through runoff forms the basis for the typical vegetation pattern observed in the so-called "tiger bush". On a transect across a tiger bush vegetation on a Continental Terminal plateau, the maximum depth of wetting front varies considerably. Downstream of the wooded

Table 2. Water erosion rate and soil loss at different sites under various landscape positions, vegetation, and soil surface types in Niger. References: 1 = Delwaulle (1973); 2 - Manu et al. (1994); 3 = Zanguina (1996); 4 = Flitcroft et al. (1991); 5 = Hoogmoed et al. (1991); and 6 = Rockstrom and Valentin (1997).

Location	Runoff coefficient (%)	Landscape position	Vegetation and soil surface type	Erosion (t ha^{-1})	Reference
Allokoto	16	-	-	3-6	1
Hamdallaye	55	Hill slope	-	-	2
		Plateau	Bushes, loamy	4.5	3
	-		Between bushes, loamy	8.0	3
			Sandy soil, cultivated	0.03	3
	-	Valley	Fallow, sandy soil	0.5	3
			Sandy soil, crusted	1.9	3
Ibeceten	40	-	-	-	4
Sadore	1	Plateau	Sandy, millet - simulated rainfall	-	5
	20	Plateau	Sandy, millet, crusted - simulated rain	-	5
Samadey	12-13	Up-slope	Sandy, millet; crusted soil	-	6
	9-11	Mid-slope	Sandy, millet; crusted soil		6
	6-8	Down-slope	Loamy, millet; crusted soil		6

1. = (runoff/rainfall) x 100; - - not available.

band the wetting front reached 3-4 m, 5-6 m within the wooded area, and 1 m at the upstream part of the band. These observations are explained by the presence of a bare, crusted strip of land upstream of the vegetation band, which generates runoff water during heavy rainfall events. This runoff water infiltrates together with the direct rainfall within the vegetation band as a result of the presence of litter and intense biological activity. In essence, the tiger bush system constitutes a natural water harvesting system.

The same principle was applied on dune soils by Zaongo (1988) who tested the use of strips of plastic film to induce runoff and increase the volume of water that infiltrates between the strips. The concentration of runoff between the plastic strips resulted in an increase in available water by 41%, and in a millet grain yield gain of 61% to 119%. This increased available water also allowed deeper rooting of rainfed crops.

Gaze et al. (1997) showed that on sandy soils with a superficial crust the redistribution of rainfall by runoff during intense rainfall events results in a rainfall concentration factor (RCF = volume of water infiltrated/volume of rainfall) varying between 0.3 and 3.4 within the same experimental field. This induces a large within-field spatial variability in crop water supply. Brouwer et al. (1993) have argued that this is a major determinant of the observed spatial variability in crop growth and may significantly impact crop survival during periods of drought.

Hoogmoed et al. (1991) have shown that soil tillage on sandy soils increases the water storage capacity in the surface layer and reduces runoff. However, this effect is shortlived and surface crusts reappear after just a few rainfall events.

Casenave and Valentin (1991) described 11 soil surface feature classes with different permeability. For each surface feature type, they provided empirical relationships from which runoff can be estimated. Fox (1994) used these relationships to estimate runoff in the watershed basin of Samadey (western Niger). His results indicate that very often the quantities predicted for different surface features exceed those measured. The level of correlation between the measured values and those estimated is 74%, applying the surface feature model on the basis of the total amount of water accumulated.

The spatial variability in soil moisture resulting from runoff constitutes a major problem for crop production as well as for livestock and forestry. Therefore, several agricultural development projects have adopted water runoff management techniques to increase water storage and above-ground biomass production. One of the first projects in this domain was the Keita Integrated Project (FAO 1995). It is working on (1) soil reclamation; (2) antierosion measures on slopes by building contour bunds protected by stones or trees when the slope is very steep; and (3) control of koris with small dams to hold water and recharge the water table. Following the success of this project, other projects have used similar techniques in association with traditional water conservation methods and increased fertilization (Zai or Tassa, rock bunds, etc.).

Drainage and Water Table Recharge

Because of the sandy texture of the soils used for rainfed crop production in Niger, drainage can be a major factor in the water balance. It is rather difficult to measure and requires information on rooting depth. Drainage measured below the rooting zone was estimated at 47% of rainfall for nonfertilized millet and 33% for a field with a higher level of fertilization (Klaij and Vachaud 1992). With the HAPEX-Sahel experiment, several specialists studied the effect of drainage on the recharge of water tables. In an area covered by tiger bush, Bromley et al. (1997) estimated that only 13 mm (less than 3% of the annual rainfall) reaches the water table. Desconnets et al. (1997) estimate infiltration from temporary ponds may contribute between 10 mm and 80 mm of water (expressed over the area of the watershed) to groundwater recharge.

At a watershed scale, the use of check dams has allowed for the recharge of water tables to such an extent that it has become possible to grow flood-retreat crops (FAO 1995). Such structures can, however, have a nonnegligible impact downstream. For instance, three structures and a dam constructed in Nigeria nearly stopped the flow of water to Niger and consequently the recharge of the water table. This has deeply affected the possibilities for full or complementary irrigation in the Goulbi valley of Maradi (Dan-Jimo 1996). Despite the work done on a large scale by IUED, PCGES, GTZ, etc. projects on limiting water runoff and on increasing water infiltration in the soil, no systematic data collection was done on water table variation. One such project is currently underway to gather data and model recharge rate in the Tarka Valley.

Soil Evaporation and Transpiration

Soil evaporation is a major component in the water balance. In a tiger bush area, it represents on average 4 mm d^{-1} during the rainy season and 1.5 mm d^{-1} during the dry season. On average, sandy soils lose 1-2 mm d^{-1} during the rainy season though actual evaporation is high only for the first day after rainfall, thereafter decreasing below 1 mm d^{-1} as a result of a dry-mulching effect (Culf et al. 1993).

Evapotranspiration of millet ranges from 35-45% (Wallace 1991) to about 79% of rainfall (Payne et al. 1991b) depending on the environmental conditions and the cultural practices (sowing density, organic manure, weeding, etc.). Soil evaporation may represent 41-61% of the monthly rainfall during the rainy season (Payne et al. 1991b). Compared to total evapotranspiration (ETR) for a millet crop, soil evaporation may represent 50% immediately after the rain, and 20% 2 days after (Gash et al. 1997). Nouri and Reddy (1991) reported that evaporation represented 78% of ETR for millet and 72% for a millet/cowpea intercrop.

Using an ETR simulation model for millet, Amadou (1994) calculated that soil evaporation may exceed 50% of ETR from the beginning of the cycle until the LAI becomes 1.5, and represents on average 40% of ETR for the entire crop cycle. According to Rockstrom (1997), adding fertilizer only slightly affects soil evaporation, but it changes the transpiration of a millet crop from a maximum of 15% of ETR under conditions of low fertility to about 30% with the application of 30 kg ha^{-1} of both N and P. These results were obtained on-farm at very low sowing densities, resulting in a maximum LAI of about 0.5-0.7.

In conclusion, water loss due to evaporation varies from 1mm d^{-1} to 4 mm d^{-1}, implying that the soil layer where annual crop roots are found is quickly depleted. Hence, rainfall regularity is essential for rainfed crop production on the sandy soils traditionally used for millet cultivation. Given the observed irregularity, improved infiltration and water conservation techniques have to be developed.

Water Needs and Water-Use Efficiency

The water-use efficiency (WUE) of millet varies from 1 kg ha^{-1} mm^{-1} to 8 kg ha^{-1} mm^{-1} depending on the water and crop management practices such as fertilization (Table 3).

Table 3. Selected results on water-use efficiency (kg ha^{-1} mm^{-1}) of millet and cowpea as measured by grain or seed yield at various sites in Niger. References: 1 = Gandah (1988); 2 = Payne (1997); 3 = Sivakumar and Salaam (1999); and 4 = Sivakumar et al. (1996).

Crop	Location	Observations	WUE	Reference
Millet	N'Dounga	30,000 plants ha^{-1} normal sowing	1.8	1
		80,000 plants ha^{-1} normal sowing	2.7	1
		30,000 plants ha^{-1} late sowing	1.3	1
		80,000 plants ha^{-1} late sowing	1.1	1
	Sadore	5,000 (1984-1983-1985)[1]	1.3-2.5-2.8	2
		10,000 (1984-1985-1983)[1]	1.5-3.5-7.8	2
		20,000 (1984-1985-1983)[1]	1.7-3.2-7.3	2
		Low fertility (1984-1990-1983)[1]	1.2-1.4-4.5	2
		Medium fertility (1984-1990-1983)[1]	1.7-3.0-7.2	2
		High fertility (1984-1990-1983)[1]	1.6-3.6-5.9	2
		Sadore local (1984-1990)	1.0-2.2	2
		CIVT (1984-1985)	1.7-3.3	2
		1CH 412 (1984-1985)	2.2-3.5	2
		P3-Kolo (1990)	3.6	2
		CIVT (1984-1987) non-fertilized	1.8	3
		CIVT (1984-1987) 45 kg ha^{-1} N, 13 P	3.1	3
Cowpea	Sadore	IT82D-716 (1985, 1986)	1.6-2.7	4
		IT83S-947 (1985, 1986)	2.1-4.1	4
		TVX 4659-03E (1985, 1986)	2.5-4.9	4
		Sadore local (1985, 1986)	0.1	4

1. Varieties changed over years, hence no average given. Medium fertility = 23 kg N ha^{-1} and 8.8 kg P ha^{-1}. High fertility is twice the rate of medium fertility.

Given the water needs of windbreaks of 29.2 dm^3 d^{-1} m^{-1} (Brenner et al. 1991), the efficiency of using windbreaks in crop protection may be limited due to the competition for water. This was observed and simulated with a millet-windbreak simulation model by Mayus (1998). Smith et al. (1997) have shown that the influence of windbreaks on crops depends on the depth of the water table.

Water-use efficiency is determined by the sowing pattern of crops. The ETR for a millet/cowpea intercrop is 360 mm compared to 330 mm for millet alone, resulting in increased water-use efficiency in the intercrop by 36% (Nouri and Reddy 1991).

Another way to increase WUE (and yield) includes higher sowing density and timely sowing (Gandah 1988). Early sowing (beginning of June) increases WUE, and sowing after early July decreases WUE (Table 3). Increasing the sowing density increases the risk of drought, as demonstrated in the same study when a two-week drought spell killed plants at higher density. This effect was, however, not observed in all the years. Payne (1997) observed no significant millet yield difference for sowing densities between 10,000 and 20,000 hills ha^{-1} in 1984, a year with a major end-of-season drought (rainfall 50% below average; Table 3).

Although modest fertilizer application increases total evapotranspiration by only 5% to 15% on an average for sparse millet canopies on sandy soils, WUE is usually greatly increased (e.g. up to 84%; Sivakumar and Salaam 1999) as a result of fertilization because of the observed large yield increases on these very nutrient-deficient soils. Fertilization of millet increased ETR from 211 mm to 268 mm, but biomass increased from 1.14 t ha^{-1} to 3.8 t ha^{-1} (Klaij and Vachaud 1992). This effect will be further discussed later. Payne (1997) observed between 60% and 110% increase in WUE as a result of modest fertilizer application, except in a severe drought year (1984) when the response to fertilizer was negligible (Table 3).

The use of short-duration varieties can, under certain circumstances, significantly improve WUE. Although they cannot be expected to outyield longer-duration varieties at similar sowing densities, such short-duration varieties can escape end-of-season droughts and thereby produce higher grain yields. This was observed by Payne (1997) for the 1984 season, where the use of 90-day varieties increased WUE by 70% to 120% over the local 120-day variety (Table 3).

Modeling

Various models have been tested at the field level and sometimes at the regional level. For instance, using daily rainfall data as input in a deterministic water-balance model, Flitcroft et al. (1991) confirmed the spatial variability of factors such as infiltration, transpiration, and drainage. Since 1988, a crop water diagnostic model (DHC) has been tested in CILSS countries in collaboration with AGRHYMET in Niamey (Forest and Cortier 1991). This model calculates a grain yield index (Y) for millet or sorghum as a function of the degree of water requirement satisfaction during the most critical development stage (flowering), taking into account ETP-Penmann, daily rainfall, and soil moisture, following:

$$Y_i = \frac{ETR_{cycle} \times ETR_{period}}{ETM_{critical}}$$

where, ETM = Maximum Evapotranspiration.

A good correlation was observed between the grain yield index and grain yield (Y, kg ha^{-1}) for millet in Niger (Y = 10.9 Y + 52.7; r^2 = 0.70). This model has also been used to define agroecological zones, and zoning of crops using different sowing dates (Forest and Cortier 1991).

Using simulation modeling, Amadou (1994) concluded that (1) drainage is an important term of the water balance; (2) WUE can be increased by fertilization; (3) there is an important difference between the amount of water consumed by millet (ETR) and rainfall; and (4) the intraseason rainfall distribution is more important for crop production than the absolute rainfall amount. The latter was confirmed by Flitcroft et al. (1991) using a water management model.

The SWATCH model was used to calculate water flow at the watershed level (Peugeot et al. 1994). For cultivated fields, the model predicts runoff satisfactorily, but with less accuracy for fallow land due to surface changes during the course of the season. For example, the model predicts that 45% of the runoff infiltrates on the slope, 25% in the stream bed within the watershed, and the remaining 30% is lost to a downstream outlet.

Water and Nutrient Interaction

The interactions between water and nutrient availability are complex, often making it difficult to diagnose the principal limiting factors for a crop. Crop response varies from northern to southern Sahel, from one soil type to another, from one year to the next, and from one part of a field to another.

In general, the nutritional status of a crop affects WUE through its influence on canopy development and ground cover, thus regulating the E/ET ratio (greater leaf area increases T, denser canopy decreases E), and through effects on root development, leaf senescence, photosynthesis, and transpiration efficiency. The efficiency of nutrient use is dependent on the soil moisture status, which affects root development, nutrient diffusion and uptake by roots, and transpiration rate. In addition, WUE expressed on the basis of grain yield is strongly determined by the phenological stage at which water stress occurs (Rockstrom and de Rouw 1997).

Mineral phosphorus (P) application has large effects on millet root development and on WUE in the P-deficient sandy soils. An increased P level not only causes increased root density, but also increased rooting depth (Payne et al. 1991c, 1992, 1994, 1995). In addition, WUE_t (kg grains/mm of water transpired) increases with P application (Payne et al. 1991c/1992, 1995). In case of water stre s, WUE_t decreases compared to nonstressed plants, but increases when the total biomass is used to calculate $WUE_{t\text{-}total}$. This demonstrates not only the importance of good plant nutrition for WUE, but also that it is important not to use only WUE_t as the criterion while evaluating production techniques.

Because of the low soil fertility and the unequal distribution of rains, the interactions between availability of water and nutritional elements play a crucial role in the evaluation of production systems in the Sahel. Increasing the water supply does not necessarily lead to a substantial increase in yield. This is illustrated by a millet grain yield of 1807 kg ha'^{1} on a fertile field in a wet year, but only 256 kg ha^{-1} in a year with a drought spell during millet flowering, the most drought-sensitive phenological stage in millet. Another plot of land, less fertile to begin with, produced 634 kg ha^{-1} of grains in the wet year and 678 kg ha^{-1} in the dry year (Hermann 1991). It is also clear that the same parts of a field need not be the most productive during a wet or a dry year (Brouwer et al. 1993). These authors suggest that during a dry year only the lower, wetter parts of a field produce acceptable yields, despite lower fertility. In a wet year, the lower parts produce relatively little as compared to the more elevated parts which also receive sufficient water but are less leached and therefore more fertile.

All measurements on water use with mineral or organic fertilizer indicate that with a slight increase in total evapotranspiration, the water-use efficiency increases significantly (Klaij and Serafini 1989; Gandah 1988). However, the effect of chemical or organic fertilizer may be limited by insufficient water availability. Hence, techniques toward improving the crop production systems of the Sahel need to take into account improvements of both soil fertility and water availability. This explains why the Zai' technique, a soil and water conservation technique that addresses both constraints and is relatively low-cost though labor-intensive, is applied more often by farmers than those techniques that aim at controlling only one factor (such as stone lines, half-moons, fertilizer, etc.).

Water Management Techniques and Cultural Practices

Several water management techniques exist and have been transferred to farmers (PDRT 1997):

- Zai, a traditional water harvesting and nutrient management system in which small quantities of organic amendments are hill-placed in small holes (25-40 cm diameter, 15 cm deep) that act as water harvesting devices. The technique is usually used for rehabilitation of chemically poor, severely crusted, or compacted soils;
- Stone lines, a traditional system of runoff water control using lines of stones placed along the contour lines. This system has secondary benefits of wind erosion control;
- Half-moons, a relatively new system for low permeability soils. A small catchment 1-2 m in diameter in the shape of a half-moon acts as a water harvesting device. It is used for rehabilitation of cropland and afforestation;
- Tied ridges done at weeding time to improve storage and infiltration of water;
- Holes dug late in the growing season, similar to Zai, but dug during the growing season to avoid filling by windblown sand; and
- Plowing before or at the beginning of the growing season, another traditional technique from the Adar region, which also improves infiltration and results in 60-70% higher millet yields compared to nonplowed soil (GTZ 1997).

Maintaining water in the soil profile during the dry season until the next growing season is very difficult, and can certainly not be done through mulch or bare fallow (Payne et al. 1990).

Cereal-legume relay-cropping has been proposed by Sivakumar (1990) to increase water-use efficiency. The system is based on the early sowing of a short-duration millet crop, followed by a crop of cowpea, which will mature by making maximum use of the residual water. The system necessitates the adoption by farmers of short-cycle millet varieties, and a harvest late in August to allow for the establishment of the legume, and a normal or early cropping season. Using millet with a 70-day cycle sown at the beginning of July increases the chance of success between 29% and 100% compared to a 90-day variety. If rains start in May, a 90-100-day variety can be used (Eldin 1991).

Supplemental irrigation has been implemented in some of the irrigation schemes for crops other than rice (e.g. cotton, sorghum, and maize) to avoid significant yield decreases or even crop failures. This type of water management is used in fields with water supply from small reservoirs or with a high water table. The financial returns from supplementary irrigation may exceed investments, as demonstrated for sorghum by a 108,000 FCFA (177 US$) return for a 5,000 FCFA (8 US$) investment (Sawadogo 1997).

Analysis and Interpretation of Past Research

Efficient Water Management and Improved Agricultural Production

The main sources of water loss are runoff, evaporation, and drainage. Runoff is most significant on plateaus, slopes, and even on sandy aeolian soils where surface crusting affects local redistribution of water. Local redistribution often does not constitute an important loss of water at the field level, but is rather a redistribution of water within the fields, leading to increased spatial variability in crop growth. In practice, farmers manage crops on the basis of indigenous knowledge by using intercrops and species with low water needs, and a sowing strategy to avoid water stress. This adaptation to agroecological conditions has developed over a long period but has now become partially inadequate in view of the rapid climatic variations of the last 30 years (i.e., reduction of average rainfall).

Evaporation is an important component in the water balance due to climatic conditions and the practice of low sowing density of the main cereal crops. Drainage beyond the rooting zone is important because of the low water-holding capacity and rapid drainage of the sandy soils, especially during August when the rains are abundant.

Large differences exist between the on-farm yields (300-400 kg ha^{-1}) and the potential yields demonstrated by research institutions (2-3 t ha^{-1} for millet and sorghum). Essentially, inadequate water and nutrient supplies for plants cause this large disparity. Regarding water supply, even in low rainfall years, a good distribution in space and time will assure acceptable crop production. Increased nutrient availability for crop uptake (especially P) will greatly improve water-use efficiency. Research into efficient water management thus can not be dissociated from soil fertility aspects. The difference between on-farm yields and potential yields cannot be attributed solely to differences in water and nutrient management practices. Other factors, such as control of pests and diseases, also contribute to the achievement of crop yield potential.

Water Management and Improved Socioeconomic Conditions

Crop production systems and socioeconomic conditions are interdependent and play a primary role in the low water-use efficiency and in the low adoption of improved agricultural techniques by farmers. The use of new crop species, application of cultural techniques (such as mineral fertilizers), and improved water management techniques often come into conflict with socioeconomic conditions. Some management options require measures to be implemented at the landscape level, implying communal action, which is often difficult to organize. For instance, water management in the Hamdallaye watershed shows that the plateau is the major source of erosion. This is communal land. However, implementing and maintaining antierosion measures and tree-planting, a collective responsibility, are not always seen as important by farmers, who often prefer to work on their own fields. In addition, such communal land is often exploited as grazing land by nomadic or seminomadic ethnic groups, whose participation in communal activities is even more difficult to ensure.

The lack of financial resources and/or a weak credit system is another constraint to adoption of new technologies. An alternative strategy, used by development projects, is to create awareness among farmers of principles required for collective actions, train them in different soil and water conservation techniques, and launch 'food for work' programs that reward farmers for their collective work.

Future Research Activities

The research carried out by INRAN and collaborating institutions has strengths and weaknesses that affect future research and impact. For instance, past research was not coordinated to solve the defined problems of water management. Hence, integration of research and existing results is needed to solve the problems of farmers in this research domain.

The strengths of INRAN include: (1) linkage with development projects that are ready to use acquired research results; (2) access to indigenous cereal and legume species that have low water needs and short growing cycles which can be used in alternative water management techniques; (3) ability to provide a range of recommendations with different levels of inputs to the various types of farmers to increase yields; and (4) through participation in international networks (e.g., Desert Margins Program and OSWU) and collaboration with international research institutions, access to potential support for research on optimizing rainwater use and opportunities to profit from the experiences of other institutions under similar agroecological conditions.

The weaknesses of INRAN include: (1) the nonexistence of a long-term research program regarding optimizing soil water use; (2) research programs that insufficiently exploit knowledge from more experienced institutions not represented in Niger (ICARDA, CAZRI, etc.); and (3) insufficient funding to allow long-term research.

On the basis of an analysis of past research on rainwater management in Niger, and in the context of INRAN's research capacity and the national agricultural production priorities, the following main future research thrusts can be identified:

- Reduction of runoff and/or efficient use of runoff water on the plateaus and other areas subject to erosion. Research should focus on techniques to reduce runoff, increase infiltration to improve soil water storage levels, increase surface water storage to be used in supplementary irrigation, etc.

- Reduction of drainage and soil evaporation by crop management practices that allow a more efficient water use by transpiration (e.g. increased fertility, increased sowing density, relay-cropping, intercropping) that are fully acceptable to farmers.
- Limit water erosion on the slopes to reduce sedimentation in water reservoirs and rivers (through tree-planting, antierosion measures, etc.), with associated consequences of reduced environmental risks and preservation of wet areas. This also includes identification of mechanisms to involve the farmers in addressing relevant field-scale management issues.
- Research on the methodology of upscaling results obtained at experimental stations or on-farm to a region or a country by using simple models.
- Inventory of 'who (NGOs, research institutions, and development projects) is doing what' in Niger in the field of soil water-use efficiency (including soil and water conservation) and analyze their experiences to define new recommendations, taking into account both socioeconomic and agroecological conditions.

Conclusion

Research on optimizing soil water use in Niger has focused on various aspects of the water balance, with emphasis on technical aspects at plant and field levels. Some socioeconomic constraints have been identified and need to be addressed in future research in this domain. Other future research topics include working beyond the field scale and improved exchange of information among the stakeholders in Niger.

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Optimization of Soil Water Use in the Dry Crop Production Areas of South Africa

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Abstract

The wide variation in its natural agricultural resources makes South Africa a country of great diversity. This exemplified in the rainfall and production-potential maps presented, and also by the wide variety of crops grown and production techniques employed. The latter range from advanced technology to traditional subsistence procedures. Of the total area, less than 14% is arable and less than 4% of high potential, with rainfall the main limiting factor. Maize and wheat are the main cereal crops. Results are presented of extensive on-station and on-farm research to quantify water losses through evaporation, run-off, and deep drainage, and on measures to minimize these losses, such as mulching, soil surface modification, and sowing patterns. Success depends on correct technique/ soil type matching. Increased soil water storage through fallowing, improved infiltration and water harvesting have received some attention. Reset rch needs include studies about the simultaneous optimization of soil water and nutrient use, water harvesting, and mulching to reduce evaporation losses. A crop growth simulation model, with a rainfall-intensity subroutine, which has proved reliable for different soil-climate-crop combinations in dry areas is needed to extrapolate research results and make long-term yield predictions to quantify productivity and facilitate matching of farmer needs and farm size.

Resume

Les grandes variations observees dans les ressources agricoles naturelles font de l'Afrique de Sud un pays d'une grande diversite. Cette diversite se retrouve dans les cartes pluviometrique et de potentiel de production, ainsi que dans la grande variete des cultures et des techniques de production

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utilisees. Ces dernieres vont depuis des techniques traditionnelles de subsistance jusqu'aux technologies avancees. Moins de 14% du pays est cultivable, et moins de 4% est a haut potentiel, la pluviometrie etant le facteur le plus limitant. Le mats et le ble sont les cultures cerealieres principales. On presente ici les resultats de recherches approfondies en station et en milieu paysan sur la quantification des pertes en eau par evaporation, erosion et drainage profond, ainsi que le developpement de mesures qui minimisent ces pertes comme le paillage, la modification de la surface du sol et la geometrie de plantation. Le succes depend du choix de la technologies appropriees pour chaque type de sol. Laccent a ete mis sur l'augmentation du stockage de l'eau du sol par la jachere, l'amelioration de l'infiltration et les techniques de collecte de l'eau. Les priorites de la recherche incluent les etudes sur l'optimisation simultanee de l'utilisation de l'eau et des nutriments, la collecte de l'eau, et le paillage pour reduire les pertes par evaporation. En plus, il convient de developper un modele de simulation de croissance des cultures comprenant un module d'intensite pluviometrique dont la fiabilite a ete eprouvee pour differentes combinaisons de sol-climat-culture dans les zones seches, afin de pouvoir extrapoler les resultats de la recherche et de faire des predictions de rendements a long terme pour quantifier la productivite et faciliter l'ajustement des besoins du producteur a la taille de leur exploitation.

Characterization of Dryland and Rainfed Crop Production Systems

South Africa occupies the southern most part of the African continent and lies between latitude 22°S and 35°S and longitudes 17°E and 33°E. It comprises nine provinces (Fig. 1) and shares boundaries with Lesotho, Swaziland, Mozambique, Zimbabwe, Botswana, and Namibia. The wide variation in its natural agricultural resources, especially climate, soils, and topography, makes South Africa a country of great diversity. The conditions range from semidesert to subtropical rain forests; from floods to severe droughts; from snow in winter to heat waves in summer; from winter to summer rainfall, and from barren sand dunes to soils of high productivity. Such variety enables the country to produce a wide range of agricultural commodities, but at the same time demands managerial skills of a high order to prevent overexploitation of the natural resources. South Africa is a world in miniature, a fragile and unique system of nature with resources of great value to man. It poses many challenges for the future. One such challenge is how to optimize the use of one of the country's scarce natural resources, namely water (Scotney et al. 1990).

The Natural Resource Base

South Africa covers an area of 122.34 million ha, with less than 14% of it suitable for dryland and rainfed cropping (as defined by Stewart and Burnett 1987), of which

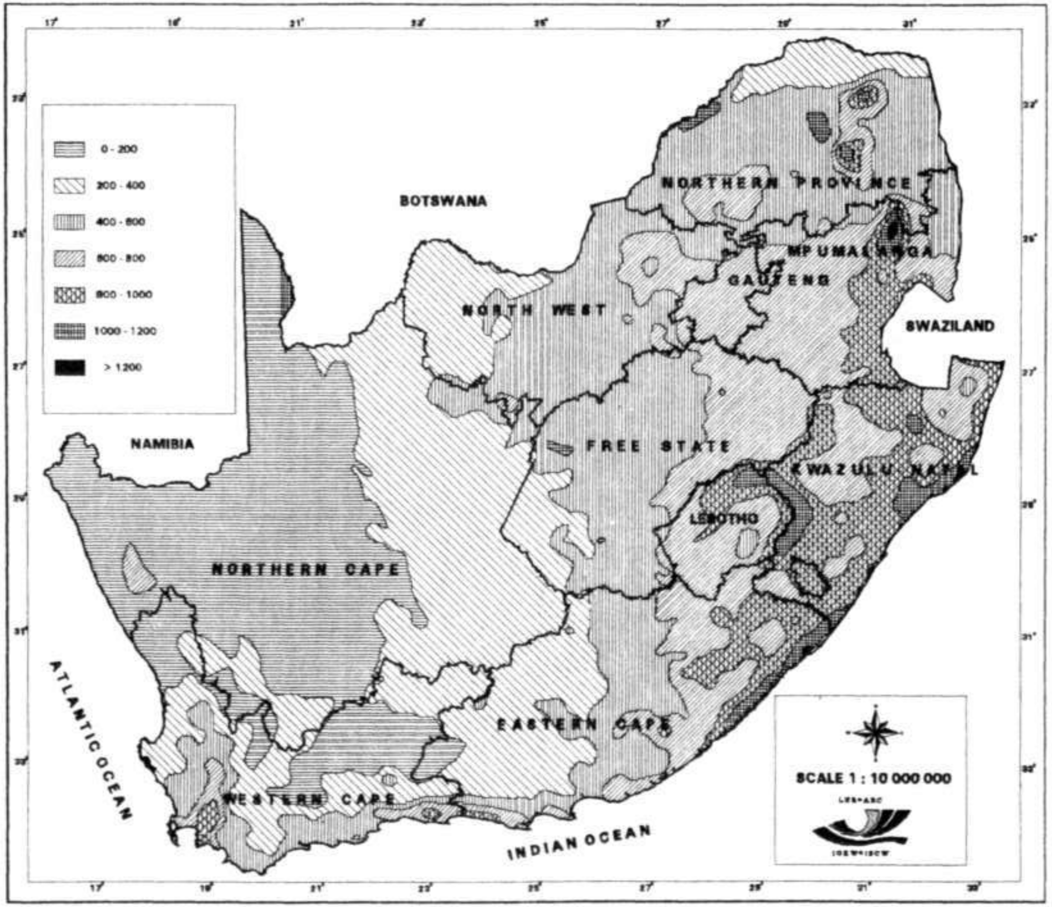


Figure 1. Mean annual rainfall (mm) in South Africa.

only about a quarter is land of high potential. Rainfall, both total and seasonal distribution, plays a dominant role in determining the resource situation, crop selection, yield horizons, and risk of agricultural production. There are two main rainfall regions, namely a winter rainfall region in the southern part of the country, which includes a small all-year-round rainfall area, and a summer rainfall region, which covers the remainder of the country. There is an increase in annual rainfall from less than 125 mm along the arid west coast to more than 1000 mm on the eastern seaboard (Fig. 1). The mean annual rainfall is 511 mm, but more than 60% of the country receives less than 500 mm per annum. Rainfall is extremely variable with wide deviations from the mean annual values, especially in the low-rainfall areas. The country is characterized by the occurrence of regular droughts of varying intensity, some of which may have devastating consequences. In contrast, severe floods are also not uncommon (Scotney et al. 1990).

The composition of the soil mantle of South Africa is well understood. An efficient soil classification system has been developed (SCWG 1991), and the task of mapping the soil patterns in the form of a 'land type' survey on a scale of 1:250,000 for the whole country is nearing completion. Around 6000 land types and 2300 climate zones have been defined, and 2000 modal soil profiles have been described and analyzed. In the areas of high potential for cropping (Fig. 2) the two main soil types are *(1)* fairly deep, red and yellow well-drained soils with a medium-to-high clay content; and (2) medium-textured soils with a plinthic horizon at depths of between 600 mm and 1200 mm.

The main soils in the medium-potential cropping areas are (1) soils with a plinthic catena as described above, but with a lower rainfall, and (2) soils with a high clay content, many of them Vertisols.

Figure 2 reflects the distribution of several crop-potential classes over the country, although the extent of land suitable for cropping may vary considerably within each class. The latter was derived from soil, terrain, and climate data, with the aid of crop simulation models, assuming good management practices. The scarcity of high-potential agricultural land in South Africa is quite evident from the map, making it a critical resource that should be preserved at all costs.

Crops and Management Practices

Winter Rainfall Region

Under the Mediterranean climate of the southern coastal area the annual rainfall can vary from 200 mm to more than 3000 mm in the mountainous areas, with the main (80-85%) incidence being between April and September. This gives rise to hot and dry summer months. The eastern part is primarily a sowing and grazing region where small grain (wheat and barley) and stock farming on established pastures are practised complementary to each other under an annual rainfall of 350-500 mm. In the western part wheat is the major crop grown primarily in a monoculture system under an annual rainfall of 250-500 mm. In both areas, dryland viticulture is

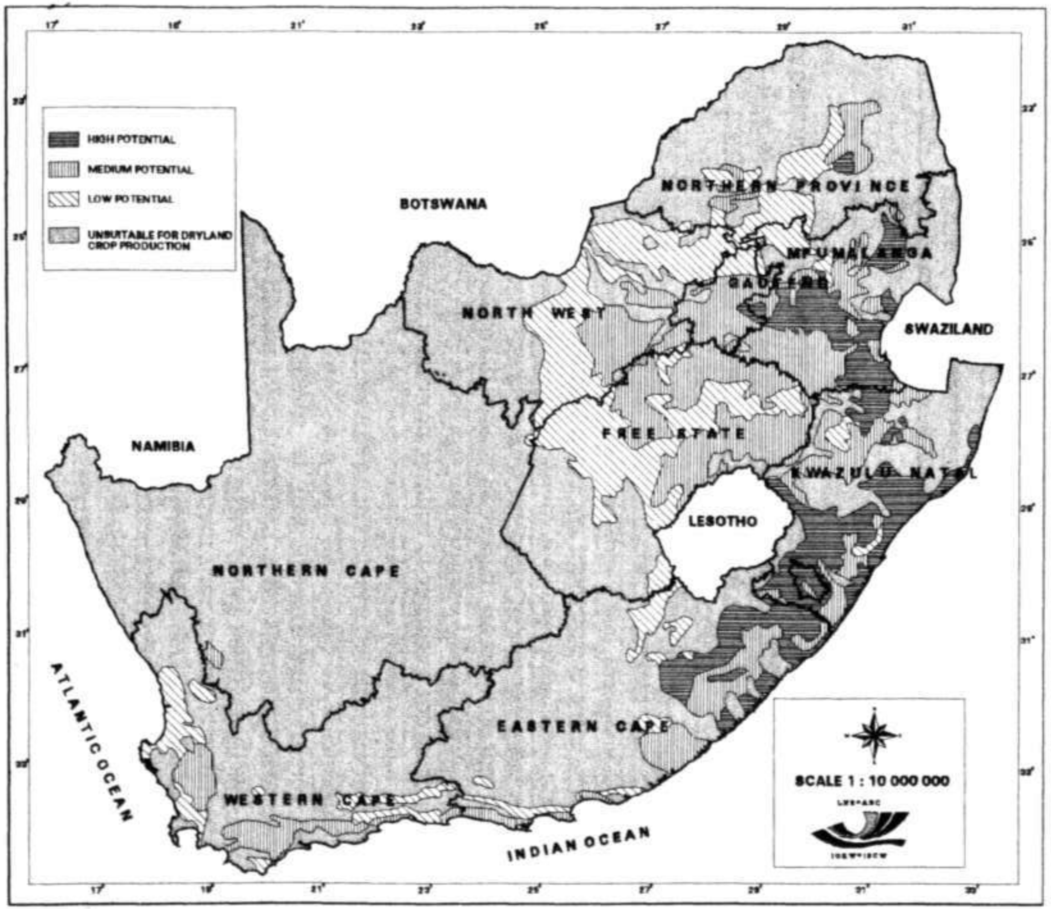


Figure 2. Generalized crop production potential of South Africa.

historically and culturally a very important farming activity. Fallowing of lands is a practice on 6-20% of the 830,000 ha under winter cereal production. Although dryland agricultural production (on 1.8 million ha) is the major enterprise, intensive vegetable, viticulture, and fruit farming under irrigation make a valuable contribution to agricultural production. In both parts winter cereals are grown mainly on shallow duplex or stony soils derived from shale and schists. These soils have low water and nutrient storage capacities, low organic carbon and pH values, and are prone to crusting and water erosion. Heavy downpours often lead to waterlogging and runoff, thus aggravating the situation. Cultivation is by conventional moldboard and disc plowing, while there is a trend toward shallow tine and no-till to cut down production costs.

Summer Rainfall Region

This region is situated on the central high plateau of South Africa, encompassing parts of Free State, KwaZulu-Natal, Northern, and North-West Provinces, as well as the provinces of Gauteng and Mpumalanga (Fig. 2). Annual rainfall varies from 400 mm in the west to more than 900 mm in the east. More than 75% of the rainfall occurs between November and March. Midsummer drought is a general phenomenon, coinciding with the flowering period of the summer crops, often causing poor flowering and consequent low yields. In this region maize, wheat, grain sorghum, groundnuts, dry beans and soybean are being produced on 5.9 million ha of land. Maize and grain sorghum are grown in monoculture systems while the other crops are produced in rotation because of problems with soilborne diseases. Cultivation is done by moldboard and disc plowing. Reduced tillage with residue mulching, under tine or chisel plow cultivation, is also practised but to a lesser degree. Although the beneficial effects of mulching due to organic-C buildup, protection against raindrop impact, and improved soil water storage are well-understood by farmers, residue-borne diseases of maize and wheat have led to a decline of this practice. On the vast areas of sandy soils tine implements are extensively used in a controlled traffic system to conserve soil water, combat wind erosion, and to alleviate subsoil compaction. Other management practices employed to optimize use of rainfall in maize production are to sow area-specific cultivars and to make use of wide (2.2 m) rows.

In the central and northern parts there is an estimated 3.6 million ha of Vertisols, a large portion of which is arable. Mostly grain sorghum, sunflower, wheat, cotton, and tobacco are grown under dryland conditions on these soils. Both self-mulching and crusting have been dramatically increased by long-term tillage, causing a decrease in soil organic matter, resulting in structural degradation with consequent impeded infiltration, enhanced runoff, lower soil water storage, and increased wind and water erosion. Climatic constraints such as high summer temperatures, low and erratic rainfall, and high evaporation rates often lead to low crop yields and sometimes total crop failures on these soils. It is therefore essential that tillage practices aim at maximum soil water storage and conservation (Jacobs and Beukes 1997).

An inventory of the approximate distribution of different crops grown by commercial farmers on 6.7 million ha of dryland and rainfed land is presented in Table 1. It is evident that maize and wheat are by far the most important crops.

Table 1. Percentage of the total dryland and rainfed cultivated area under different crops (after FSSA 1997).

Crop	Area (%)	Crop	Area (%)
Maize	50	Groundnuts	2
Wheat	19	Soybeans	1
Sunflower	8	Barley	1
Oats	8	Rye	1
Sugarcane	5	Dry beans	1
Grain sorghum	3	Cotton	1

Socioeconomic Conditions

For historical, political, and economic reasons a dual agrarian structure exists in South Africa, with approximately 62,000 commercial farmers on about 11.6 million ha of arable land, and about 1.27 million small-scale farmers on approximately 2.2 million ha of arable land (Scotney et al. 1990). Most of the latter area is held under communal or traditional tribal tenure, production is of a subsistence nature, and food has to be imported (DEA 1992). The land tenure system in these areas is a serious problem inhibiting healthy agricultural development, and is presently under review by the government. Agricultural production of maize, fruit, and sugar in South Africa generally exceeds consumption by a considerable amount, and as a whole the industry contributes about 6% to the gross domestic product (GDP; Scotney et al. 1990). When the indirect effects of agriculture are included, the contribution to the GDP is about 12%, while involving approximately 24% of the economically active population (DEA 1992).

Research Findings

Principles of Efficient Soil Water Use

In this paper, water-use efficiency will be defined as being the yield of the crop per unit of water-used for transpiration (WUE_t). This is one of two possible definitions presented by Tanner and Sinclair (1983). Water losses due to runoff, evaporation, and deep percolation are not taken into account. In contrast, precipitation-use efficiency (PUE) is a comprehensive term where yield is divided by the total amount of rainfall from harvesting of the previous crop until harvesting of the present crop, phis or minus the change in soil water content (Hensley et al. 1990). The basic principle of efficient water-use for plant production lies in optimizing each of the components of the soil water balance. There are two distinct management periods. The first is the period of rain storage lasting from harvesting of the previous crop till sowing of the next. Under semi-arid climatic conditions, the soil and water management strategies during this period should be to maximize the gains and minimize the losses in equation 1. The soil water balance during the period of rain storage can be written as follows (adapted from Hillel 1982):

$$\Delta S = P + I \pm D \pm R - E - T \qquad (1)$$

where, ΔS = change in the water content in the potential root zone; P = precipitation; I = irrigation; D = downward drainage out of the root zone (-) or upward capillary flow into the root zone (+); R = runoff (-) or runon (+); E = evaporation from the soil surface; and T = transpiration.

The growing season is the second management period, lasting from sowing till harvesting of the crop. The soil water balance can then be rearranged in the following form:

$$T = P + I \pm \Delta S \pm D \pm R - E \qquad (2)$$

To allow for the maximum amount of water to be available for transpiration (T), and thereby leading to maximum plant production, the parameters on the right hand side of equation 2 should be optimized. A wide range of soil and water management practices are currently being applied or tested in South Africa to achieve these goals.

Optimizing Soil Water Balance Components

Rainfall

In South Africa an area of about 3.4 million ha can be considered as high-potential agricultural land with a rainfall of more than 800 mm per annum (Fig. 1). Rainfed commodities such as natural and commercial forests, perennial agricultural crops, horticultural crops, and vegetables are mainly grown. Only small areas are used for the production of cereal crops. The main cereal producing areas have a semi-arid climate with a mean annual rainfall varying between 25 and 50% of the mean annual evaporation. However, rainfall distribution is erratic with short seasonal droughts a common phenomenon and longer droughts occurring in 6-12-year cycles (Tyson and Dyer 1978). Long-term weather forecasting is still virtually impossible but progress is being made in relating regional weather behavior to the El Nino and Southern Oscillation Index (SOI) phenomena.

Irrigation

Although it is the aim of this review to concentrate on efficient utilization of rainfall, the collection of runoff by large dams constructed on rivers, and using this water for irrigation, also contributes toward achieving the original aim. The South African Government had since the beginning of the 20th century embarked on a program of building large dams on rivers and water transfer schemes between catchments. This ensured the retention of sufficient runoff to support the irrigation of 1.3 million ha, or almost 10% of the cultivated area. Of the total irrigated area, 22% is under supplemental irrigation. Full irrigation requires between 750 mm and 1000 mm of irrigation additional to the rainfall, whereas supplemental irrigation on average only needs 350 mm. Irrigated agriculture is responsible for 15% of the total cereal production in South Africa.

Preplant Soil Water Storage

The majority of the soils cultivated for annual crop production, especially cereal crops in the semi-arid regions, have sandy topsoils with clay contents lower than 25%. Approximately 2 million ha, or 15% of the cultivated soils, contain pedogenic horizons below the root zone that restrict deep percolation. The plant-available water storage capacity of these soils varies between 120 mm and 200 mm. In approximately 1 million ha of these soils, shallow-perched water tables can be observed in wet seasons. In an extensive research program on the efficiency of the storage and utilization of rainfall for dryland crop production, Bennie et al. (1994) reported preplant rain storage efficiencies varying between 2% and 37%. They defined the latter term as the change in the soil water content above the potential rooting depth (1.8 m) of cereal crops from the harvest of the previous crop till the sowing of the present, expressed as a percentage of the rainfall over the same period.

The advantage of increasing the length of fallow for preplant rain storage from 5 months to 10 months was illustrated by Bennie et al. (1995) who reported yield increases of maize varying, between 26% and 50%, and of wheat varying between 0% and 68%. A problem associated with fallowing is the large evaporation losses from the bare soil during this period. As a result of this the mean PUE, measured over three seasons of maize production, decreased from 6.0 kg ha^{-1} mm^{-1} for the short 5-month fallowing to 5.1 kg ha^{-1} mm^{-1} for the long 10-month fallowing. For wheat production over the same period, the decrease was even greater, i.e., from 6.2 kg ha^{-1} mm^{-1} to 3.1 kg ha^{-1} mm^{-1} for the short and long fallowing, respectively. Under the Mediterranean climate of the southern coastal area it was found that a long (12-month) fallow practice was unsuccessful in increasing winter wheat yields because water storage was insufficient due to the low water-holding capacities of the soils and the very low summer rainfall (Agenbag 1987).

Deep Percolation

Quantification of deep percolation from field measurements is difficult. When a drainage curve is available, good estimates can be made. Bennie et al. (1994) reported values ranging from 0% to 20% of the seasonal rainfall under semi-arid conditions measured on well-drained sandy aeolian soils. The magnitude of deep percolation depends on antecedent soil wetness and the amount of seasonal rainfall. Less deep percolation occurred in soils with clayey horizons in or below the root zone. The same authors reported upward fluxes of soil water into the root zone equivalent to between 0% and 8% of the mean seasonal rainfall.

Runoff and Infiltration

A reduction in runoff will result from practices that successfully increase the infiltration capacity of the soil, increase the contact time, and/or reduce surface sealing. It is commonly accepted that covering the soil with a mulch, for example crop residue, will achieve these goals (Unger 1990). The most promising results have been obtained in the high-rainfall subhumid climatic regions (Fig. 1) where Lang and Mallett (1984) reported a reduction in runoff and soil loss when the residue cover exceeded 30% on a highly weathered and weakly structured clay loam soil in the KwaZulu-Natal Province. In contrast, Bennie et al. (1994) found in studies on sandy soils with slopes less than 2% in a semi-arid area in the Free State Province, higher runoff from shallow tilled residue mulching and no-till than from the deeper-tilled conventional moldboard plowing. Compared with the runoff values measured from undisturbed natural grass cover, tillage of the soil increased the runoff. The amount of crop residue retained over all four years of the study was only 4 t ha^{-1}. A threshold value of 6 t maize residue ha^{-1} for effective runoff control was determined with rainfall simulator studies by Bennie and co-workers (A.T.P Bennie, personal communication). This value will seldom be attained under low-yielding climatic conditions.

Long-term runoff measurements have also been made elsewhere (Table 2). These results are particularly valuable because of the long duration of the experiments, and the similar soils and slopes at the two sites. As expected, the runoff and soil loss at both sites are much lower for natural veld than for continuous maize. The much higher rainfall at the Pretoria Experimental Station resulted in a runoff three times

Table.2. Long-term runoff values on similar soils at Glen (after Du Plessis and Mostert 1965) and at Pretoria (after Haylett 1960).

Site	MAP[1] (mm)	Period[2] (yrs)	Slope (%)	Soil	Treatment.	Mean[3] annual runoff (%)	Mean annual soil loss (t ha^{-1})
Glen	508	18	5.0	Red, well-drained sandy loam	Natural veld	4.4	0.26
					Continuous maize	8.5	8.56
					Bare tilled plots	10.3	13.22
Pretoria	721	27	3.75	Red, well-drained sandy loam	Natural veld	4.2	1.12
					Continuous maize	26.7	22.62
					Bare-tilled plots	24.4	22.40
Pretoria	737	21	7.0	Red, well-drained sandy loam	Natural veld	6.8	0.90
					Continuous maize	23.6	65.41
					Bare-tilled plots	24.4	86.02

1. MAP = Mean annual precipitation during the experiment.
2. Duration of the experiment.
3. Expressed as a percentage of the rainfall

higher than at the Glen Experimental Station under continuous maize cropping. Another significant observation is that runoff from the Pretoria plots was not significantly affected by doubling the slope, whereas the soil loss was tripled where the soil had been cultivated. The influence of gravity on raindrop splash action evidently dominated the erosion process on the latter soil with its rapid infiltration rate.

In order to address the nonsustainability of conventional tillage practices on vertic soils, evidenced by the deterioration of physical properties, Beukes (1987, 1992) evaluated the effects of stubble and conventional (moldboard + disc) tillage (CT) on these properties and on growth and yield of grain sorghum in a long-term tillage trial. Nutrient management was based on soil analyses, crop withdrawal, and commercially accepted norms for fertilization that ranged from 10 kg N ha^{-1} to 15 kg N ha^{-1} and from 40 P ha^{-1} to 50 kg P ha^{-1} in general. The no-till and tine tillage practices, boan with stubble retained, gave the highest soil water contents (Fig. 3a). The same cultivations, but with stubble removed, gave the lowest water contents.

The favorable effect of stubble mulch on soil water contents was particularly noticeable during the early part of the growing season. With the exception of CT + stubble (CTS), the retention of stubble increased infiltration significantly (Table 3). This can best be explained in terms of increased soil aggregation and aggregate stability due to stubble mulching (Fig. 3b). Soil carbon (C) and nitrogen (N) contents were maintained and even increased under stubble mulching. The conventional CTS and tillage practices where stubble was removed, led to a major reduction in soil C over years. The retention of stubble (CTS excluded) in the tillage practices led to a dramatic increase in grain yield, especially in dry years (Table 3). The sequence in plant heights and grain yields in terms of the treatments was similar to that of soil water contents. This indicates that available soil water is a major factor that

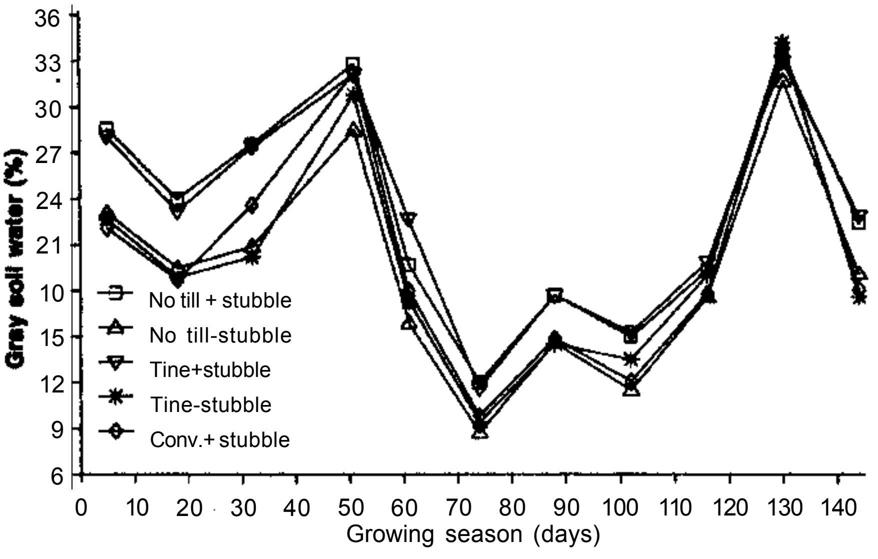
Table 3. Sorghum grain yield (kg ha^{-1}) and cumulative infiltration values (mm) after two experimental seasons (after Beukes 1987).

Treatment	Yield	Cumulative infiltration[1]
Tine tillage, stubble removed	833a[2]	99a[2]
No tillage, stubble removed	567a	118a
Conventional tillage, stubble retained	855a	139a
No tillage, stubble retained	1880b	188b
Tine tillage, stubble retained	1838b	205b
Mean	1195	150
LSD (P<0.05)	345	44
LSD(P<0.01)	466	59
F-value	26.8***	8.0***

***(P<0.001).

1. Cumulative infiltration after a 40-mimite measurement period.
2. Column values not followed by the same letter are significantly different at P<0.05.

a



b

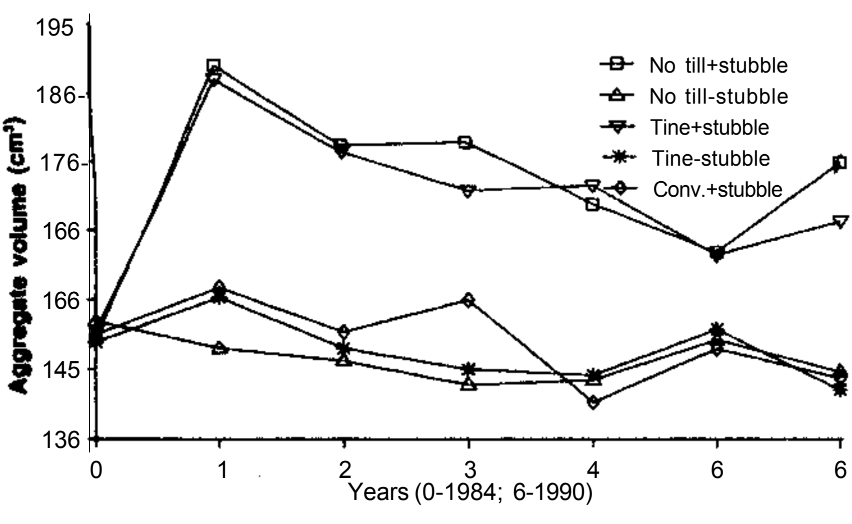


Figure 3. Tillage and soil water contents (a) and changes in aggregate stability (b) (after Beukes 1987).

influences growth and yield of grain sorghum on a vertic soil. Higher N contents might also have contributed to higher yields. Under the same semi-arid climate Hattingh (1995) evaluated in a long-term trial the effects of various levels of stubble mulch and plant population densities on the soil water regime and yield of maize on a Hutton soil form (SCWG 1991) with 12% clay. She found an increase in soil water storage under stubble, which led to an increase in maize yield. Most encouraging was the increase in organic C in the topsoil layer from the third season onwards due to stubble mulching.

In a comprehensive study of Vertisols in the northern summer rainfall region, Grubb (1993) found that tillage and cropping markedly affected soil structure and other properties. Soil degradation manifested itself primarily in the form of reduced dry aggregate stability leading ultimately to increased self-mulching. He found that the water storage, especially of the gilgai mounds (microrelief produced by swelling clays), was very poor. Given the low and erratic rainfall, this had a direct effect on the observed crop failures. On these heavy clay soils Birch et al. (1986) found that basin tillage was the most effective way to retain rainfall, thereby improving soil water storage and, consequently, sunflower yields.

Evaporation from the Soil Surface

This is by far the most important water loss contributing to inefficient water-use in dryland crop production. Under semi-arid climatic conditions in South Africa, evaporation from bare soils during the fallow period can amount to 60-75% of the rainfall in the driest summer-cropping areas (Bennie et al. 1994). The percentages of rainfall lost by evaporation during the period of water storage for different soil types, tillage, and cropping practices, are presented in Table 4. These are mean values for four years, comprising two dry, one average, and one above-average, rainfall years.

Table 4. Percentage of rainfall lost by evaporation during water storage periods (Bennie et al. 1994).

	Bainsvlei[1]			Westleigh[1]		
Cropping practice	CT[2]	SM	NT	CT	SM	NT
Continuous wheat (5 months fallow)	69.0	68.9	72.0	70.0	62.7	70.5
Continuous summer grain (5 months fallow)	68.4	74.1	76.5	74.6	62.2	60.7
Summer grain/wheat rotation (10 months fallow)	72.5	69.3	67.6	78.9	75.5	72.2
Mean	70.0	70.8	72.0	74.5	66.8	67.8

1. Soil form (SCWG 1991).
2. CT = Conventional moldboard plowing and shallow-tine harrowing; SM = Shallow sweep tillage retaining crop residue on the surface; and NT = No tillage, chemical weed control.

Evaporation was highest for the CT treatment on the Westleigh soil with a more clayey topsoil. The small amounts of crop residue (1024-3880 kg ha^{-1}) retained on both soils shaded less than 30% of the soil surface. Hoffman (1997) used microlysimeters to measure the evaporation from a wide range of soils with silt + clay contents ranging from 4% to 66% under similar evaporative demand conditions. He found that the cumulative evaporation increased with increasing silt + clay contents or water-holding capacities. He also determined that a minimum of 80% shading is required to ensure a significant decrease in the cumulative evaporation within the first 10 days after wetting under dry climatic conditions. When the drying-out period exceeded 15 to 20 days, the beneficial effect disappeared. Berry and Mallett (1988) found that with a maize residue cover greater than 70%, evaporation losses decreased for wetting frequencies shorter than 14 days, under subhumid climatic conditions. In order to obtain a 70% ground cover, a minimum of 6000 kg crop residue ha^{-1} was required.

Van Averbeke and Mkile (1996) compared the potential of straw and stones for use as a mulch to reduce evaporation during the growing season in a lysimeter experiment involving maize. Four soil surface treatments, consisting of a control, straw or stones on the soil surface, and stones placed in trays for easy removal before tillage, were maintained throughout the growing season. Relative to the control, stone mulching reduced evapotranspiration by 18%. The WUE_t of maize was 9.8 kg ha^{-1} mm^{-1} in the control, compared to 13.6 kg ha^{-1} mm^{-1} (straw and stone mulching), and 16.6 kg ha^{-1} mm^{-1} (tray mulch). When separating the evaporation and transpiration components using microlysimeters, it was shown that the soil evaporation component comprises between 50% and 67% for maize (Haarhoff 1989; Hattingh 1993) and between 42% and 50% for wheat (Hoffman 1990; Hattingh 1993) of the total evapotranspiration. Bennie et al. (1994) have shown that of the total rainfall during the rain storage plus growing period, 73% is lost through evaporation from the soil when winter wheat is grown on stored soil water under semi-arid summer/rainfall conditions. For maize the equivalent evaporative loss is 60%.

Evapotranspiration and Yield

The amount of water transpired by a crop is a function of the total biomass produced and the climatic conditions controlling the evaporative demand of the atmosphere (De Wit 1958, after Hanks and Rasmussen 1982). Therefore, any cropping or tillage practice that affects crop growth and development will have a similar effect on transpiration (and on evaporation from the soil surface) under comparable climatic conditions.

Effect of tillage. Bennie et al. (1994) determined, under optimal soil fertility conditions, the effects of tillage and cropping practices on the yields and ET of wheat, maize, and grain sorghum. The yield and ET results, average of four years, are presented, respectively, in Tables 5 and 6. Yields and ET of both wheat and grain sorghum were in the order of CT > SM > NT for the more sandy Bainsvlei soil. The reduction in growth in the SM and NT treatments, compared with the CT treatment, was attributed to poorer root development due to the shallower tillage depth. This

Table 5. Total biomass and grain yields (kg ha^{-1}) of wheat (W), grain sorghum (GS), and maize (M) (Bennie et al. 1994).

Cropping practice	Bainsvlei						Westleigh					
	CT[1]		SM[1]		NT[1]		CT		SM		NT	
	W	GS	W	GS	W	GS	W	M	W	M	W	M
Continuous wheat	3623	-	1469	-	1494	-	2791	-	2445	-	3001	-
(5 months fallow)	1061	-	430	-	445	-	845	-	737	-	1067	-
Continuous summer grain	-	7706	-	6192	-	3296	-	5955	-	6173	-	5146
(5 months fallow)	-	1918	-	1604	-	950	-	2665	-	2703	-	2278
Summer grain/wheat rotation	4400	1181	3244	9436	2585	6489	3374	8092	2844	6846	2440	5554
(10 months fallow)	1289	3379	1006	2544	826	1860	1038	3503	812	3006	764	2396
Mean	4012	9760	2357	7814	2040	4893	3083	7024	2645	6511	2721	5350
	1165	2649	718	2074	636	1405	942	3084	775	2855	916	2337

1. CT = Conventional moldboard plowing and shallow-tine harrowing; SM = shallow sweep tillage retaining crop residue on the surface; and NT = no tillage, chemical weed control.

Table.6. Evapotranspiration (mm) values for the growing seasons of wheat (W), grain sorghum (GS), and maize (M) (Bennie et al. 1994).

Cropping practice	Bainsvlei						Westleigh					
	CT[1]		SM[1]		NT[1]		CT		SM		NT	
	W[2]	GS	W	GS	W	GS	W	M	W	M	W	M
Rainfall (mm)	143	254	143	254	143	254	159	342	159	342	159	342
Continuous wheat (5 months fallow)	233	-	194	-	183	-	212	-	203	-	214	-
Continuous summer grain (5 months fallow)	-	261	-	267	-	217	-	345	-	358	-	348
Summer grain/wheat rotation (10 months fallow)	239	382	218	322	208	351	214	394	227	392	210	360
Mean	236	322	206	295	196	284	213	370	215	375	212	354

1. CT = Conventional moldboard plowing and shallow-tine harrowing; SM = Shallow sweep tillage retaining crop residue on the surface; and NT = No tillage, chemical weed control.

was to a lesser extent also the case in the Westleigh soil with a 6% higher silt + clay content. Agenbag and Stander (1988) and Agenbag and Maree (1991) also ascribed lower wheat yields, obtained with stubble mulching and no-till during dry seasons, to poorer root development due to higher penetration resistance values in the topsoil. During wet seasons no-till equalled and in some years out-yielded conventional-tilled wheat on a shallow stony soil with 30% silt + clay in the topsoil. V/orking under the Mediterranean climate of the southern coastal areas, they concluded that in the long term, tillage-induced differences in the soil water content had no significant effect on wheat yield. This is because of the low water storage capacity of the predominantly shallow stony soils of the region and the well-distributed rainfall during the growing season. Bennie et al. (1995) reported lower wheat and maize yields with stubble mulching compared with conventional tillage on a sandy soil, although deep ripping and controlled wheel traffic were used in both practices to alleviate the effect of soil compaction.

Berry et al. (1987) and Mallett et al. (1987) obtained better or the same maize yields with no-till compared with conventional tillage. The results were obtained on a well-drained and fertilized soil with 60% silt+clay under subhumid climatic conditions. From the limited research on conservation tillage practices, where the crop residues are retained on the surface, it can be concluded that lower yields can be expected on soils with less than approximately 20% silt + clay in the topsoil. Soils with higher silt plus clay contents seem to have a better structure allowing for better root development. Engelbrecht et al. (1986) showed that for wheat a long fallow (sowing every second year) resulted in significantly higher yields. Testing five different conservation tillage practices for wheat, Snyman et al. (1992) found that no-till treatments were not beneficial and that higher grain yields were obtained as the intensity of tillage increased, probably mainly due to improved infiltration and decreased evaporation losses.

Effect of sowing density. Efficient water-use also requires that the plant population density should be matched with the water supply, which is determined by the stored soil water at sowing plus the expected rainfall. An experiment involving maize sown in well-fertilized soil at seven population densities ranging from 4000 plants ha^{-1} to 111 ,000 plants ha^{-1}, and different levels of water supply, showed a positive interaction between sowing density and water supply on the yield of maize (Van Averbeke and Marais 1992). Figure 4 shows that the plant population for optimum yields decreases from 60,000 plants ha^{-1} with 650 mm water supply to 10,000 plants ha^{-1} when 238 mm water is available. The authors concluded that matching sowing density with prevailing water supply was indeed a management practice that could result in an increase in yield and reduce risk in local maize production, De Bruyn (1974) found over 10 seasons with annual rainfall of 540 mm on a deep soil that the optimum row width was 1.83 m and plant population 17,000 plants, and that long fallow increased the average yield from 1665 kg ha^{-1} to 2250 kg ha^{-1}.

Well-established guidelines for fertilization and plant population densities for all the major crops and production regions are being followed by the commercial farming community of South Africa. In the low-potential production regions (Fig.2)

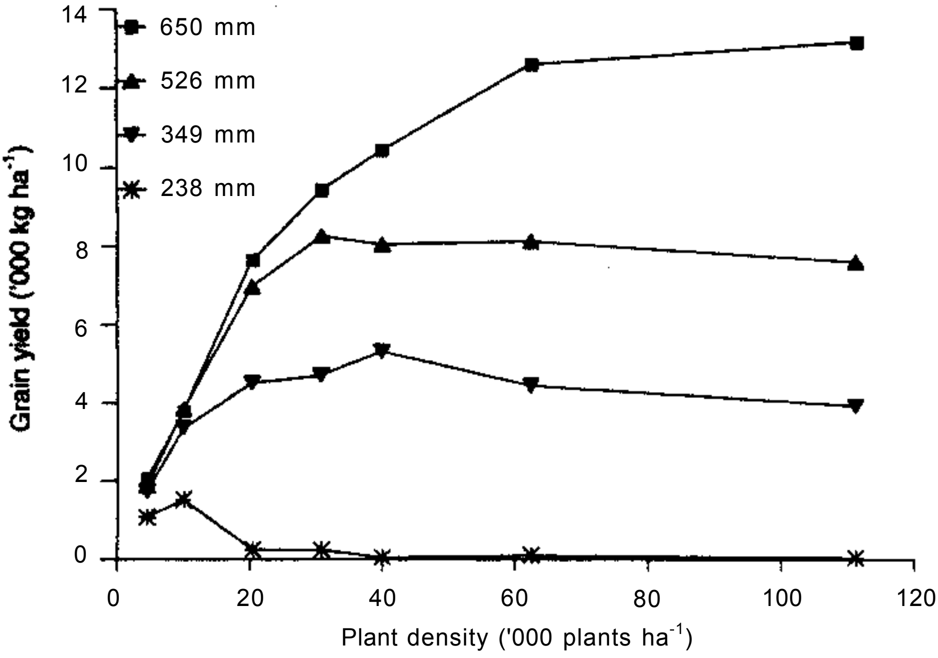


Figure 4. Relationship between grain yield of maize at different sowing densities and levels of water supply (adapted from Van Averbeke & Marais 1992).

the recommended maize plant populations vary between 10,000 plants ha^{-1} and 18,000 plants ha^{-1} with 1.5 m or 2.3 m row spacing. Under these conditions, yields of between 2000 kg ha^{-1} and 6000 kg ha^{-1} can be obtained, depending on the rainfall.

Effect of weed control. A major problem contributing to higher evapotranspiration values during the growing season is ineffective control of weeds. Weed control, which is most often by hand hoeing, is one of the main constraints of small-scale crop farmers. When weeds are not controlled effectively, the advantage of sowing at low densities is lost, and the practice may actually result in a reduction in yield (W. van Averbeke, personal communication). Timeliness of tillage for weed control is absolutely crucial for effective preplant water storage, as well as for reducing competition for the available soil water during the growing season.

Production functions. Water production functions relating crop yield to evapotranspiration have been determined for local climatic conditions for a wide variety of crops (Streutker 1983a,b; Bennie et al. 1998). Guidelines for crop factors relating atmospheric evaporative demand to evapotranspiration during the different growth stages of crops have been published by the Department of agriculture and water supply (DAWS 1985). All this information is being used by agricultural advisory services, researchers, and farmers to optimize soil water-use and crop production by applying computer and modeling technology in irrigation scheduling.

Effect of inefficient water use on yields. Unfortunately all the research reported so far has been aimed at improving specific aspects of water-use efficiency for crop production while all the other variables were kept constant. The yield responses under experimental conditions varied between 50% when increasing the rooting depth of crops by deep ripping of compacted subsoils, to 7% by reducing runoff. Lower response is anticipated on farmers' fields due to spatial variability and lower management inputs. It can be expected that yield losses resulting from inefficient water-use practices can vary between 15% on sandy soils to 35% on clayey soils under semi-arid climatic conditions.

The Application of Simulation Models in Efficient Soil Water Use

Locally and internationally developed crop growth and soil water balance computer models are currently being used in South Africa by several institutions. Their aim is to integrate the existing research results for a better understanding of the soil-plant-atmosphere system. A list of the local models and applications is given in Table 7. Apart from these, several international crop growth models are continuously being tested and adapted to local conditions. Hensley (1990) and Hensley and Snyman (1991) concluded that long-term results are necessary for reliable production technique recommendations and production-risk quantification under semi-arid conditions. These are obtainable using tested crop models and long-term climate

Table 7. Locally developed computer models and programs in the fields of soil and crop water use.

Model	Application	Institution
ACRU	Hydrology and Agrohydrology	Department of Agriculture Engineering, University of Natal, Pietermaritzburg
BEWAB	Irrigation schedule of various annual cash crops	Department of Soil Science, University of the Orange Free State, Bloemfontein
CANE-GRO	Simulation of sugarcane growth	SA Sugar Association, Mt. Edgecomb
PUTU	Dryland crop simulation and irrigation schedule	Department of Agrometeorology, University of the Orange Free State, Bloemfontein
SAPWAT	Water requirements of crops	MBB Consultant Engineers, Pretoria
SWAMP	Managing the soil water balance for dryland crop production	Department of Soil Science, University of the Orange Free State, Bloemfontein
SWB	Irrigation schedule and crop growth simulation	Department of Crop Production and Soil Science, University of Pretoria, Pretoria

data. Noteworthy attempts in this regard have been made by Hensley and Snyman (1991), Potgieter et ai. (1997), Anderson and De Jager (1998), and Singels and Potgieter (1998). A useful strategy on these ecotopes (i.e., a land-use unit with homogenous climate, soil, and aspect characteristics) is to perform long-term simulations for each of a number of root-zone water contents at sowing. The resultant cumulative distribution functions of yield for each of these scenarios provide valuable information about the productivity and management of an ecotope. For example, Anderson and De Jager (1998) compared expected maize yields on a marginal ecotope when sowing on quarter-full and full root zones. The results indicated that there was a 70% probability that yields would be lower than 1,400 kg ha^{-1} and 2,200 kg ha^{-1}, respectively. Attempts to improve the reliability of the PUTU and DSSAT wheat and maize models by comparing measured and simulated yields on a range of ecotopes have also been made (Hattingh 1993; Botha et al. 1997, 1998; Hensley et al. 1997).

Discussion and Conclusions

The basic principle of efficient soil water-use for plant production lies in maximizing the gains and minimizing the losses of water. It was shown that crop production risks are lower with practices which assure good soil water storage at sowing. The largest soil water losses are due to evaporation from the soil surface. These losses can be of the order of 60-75% of the annual rainfall under semi-arid climatic conditions. Soil water evaporation losses can be decreased over periods shorter than 14 days, provided that a 70% or higher shading is maintained through mulching practices. Yield reductions of several crops have been reported with crop residue mulching and reduced tillage on sandy to loamy sand-textured soils, while the opposite results were obtained on soils with a higher clay content in the topsoil. Runoff from cultivated fields can amount to 10% of the annual precipitation. The practice of using crop residue as a mulch to control runoff is seldom economically feasible, when compared with utilizing it as animal feed under low-rainfall situations. Poor control of weeds during the period of preplant water storage, as well as during the growing season, will almost always result in reduced yields or even total failure in below-average rainfall years. Plant populations should always be adapted to the available supply of stored soil water plus the rainfall that can be expected. Drainage losses can be as high as 20% on deep, well-drained sandy soils. Cultivation of soil types with clayey horizons below the potential rooting depth which will impede deep percolation could be advantageous because of the increased water supply to crops in low-rainfall areas.

On clayey soils in areas with marginal and erratic rainfall, especially where a large proportion falls as thunderstorms, the major forms of water loss are runoff and evaporation. Realizing this, researchers have successfully employed water harvesting techniques to increase yields in various parts of Africa (Kronen 1994). Similar work is currently being undertaken at the Glen Experimental Station in the Free State Province on clayey soils, focusing on the needs of small farmers, and combining the benefits of water harvesting, basin tillage with mulch in the basins to reduce evaporation and long fallow.

There is limited scope to optimize stored soil water-use for wheat production on the shallow, stony soils of the southern coastal areas. Because of the low water-storage capacities of these soils, the contribution of efficient stored soil water-use to production is inferior to the amount and distribution of rainfall. However, reduced tillage and residue mulching are gaining momentum because of their beneficial effects on the biological and physical properties of the soils. The beneficial effects of crop rotation including wheat and leguminous species are also well-known to farmers.

In addressing the adverse effects of long-term conventional tillage on vertic soils, Beukes (1987, 1992) found that available soil water is a major factor that determines growth and yield of grain sorghum. Stubble mulch practices improved aggregation in these soils, thereby increasing infiltration and soil water content, with consequent increases in yield. Gmbb (1993) is of the opinion that the nonsustainable cultivation of Vertisols can, *inter alia,* be arrested by retention of stubble mulch, restricting tillage methods to tine and disc plow only, and crop-rotation practices.

The South African experience has shown that for small-scale crop production under subhumid climatic conditions with an annual rainfall exceeding 800 mm, the goals of economic viability and natural resource sustainability are relatively easy to achieve. In the lower rainfall areas (<600 mm per annum), and based on a PUE for maize of 3.5 kg ha^{-1} mm^{-1} (Bennie et al. 1994), the conclusion can be made that the large farm area needed to sustain a living standard comparable to the rest of the population will require large-scale extensive practices when using conventional tillage. However, it is well-known that by reducing runoff and evaporation and increasing soil water storage, e.g., with various mulch practices, PUE can be improved, thereby reducing the area needed for a sustainable living. The various water harvesting techniques to improve PUE, especially on marginal soils and under erratic and low rainfall, have not yet been sufficiently investigated in South Africa.

Priority Issues for Further Research

Research Needs

- There is an urgent need for an integrated approach to simultaneously optimize soil water and nutrient use by crops in dry areas for greater efficiency and sustainability. For too long have these two aspects been researched independently. Furthermore, an integrated catchment management approach where the soil water and nutrient balances are determined as per the land-use pattern in a catchment has never been investigated in South Africa. This is a broader natural resource management perspective that can also supply information to off-site, downstream soil and water-users.
- Under the Mediterranean climate of the southern coastal areas the storing of light rainfalls prior to sowing should be investigated. Not only will the accumulated soil water prompt earlier sowing of wheat, but N mineralization can also be enhanced. The beneficial effects of reduced tillage and use of crop residues on *inter alia* soil organic C, soil structure, and soil water properties, such as water retention, need

further clarification. The positive effects of crop rotation systems to improve soil conditions and to combat soil erosion should also be studied in long-term trials.

- Due to their unique features, vertic soils are inherently fertile and productive when properly managed; However, their high clay contents, and structural degradation due to long-term conventional tillage, cause low infiltration capacities and, consequently, low water storage. The beneficial effects of reduced tillage and stubble mulching should further be investigated, especially on vertic soils with strong crusting and self-mulching properties.
- Various water harvesting techniques, such as sowing in microbasins and varying ratios of catchment area (runoff) to cropped area (runon), should also be evaluated. The latter techniques, when adapted for local conditions, could be of great benefit to sustain food production by small farmers who have to make a living on high clay soils and under marginal rainfall.
- The critical levels of different types of mulching materials to effectively reduce evaporative losses under different climatic conditions on different soil types must be determined. The water-use efficiency in large-scale crop production can be improved if the problem of lower yields with stubble mulching on sandy soils can be solved.
- With regard to modeling there is a need for (1) a resource-based model or procedure that can be used to calculate the minimum farm size to produce a required income from crop production, with given soil-climate-crop resource combinations; (2) a model to enable daily rainfall data to be converted into intensity data; such a model is considered essential to obtain reliable long-term runoff values; and (3) testing the employment of ENSO-based climate predictions in modeling approaches to assist in long-term assessments of the value of different production techniques. The value of having a crop model which can reliably predict yields on an ecotope with any set of production techniques cannot be overemphasized. If such a model were available, it would have greatly facilitated the attaining of the overall long-term goal of the OSWU Consortium for WANA and SSA. No such model, which focuses specifically on dry areas and the crops grown there, is currently available.

Ongoing National Research Activities and Linkages

A levy on all water sold in South Africa goes by law into a water research fund controlled by the Water Research Commission (WRC). This commission then funds contract research projects with the objective of improving the efficiency of agricultural, domestic, industrial, and mining water-use , as well as environmental issues. As a result of continuous funding over several years, centres of excellence in terms of soil water-use have been established at the Agricultural Research Council, universities, and consulting engineering firms.

Years of international isolation of South Africa prevented the establishment of official linkages with international research centers. However, opportunities for increased collaboration, both on a regional and international scale, are now a reality, and should be followed up. The advantages for South Africa of recently joining the CGIAR System must now be fully utilized. We must strive to actively participate *inter alia* in the Systemwide Soil, Water, and Nutrient Management Program, which is aimed at a coordinated global multiscale research approach not only to alleviate poverty but also to protect the environment.

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Review Paper on Optimizing Soil Water Use in Syria

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Abstract

Syria has an annual rainfall of 200-600 mm. The variable and often chronic deficiency of rainfall is coupled unth widespread nutrient deficiencies and improper soil and crop management which result in low water-use efficiency (WUE), and eventually lower crop yields as well as poor animal production. About 6 million ha are suitable for cropping. Only about 20% of the cultivable land is under irrigation, the remainder being under rainfed farming systems. Wheat and barley are the major rainfed field crops followed by lentil, chickpea and forage crops. Since the limiting factor in agricultural production is water, most of the research has been directed at improving water-use efficiency through crop improvement and soil and crop management, the main emphasis being on factors affecting the proportion of available water transpired by crops. Major attention has been given to tillage practices and residue management; crop rotations; selection of varieties with rapid early growth, deep roots, and early maturity; early sowing and optimum plant population; application of fertilizer; weed control; supplemental irrigation and water harvesting. Two crop simulation models have been tested under Syrian conditions and found to have worked well for the northwestern region, but they need to be validated for other regions to extrapolate research findings to larger areas, in order to support sound decision-making in prioritization of research and development. Future research should aim at filling the knowledge gap for the drier areas of the country, particularly with respect to supplemental irrigation, water harvesting, minimum tillage, and the transfer of promising soil and crop management practices together with improved crop varieties to farmers for optimal use of the limited water resources.

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Resume

La pluviometrie en Syrie varie de 200 a 600 mm. La variabilite et le deficit chronique de la pluviometrie sont couples avec des deficiences gSniralisees en elements nutritifs et des pratiques de gestion des sols et des cultures inappropriees. Celles-ci entrainent une faible efficience de l'utilisation de l'eau du sol, allant mime jusqu' a faire baisser la productivite des cultures et de l'elevage. Environ 6 millions ha sont aptes a la culture. Seul 20% de ces terres sont sous irrigation, le reste etant utilise dans des systemes de production pluviaux. Le ble et l'orge sont les principales cultures pluviales, suivi par les lentilles, le poids chiche et les cultures fourrageres. Etant donne que I'eau constitue le principal facteur limitant pour l'agriculture, la recherche a surtout ete menee afin d'ameliorer I'efficience de I'utilisation de I'eau au travers de l'amelioration ginetique des cultures et la gestion des sob et des cultures, avec un accent particulier sur les facteurs qui affectent la proportion de I'eau disponible utilisee pour la transpiration. On s'est particulierement attache au travail du sol et a la gestion des residus, la rotation, la selection de varietes hatives avec une croissance initiale rapide et un enracinement profond, le semis precoce et les densites de semis optimales, l'application d'engrais, le controle des adventices, l'irrigation d'appoint et la collecte des eaux de ruissellement. Deux modeles de simulation ont ete testes pour la Syrie et sont adequats pour la region du nord-ouest. Ces modeles doivent encore etre valides pour les autres regions afin de pouvoir extrapoler les resultats de la recherche it des zones plus etendues et pour pouvoir soutenir les prises de decision saines en matiere de priorites pour la recherche et le diveloppement. Les recherches futures doivent chercher en priorite a completer les manquements dans les connaissances pour les regions plus siches du pays, en particulier en matiere d'irrigation d'appoint, de collecte des eaux de ruissellement, de travail du sol minimum, ainsi que le transfert vers les paysans de pratiques prometteuses de gestion des sols et des cultures et de varietes ameliorees pour une utilisation optimale des ressources en eau limitees.

Introduction

Syria lies between latitudes 32°N and 37.5°N, and longitudes 35°E and 43°E. It has a land area of 18.5 million ha, out of which about 6 million ha are actually cultivable land, and the remainder is desert, steppe, and mountains (SMAAR 1997; SCBS 1998). The steppe is used as rangeland when enough rainfall is available. Geographically, Syria is divided into four regions:

- Western coastal region between the mountains and the Mediterranean Sea.
- Mountain region running north to south parallel to the Mediterranean Sea and extending some 30 km inland.

- Internal region including the plains of Damascus, Horns, Hama, Aleppo, Hassakeh, and Daraa, east of the mountain region.
- Steppe region or the desert plains in the southeast of the country on the border with Jordan and Iraq.

Only about 20% of the cultivable land is under irrigated agriculture, the rest being under rainfed farming systems which have developed over centuries in areas receiving annual rainfall between 200 mm and 600 mm, associated with high temporal and spatial variability. This variable and often chronically deficient rainfall is coupled with widespread nutrient deficiencies and improper soil and crop management, which results in low water-use efficiency (WUE), low crop yields, as well as poor animal production.

Therefore, it is imperative to use the scarce natural resources, water in particular, with improved efficiency in rainfed agricultural systems, where the soil and water resources largely determine the level of production. Soil and crop management practices combined with adapted, improved cultivars geared for improved water-use efficiency are the possible alternatives for farmers to apply for increased and sustainable crop production.

In this paper, Syria's natural resource base, its agricultural production systems and socioeconomic aspects are characterized, past research in relation to optimizing soil water use is analyzed and interpreted, and future directions for research identified.

Characterization at the National Level

Climate

The prevailing climate in Syria is of the Mediterranean type, having rainy winters and dry summers with two short seasons in between. There are four climatic regions corresponding to the four geographical ones. The coastal area has heavy rainfall during winter, moderate temperature with daily maximum and minimum changes of 13° C, and high humidity in summer. The internal region has rainy winters and hot, dry summers, with daily changes in temperature of 25°C. The mountain region, around 1000 m above sea level, has heavy rainfall during winter and moderate weather in summer. The steppe has little rain in winter and dry, hot summers. In the whole country except the coastal area, the relative humidity is high in winter and low in summer; the contrary occurs on the coast because of its proximity to the sea. The desert and semidesert regions have the lowest humidity. A long-term rainfall isohyet map is given in Figure 1.

December and January are the coldest months of the year, July and August the hottest. Temperature can fall below zero in winter, but rarely to -10°C, and sometimes, the maximum can reach 48°C in summer.

Syria is divided into five agricultural or so-called settlement zones based on the average annual precipitation and the probability of dry farming sustainability or the success of dryland farming:

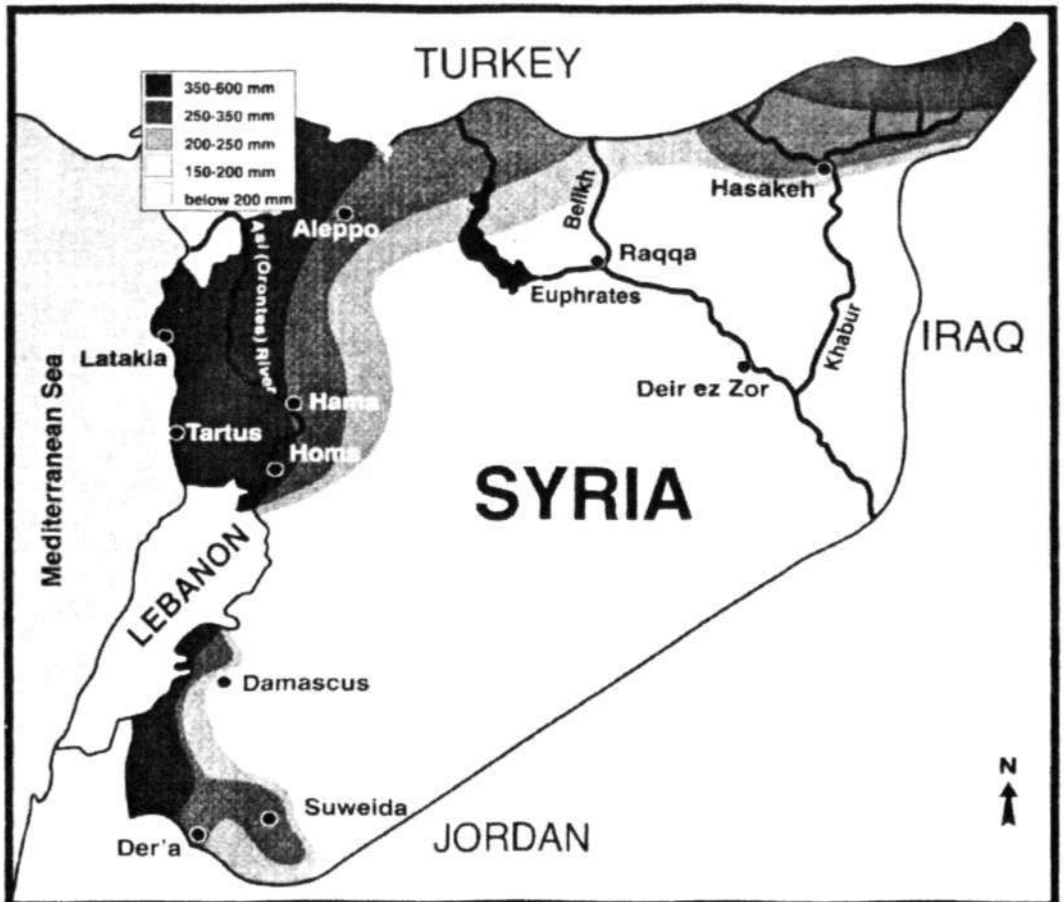

Figure 1. Rainfall isohyets in Syria on the basis of 30-40 years of data.

Zone 1. This zone makes up 24.46% of the total cultivable area in Syria, comprising 1 177 000 ha that are further divided into two subzones. The first receives more than 600 mm annually, where dryland farming is successful. The second includes 752 000 ha and receives an annual average rainfall of 350-600 mm; dryland farming is successful in two out of every three years.

Zone 2. This zone makes up 33.38% or 1 606 000 ha of the total cultivable area in the country. It receives 250-300 mm precipitation annually. Wheat is the main winter crop in this zone, and crops succeed - on average - in two out of three years.

Zone 3. This zone accounts for 15.92% or 766 000 ha of the total cultivable area in the country and receives not less than 250 mm precipitation annually. Barley is the main crop, which could be successful in one to two out of every three years.

Zone 4. This includes marginal lands which make up 18.66% or 898 000 ha of the total cultivable area and receive 200-250 mm precipitation annually. The chances of success of barley cropping is 50%. This area was utilized as permanent natural rangelands in the past.

Zone 5. These steppe lands make up 55% of the total area of the country and receive less than 200 mm precipitation annually. Rainfall is characterized by being erratic, not well-distributed over the growing season, and occurring in storms. The largest portion of steppe lands is in governorates of Horns and Deir Ezzor.

The overall extent and characteristics of the five zones have been summarized in Table 1.

Table 1. Rainfall zones and area under cultivation in each zone.

Zone	Annual rainfall (mm)	Area ('000 ha)	Types of crops
1	above 350	2698 (15)	Wheat, legumes, summer crops, fruits, vegetables
2	300-350	2473 (13)	Wheat, barley, legumes, summer crops, fruit trees
3	250-300	1306 (7)	Barley, feed
4	200- 250	1823 (10)	Barley
5	below 200	10218 (55)	Shrubs for animal feed, pasture

1. Figures in parentheses are percentages.

Soils

The soils in Syria have been grouped into six types: Aridisols, Inceptisols, Entisols, Vertisols, Mollisols, and others. The most widespread are gypsiferous soils, which occur in the Euphrates valley in the northeast and in the desert in the southeast. A national soil classification program has been completed on a scale of 1:25000 for cultivated areas and 1:100 000 for the steppe area. Soil maps for each extension unit have been completed on a scale of 1:25 000.

A brief description of each soil order follows.

Aridisols

- Cover 48% of the total Syrian territory
- Soils of arid and semi-arid regions
- Moisture regime is predominantly aridic

***Entisols* (17%)**

- Soils with very little or no horizon development
- Some poorly drained ones may have a histic epipedon
- Soils are on steep, actively eroded slopes; or
- Soils are flood plains

***Inceptisols* (22%)**

- Soils of humid regions that have altered horizons
- If the soil is saturated with water, salic horizon is not present
- Do not have aridic moisture regime

***Vertisols* (2%)**

- Deep, clayey soils with high bulk density, developing deep, wide cracks at some time of the year
- Have 30% or more clay
- Have cracks at least 1 cm wide and 50 cm deep unless the soil is irrigated

***Mollisols* (2%)**

- Soils of the steppes
- Freely drained soils
- Do not have wide cracks
- Organic matter decreases with depth

***Others* (9%)**

- Rocky outcrops, Alfisols, Xeralfa, Haploxeralfa, Natric, Andisols, Chromoxerets, Lithic Xerorthents, and Camborthids.

Water Resources

In normal years, about 55% of Syria has an average rainfall of less than 200 mm, and receives about 27% of the total annual rainfall. This area includes the steppe and rangeland (settlement zone 5). In dry years, this area may increase to 64% and in wet years, decrease to about 40%.

The area enclosed by the 200 mm and 600 mm rainfall isohyets occupies about 45% of the country and receives about 55% of the total rainfall. This area comprises Zones 2, 3, and 4 and a large part of Zone 1. It includes most of the rainfed areas where cereals, field crops, vegetables, and fruit trees are grown. A small part of the country receives higher rainfall varying from 600 mm to 1400 mm; this area includes the coastal plain and the mountainous areas of Zone 1. In these areas, fruit trees such as apples, pears, and cherries, and vegetables are grown. In the coastal plain, citrus fruits and vegetables are the main crops. In general, most of the country is characterized as arid and semi-arid, and rainfed agriculture is subject to wide variations in productivity, depending on the annual variation of rainfall in amount and distribution.

The total annual rainfall is equivalent to 46.64 billion m^3. Excluding the Euphrates and Tigris river supply, the calculated annual average surface water and groundwater availability is 9.94 billion m^3, i.e., about 21% of the yearly rainfall, which can be safely utilized from surface supply, springs, and recharge to groundwater. If the Euphrates system were included, the corresponding figure would be 35.94 billion m^3, equivalent to about 77% of the total rainfall. The average annual discharge of the Euphrates river at the Turkey-Syrian border is estimated at around 28 billion m^3. According to a tentative understanding among Turkey, Iraq, and Syria, Turkey is to release a minimum discharge of 500 m^3 per second, 58% of which is to Iraq and 42% to Syria. According to this understanding, the Syrian share will amount to about 6.62 billion m^3.

Excluding the Euphrates water, groundwater provides about 57% of the local water supply while surface water provides the balance of 43%. The total amount of water that could be pumped from groundwater by wells is estimated at about 2.02 billion m^3, which is about 36% of the total groundwater contribution of 5.66 billion m^3, the balance of 64%, or 3.64 billion m^3, being the flow from springs.

Syria has been divided into seven main hydrological basins: Yarmouk; Damascus; the steppe and pasture land; the Euphrates/Khabour, together with a portion of the Tigris river basin situated in Syria; Aleppo; Orontes; and the coastal plain. Preliminary studies of these basins have shown that the average annual utilizable water resources can reach 10 billion m^3.

Given the present utilization of the principal aquifers and the evidence of decline in water levels and quality, it is unlikely that further underground reserves will be found or be able to be economically tapped. The shallow aquifers already in use are in some cases showing saline ingression, and the deep aquifers recently test-drilled into the fossil water reservoirs tend to produce saline and/or sulphurous water at high temperatures; their usability is therefore uncertain. Considering the widespread inefficient water application, the emphasis for future water development is more likely to be placed on improving water management, recovery of wastewater, and investment in surface water and river supplies. However, since 80% of the cultivable area is under rainfed conditions, emphasis has to be given to improvement of rainwater use through improved soil and crop management practices to be able to sustain production and natural resources for future generations.

Agricultural Production Systems

The official figures for 1997 classify the land area of Syria into 5.986 million ha cultivable land, 8.283 million ha steppe and pastures, 0.522 million ha forests, and 3.727 million ha uncultivable land. Of the cultivable land, 72.7% or 4.354 million ha are rainfed (including 0.718 million ha fallow land), 19.5% or 1.168 million ha are irrigated land (0.228 million ha by gravity, and 0.939 million ha by pumping), and 7.8% or 0.465 million ha are uncultivated (SCBS 1998).

The rainfed-cultivated land is spread over a wide rainfall range of 200-600 mm per year, covering Zones 1 to 4. Wheat and barley are the main rainfed crops. According to the Agricultural Plan of 1996, 90% of one million ha of rainfed wheat were sown in Zones 1 and 2 with a rainfall of over 250 mm per year. Rainfed barley is fairly evenly distributed over Zones 2, 3, and 4, with over 500 000 ha in each, and the three together accounting for 97% of the total barley grown. The area sown and harvested from both crops depends on climatic conditions, the barley area having the tendency to expand in good rainfall years. Drought and cold in late winter and early spring may lead farmers to use or rent their barley fields to herders for grazing. In 1988 when rainfall was high, barley production reached a peak of 2.8 million tons against a 10-year average of 951 000 tons and a low of 254 000 tons in 1989. Cereal straw is a valuable by-product used in sheep and cattle feeding and can fetch a good price in some seasons.

Almost all lentils and chickpeas are grown in rainfed areas; these crops account for only 4.8% and 2.3% of the area, respectively. Both crops are grown almost completely in Zones 1 and 2, in the ratio of 2:1 for lentils and 1:2 for chickpeas. This is attributed to the farmers' perception that chickpeas perform better in the cereal rotation under low rainfall, particularly if sown in winter. The only other significant winter crops are forage and fodder. The expected winter rainfall largely determines the annual cropping patterns in rainfed areas. In 1997, the total areas of wheat, barley, lentils, and chickpeas were 1.76 million ha, 1.57 million ha, 0.12 million ha, and 0.094 million ha, respectively. Their average yields were 1.7 t ha^{-1}, 0.6 t ha^{-1}, 0.7 t ha^{-1}, and 0.6 t ha^{-1}, respectively (SCBS 1998).

In the rainfed areas, farming is limited to the winter season, except in regions with relatively high rainfall, where summer cropping can be practised on residual moisture. In these areas, summer crops such as grain sorghum, tobacco, and sunflower are mainly grown in Zone 1, whereas other crops such as watermelon, sesame, tomato, and some summer vegetables may be found in Zone 2, where less soil moisture is stored during the winter. In 1997, rainfed summer crops covered about 80 200 ha (SCBS 1998). There are about 754 000 ha under tree crops, of which 67% exist in Zone 1, and 26% in Zone 2. Olives predominate, covering over 445 000 ha, but pistachio, grapes, and apples are also very important, accounting for nearly 59 000 ha, 69 000 ha, and over 47 000 ha, respectively. Input use is limited in the entire rainfed crop sector, although mechanization of farming operations is the norm.

Two farming systems are adopted in most rainfed zones, namely cereal/fallow rotations in Zones 2, 3, and 4, and cereal/legume or cereal/fallow rotations in Zone 2.

Weedy fallow land produces about 1 million tons of dry matter, making up 13% of the animal feed balance in the country; these areas are used for livestock grazing from the middle of winter to early spring. Thus, although fallowing can be viewed as a wasteful process in the context of crop production, it seems to be one of the keystones of farming systems, which is very important for livestock production. The nutritive value of weedy fallow lands is high due to the diversity of annual plant species that compose them. However, when leguminous plant species are cultivated in rotation with cereals, the nutritive values of the feeds produced are higher. In addition, fallow efficiency, i.e., increasing the amount of water available for a subsequent crop by a cereal-fallow system, was found to be low and variable (Harris et al. 1991a). However, the increased need for food and feed associated with high population growth is causing the replacement of cereal/fallow rotations with continuous cereal cropping, a practice which is not sustainable and yields low rainwater-use efficiency (Acevedo et al. 1991; Jabbour and Naji 1991; Harris et al. 1991b).

The salient feature of irrigation development during the last decade is an increase of 83% in gravity irrigation and 79% in pump irrigation, resulting in an overall increase in irrigated area by about 517 000 ha. The land reclamation and irrigation projects have led to reclassification of over 250 000 ha from uncultivable to cultivable land, mainly in the Euphrates and Khabour river basins. In Zone 5, where rainfall is less than 200 mm per year, the largest irrigated area exists. It amounts to 300 000 ha representing 25% of total irrigated lands, based on schemes on the major rivers, particularly the Euphrates, Orontes, and Khabour.

The cropping intensity under irrigation is 100%. However, in the river basins and where additional irrigation is available, the land under field and vegetable crops is increased to raise the composite overall cropping intensity to 122%. Input use, especially of fertilizer, is at or near recommended applications, and mechanization is virtually universal in the irrigated and high-rainfall areas, eventually increasing the water-use efficiency of the cropping systems.

The flood irrigation system is applied in all irrigated areas. However, inappropriate on-farm water management and nonleveled soils result in application of excessive cost-free water. To reduce the amount of pumped water, to increase water-use efficiency, and to reduce labor costs, some farmers in the Aleppo and Daraa provinces have invested in overhead irrigation equipment—sprinklers—for high-value summer crops. This system is also used extensively to supplement rainwater for winter wheat, in particular to stabilize the yield fluctuations because of the high rainfall variability. Mean wheat grain yield under irrigation is 3.5-4.0 t ha^{-1}.

Population and Socioeconomic Aspects

The population of Syria was about 15.1 million in 1997, of which 51% was living in rural areas depending on agricultural production of crops and livestock. Given the current growth rate of 3.3%, the population is estimated to reach 31.9 million by the year 2025 (SCBS 1998). The labor force in agriculture is 28.6% of the total, and 59.9% are female, showing the domination of women in agricultural operations. The Gross National Product was 17.35 billion US$ in 1997, of which 26% was generated from agricultural production (SCBS 1998).

According to the agricultural census of 1981, the latest available data on farm size, 43% of the total number of holdings of cultivated lands, which amounted to 444 000 ha, was under irrigation or high rainfall with a range from 1% to 100% in different provinces. The average farm size was 12.5 ha with a range from 2.7 ha to 45.1 ha. Average holdings vary considerably with population density. Traditionally, landowners used to have their holdings in 3 to 5 parcels according to soil characteristics and uses. As a consequence of inheritance laws and customs, farms are now understood to be very fragmented, which may not be conducive to intensive mechanization, irrigation, and soil protection. Steppe land is state-owned, and grazing is communal and subject to traditional tribal rights of use. However, due to the policies of self-sufficiency in cereal production and due to other social and political issues, settlements of Bedouin communities were encouraged in steppe land. A government decree in 1988 identified the number and locations of such settlements (Agricultural Census 1981).

The changing pattern of overall land use in the cropped area of Syria is marked by an increase in irrigated area in the period 1990-96, and an enormous expansion of the cultivated rainfed area in the period 1978-90 (SMAAR 1997). The six years (1986-1991) witnessed an increase of about 20% in agricultural production. The year 1988 was the most successful year, when the overall index reached 129 compared to the base of 100 for 1985. Field crops performed less than livestock activities in this period, but there were relatively consistent and significant gains in output of fruit, meat, wool, and other animal products. After five years, agricultural production increased by about 41% also (SCBS 1998).

Livestock is closely integrated in the farming systems of Syria and plays a key role in determining the current crop production strategy of the majority of the farmers. In 1997, 13.839 million sheep, 1.1 million goats, and 0.875 million cattle were counted in Syria (SCBS 1998). The interrelationship between crop and livestock production has important implications for improving the water-use efficiency of crop production. The majority of sheep and goats are found in the steppe or drier crop (mainly barley) production areas, whilst cattle are more commonly found in the wetter or irrigated areas and in dairies near cities (Cooper et al. 1987a). There is migration of herds through the season from steppe to other cultivated areas in the wetter and irrigated regions according to the availability of fodder for livestock.

The annual agricultural plan of the Syrian Ministry of Agriculture and Agrarian Reform (SMAAR) determines the ideal crops and cropping patterns after consultation with local civic authorities and with representative bodies of the farming community. The selection is based not only on strict agroclimatic factors but takes into consideration national objectives such as the policy of self-sufficiency in staple crops and adequate supplies of raw materials for existing agroprocessing plants. The farmer who has more than 1 ha, especially irrigated land, is expected to adhere to the prescribed crops through a system of licenses, but which, simultaneously, give the farmer access to highly subsidized input and credit. Farmers unwilling to apply for licenses must turn to the private sector for their inputs. This strict control of cropping pattern and input availability is applied with leniency in most places; the penalties are not severe and it is likely that it will be further liberalized over the next few years.

Research on Efficient Water Use

The Syrian Ministry of Agriculture and Agrarian Reform has been collaborating with ICARDA since the latter's inception in 1977. Collaborative work between different departments of the ministry and ICARDA has been very successful in prioritizing the research at ICARDA research stations as well as in the national program stations and farmers' fields. Since water is scarce and rainfall is very variable in time and space, most of the collaborative research has been directed at improving the water-use efficiency in crop production and soil and crop management. Water capture and infiltration and minimization of water loss through soil evaporation and transpiration by weeds to optimize water supply to the crop are crucial factors for improving water-use efficiency. Therefore, soil and crop management research concentrated mainly on factors affecting the proportion of water transpired by crops. Major attention was given to tillage practices and residue management; crop rotations; selection of varieties with rapid early growth, deep roots and early maturity; early sowing and optimum plant population; application of fertilizer; weed control; supplemental irrigation, and water harvesting. The main findings from this soil and crop management research are summarized.

Water Infiltration into Soil and Erosion

Because of low precipitation, drainage and deep-percolation, loss of water is not a problem in the rainfed areas of Syria (Gregory 1991). Thus, research in this area mainly focuses on the capture of rainwater on the cropped area by increasing the infiltration rate of the soil and reducing the runoff of water. Several factors such as rainfall quantity and intensity, land slope, soil characteristics, and plant cover affect infiltration and runoff, but it is mainly soil characteristics and plant cover that are directly controllable, although land slope may be changed by terracing to harvest rainfall. Generally, research on water infiltration concentrates on soil characteristics to see whether infiltration is limited by surface crusting or by slow subsurface percolation. Surface crusting and restricted infiltration are widespread problems in the dry areas of Syria, associated with the high silt content of the soils (Cooper et al. 1987a). However, there has been no research done in this area, although there is some evidence that farmers have to reseed the crop under severe conditions.

Increasing organic matter has an indirect beneficial effect on soil water-holding capacity, increased infiltration, and reduced runoff. Research results from ICARDA have shown that rotation of cereals with grazed forage legumes increased the organic matter content of soils by about 0.2% compared with continuous cereal or cereal-fallow systems (Ryan and Abdel Monem 1998). Enhanced crop growth leaving a greater amount of root residues, and minimization of mineralization through reduced-tillage systems are practical ways to improve organic matter, thus increasing water infiltration (Papendick et al. 1991).

Another area of research focuses on water harvesting in dry areas where rainfall is not sufficient to produce crops economically. Water harvesting is defined as concentrating rainfall as runoff from a larger catchment for use in a smaller (cropped) target area. Water harvesting can directly improve the efficiency of utilization of rainwater by supplementing rainfall in particularly dry areas. In this regard, SMAAR represented by the Department of Water Management has established the Mehasseh Research Center for the Integrated Development of Agricultural Natural Resources in the Syrian Steppe. Research activities carried out in collaboration with IDRC, UNDP, ICARDA, and the Japanese Peat Association aim at integrated watershed management, evaluating the impact and cost/benefits of various alternatives of water conservation, erosion control, and revegetation to improve the utilization of the resources of the Syrian steppe. The measures tested to improve the use of scarce rainfall include runoff improvement by surface treatment, runoff water harvesting reservoirs of different sizes, water-spreading dikes, contour cultivation, and various types of semicircular bunds.

The contour farming experiments showed that both methods used (ripper and ditch) clearly increased soil moisture enough to grow four tree species *(Atriplex leucoclada,* A *halimus, A. cannescens,* and *Salsola vermiculata).* The ditch method yielded higher soil moisture at all levels of line spacing tested than the ripper method. These effects were more accentuated on steeper (5% and 7%) than on gentler (3%) slopes. As for contour farming, semicircular bunds were more effective on steeper than on gentler slopes. This was particularly true with regard to survival and growth of the two tree species *(A. halimus* and S. *vermiculata)* planted within the structures. Average soil moisture within the microbasins was higher with hand-made than with mechanically-made bunds. Runoff water spreading by dikes also increased soil moisture in large areas within the watershed (Somi and Abdul Aal 1999).

On the other hand, land degradation through water erosion may also be a problem, particularly in the wetter hilly areas of northern Syria, where olive plantations substantially expanded in the last decade. Therefore, a project on 'Stabilization of marginal steeplands' has recently been initiated by ICARDA in collaboration with the Syrian Olive Bureau with the participation of farmers, to reduce soil erosion through an integrated soil and land management approach and tree management techniques (LMP 1999).

Evaporation and Transpiration

One factor controlling evaporative loss from the soil surface is the soil moisture content at that surface, which depends on the unsaturated hydraulic conductivity of the soil (a function of texture) as well as on the frequency of rewetting, e.g. by rainfall. Studies carried out at ICARDA suggest very high values for the hydraulic conductivity of the clay soils in northern Syria, which, by allowing large upward movement of soil water to the surface, foster evaporative loss and limit the efficiency of crop water use (Eberbach and Pala 1999).

The influence of row spacing on the partitioning of evapotranspiration into evaporation and transpiration in winter-grown wheat in northern Syria was studied within long-term, two-course rotation trials established at ICARDA on a swelling clay soil (Calcixerollic xerochrept). A related study at the same site showed that saturated (+5 mm tension) and unsaturated (-40 mm tension) hydraulic conductivity were inordinately high (typically between 300-500 mm hr^{-1} and 30-60 mm hr^{-1}, respectively) relative to conductivity reported in the literature for similar type of soils elsewhere. In this study, evapotranspiration from the crop was inferred from changes in the soil moisture content over time, while evaporation and rainfall interception were measured daily using microlysimetry. Between sowing and day 80 (tillering stage), evapotranspiration consisted mainly of soil evaporation. However, after day 80, transpiration became progressively more important. For both levels of row spacing, cumulative evapotranspiration over the season was approximately 390 mm of soil water. In the narrow-spaced crop, transpiration and soil evaporation was approximately 200 mm and 190 mm of water respectively. Conversely for the widely-spaced crop, 170 mm of water was transpired while 220 mm of water evaporated from the soil surface. As the amount of radiation intercepted at the soil surface did not differ significantly between the two crops over the growing season, it seems likely that the increase in evaporation was due to increased convection of water vapor to the atmosphere due to the enhanced movement of air between the rows in the wide-spaced crop (Eberbach and Pala 1999). Hence, methods to impede soil evaporation such as reducing row spacing or direct sowing into stubble may improve water-use efficiency and yields in soils with high hydraulic conductivity.

Another study conducted at ICARDA on the comparison of different tillage systems showed that evapotranspiration of bread wheat, durum wheat, chickpea, and lentil crops varied between 230 mm and 463 mm, 250 mm and 440 mm, 175 mm and 425 mm, and 173 mm and 385 mm, respectively. Evapotranspiration was close to the rainfall obtained during the cropping seasons, and did not differ significantly among tillage practices. This suggests an opportunity to reduce tillage intensity to a minimum for less degradation of the soil in the long run (Pala et al. In press).

Water use of wheat was divided into crop transpiration (T) and soil evaporation (E_5) using Ritchie's model (Ritchie 1972) in a study realized in northern Syria over five seasons (Zhang et al. 1998). Results showed that E_5 was reduced from 120 mm to 101 mm by addition of 100 kg N ha^{-1} under rainfed conditions, and T increased from 153 mm to 193 mm. Zhang et al. (1999) reported from trials over 12 seasons in northern Syria that grain yield of chickpea and lentil and their water use under rainfed conditions was mainly determined by rainfall and its distribution. Seasonal evapotranspiration (ET) was significantly correlated with seasonal rainfall for both chickpea and lentil. The mean ET over 12 seasons was 268 mm for chickpea and 259 mm for lentil. The depth of soil water extraction was, on average, 120 cm for chickpea and 80 cm for lentil, and average extractable soil water was 125 mm and 90 mm, respectively. The estimated soil evaporation was 80 mm for lentil and 105 mm for chickpea. The average transpiration efficiency was 7.1 kg ha^{-1} mm^{-1} for lentil and 6.4 kg ha^{-1} mm^{-1} for chickpea, and the estimated potential transpiration efficiency for seed yield was 11.8 kg ha^{-1} mm^{-1} and 12.2 kg ha^{-1} mm^{-1}, respectively.

Windbreaks can also serve to reduce evaporation from the soil surface by reducing the wind speed, but they have to be practical and acceptable to the local community, fitting their environment and economic conditions. Jones and Harris (1993) reported that fodder shrubs and trees like *Acacia and Atriplex* spp used as hedges along barley fields could save water by reducing evaporation from the soil surface through reduced wind flow through the barley crop.

Mean Class A pan evaporation at ICARDA station, which is representative of the major agricultural production areas in Syria, is 1.5 mm day^{-1} during the early crop growth period until February, increasing abruptly to 3.38 mm day^{-1} in March, 8.41 mm day^{-1} in May, and 13.1 mm day^{-1} in June. About 35-50% of the total water used by a crop is lost by evaporation from the soil surface, depending on factors such as soil properties, row spacing, etc. Therefore, improved soil and crop management practices to increase water-use efficiency have been investigated.

Improved Water-Use Efficiency Under Rainfed Conditions

Crop selection and breeding in Syria is performed in close collaboration with ICARDA and resulted in the release of several cereal and legume varieties with improved yield as well as resistance to drought, cold, pests, and diseases (GP 1995; 1996). The phenology and morphology of these cultivars have been improved to match the local environmental conditions, especially the pattern of water availability.

Any husbandry technique that facilitates rapid canopy development and enables the crop to cover the soil surface, to shade out weeds, arid to reduce wind speed through the canopy may, in most circumstances, be expected to increase crop water-use efficiency. Research results in WANA (e.g. Cooper and Gregory 1987; Cooper et al. 1987a; Gregory 1991; Harris et al. 1991b) have emphasized the importance of achieving early crop cover through the practices of early sowing, selection of varieties with rapid early growth (under cool conditions), adequate fertilization, and adequate plant population (e.g. narrower row spacing). In dryland crop production in winter-rainfall areas, the optimum sowing date has been proved to have a substantial effect on WUE and eventually on yield, by ensuring that crop growth is adjusted to the availability of soil moisture. Early sowing depends on the tillage/crop rotation system employed. Development of crop varieties for early growth vigor has been a major concern of winter cereal breeders in Syria for many years (Ceccarelli et al. 1991). Despite temperature limitations to growth, it pays to sow early (late fall, early winter) so that as much as possible of the crop growth cycle is completed within the cool, rainy winter/early spring period (Cooper and Gregory 1987). Since, apart from any species and genotypic differences, transpiration efficiency is a function of the atmospheric saturation deficit, directing biomass production into periods of lowest atmospheric demand confers an advantage in improving water-use efficiency (Acevedo et al 1991; Gregory 1991).

In Syria and in other similar areas of the world, there are many indications that early crop establishment and early canopy development are associated with higher wheat and barley yields (Bolton 1981; Cooper et al. 1987a). The possibility of extending the duration of the effective growth period resulting in higher yields is only possible by earlier sowing (Keatinge et al. 1986; Photiades and Hadjichristodoulous 1984; French and Shultz 1984). However, early sowing will only prove to be an advantage if emergence also occurs early and if the crop can survive potential drought conditions at the seedling stage (Pala 1991). Currently, farmers in the Mediterranean region tend to sow wheat later than at optimum time (usually mid November depending on the thermal time requirement), because of the unreliable initial rains

(Dennet et al. 1984), concerns with regard to weed control with presowing tillage operations, and the risk of frost damage to early-sown crops. The concept of early and complete canopy establishment to shade the soil and reduce evaporative loss from the surface makes good sense for winter-rainfall crops in the Mediterranean-type environment. It has been calculated that in northern Syria, each one-week delay in sowing after the beginning of November will reduce wheat yields by 4.2% (Stapper and Harris 1989). Similar considerations lie behind attempts to persuade WANA farmers to move from spring to winter sowing of chickpeas (Silim and Saxena 1991; Pala and Mazid 1992). Brown et al. (1989) reported that the water-use efficiency of chickpeas in northern Syria increased from 8.8 kg dry matter ha^{-1} mm^{-1} evapotranspiration for spring-sown chickpeas to 15.7 kg ha^{-1} mm^{-1} for the winter-sown crop, showing the importance of early sowing in improving water-use efficiency.

Since, in general, Syrian soils have low fertility as in many dry areas in WANA (Ryan and Matar 1992; Matar et al. 1992), judicious use of fertilizer is particularly important. Extensive work in Syria during the 1980s (Cooper et al. 1987a; 1987b; Shepherd et al. 1987; Brown et al., 1987; Cooper 1991) demonstrated the efficacy of appropriate fertilization on production and on the water-use efficiency of winter-sown crops, especially wheat and barley. Cooper et al. (1987a) reported a mean increase of WUE of barley biomass yield from 16 kg ha^{-1} mm^{-1} under no fertilizer to 28 kg ha^{-1} mm^{-1} under 60 kg ha^{-1} N and P fertilization. In deficient soils, seedbed phosphate application (usually with a small dose of nitrogen as well) enhances the rate of leaf expansion, tillering, root growth, and phenological development, ensuring more rapid canopy closure and earlier completion of the growth cycle before rising temperatures increase the atmospheric water demand (Gregory et al. 1984; Gregory 1991).

In addition to experiments on research stations, ICARDA and the Syrian Soils Directorate in northern Syria conducted a four-year multilocational study. Results from 70 sites in farmers' fields indicated widespread barley responses to N and P fertilizer. Responses to P were most frequent in the drier areas, while responses to N became more important with increasing rainfall (Jones and Wahbi 1992). A similar study in more favorable areas in northern Syria showed that wheat was more responsive to increased N application with increasing rainfall, but the response to P was not significant (Pala et al. 1996a). These studies were conducted to test the results of the on-station trials under farmers' conditions and to see how the results would be multiplied in farmers' fields. The study provided a clear strategy for Syrian decision-makers to prioritize fertilizer allocation strategy with respect to improving fertilizer-use and water-use efficiency through yield increases of the staple crops, barley and wheat.

Crop rotation studies have been conducted for more than ten years at several stations in Syria as well as at ICARDA with respect to increased productivity and soil quality as well as improved water_use efficiency (Harris 1995; Pilbeam et al. 1997a, 1997b, 1997c; Zhang et al. 1999). The replacement of weedy fallows with crops has been proved to yield a net gain in water-use efficiency and agricultural output. Under the pressure of increasing population and other competing land-use demands, long fallow periods are no longer possible in densely populated areas. Moreover, the storage efficiency of long fallows seems usually to be rather low. Storage efficiency at Breda (long-term mean rainfall 280 mm) never exceeded 10%, but under moister conditions at Tel Hadya (330 mm), the range was 8-37% over six years (Harris et al. 1991a). The high efficiency of 37% was recorded in the 1987/88 season when the total rainfall was about 500 mm, an amount that has a probability of 5% only. This clearly shows that, in general, fallowing is least effective in those areas of low and erratic rainfall where crops would benefit most from it. Therefore, fallow replacement with food or forage legumes or leguminous pasture crops enhances the water and nitrogen balance in comparison with fallow-cereal or continuous cereal systems (Harris et al. 1991a).

Compared with cereal-fallow rotations or continuous cereals, legumes grown in a crop sequence with cereals have a positive effect on the system water-use efficiency because of their usually shorter growing period. The water that may be left in the soil profile for the subsequent cereal crop is one of the important contributions of legumes to increased productivity (Harris et al. 1991a; Harris 1995). Harris (1995) also reported that wheat-fallow rotations show a lower WUE irrespective of the productivity level because only a single crop is grown over a two-year period. As mentioned earlier, the productivity of wheat in the cropping sequence depends mainly on the water that is stored in the soil profile after the preceding crop. Lentil is a short-season crop normally harvested one month earlier than either chickpea or wheat. It is therefore less exposed to the high evaporative demand that occurs late in the cropping season and uses less water to complete its growth cycle. Thus, some water may remain in the soil after lentil, providing some degree of buffering against temporal variability in rainfall and presumably leading to higher productivity of subsequent cereal crops (Harris 1995). In contrast, chickpea and medic pasture provide lower yields for subsequent wheat crops because their water use was close to that of wheat.

Similarly, water is used more efficiently and productivity is higher in barley-vetch rotations than in either continuous barley or fallow-barley systems (Harris et al. 1991a). In barley-based systems at Breda, northern Syria, a rotation of barley with vetch cut as hay produced 0.6-0.9 t ha^{-1} $year^{-1}$ more biomass than continuous barley. This represents a 20-30% improvement in water-use efficiency: fertilized barley grown after vetch produced 36.7 kg biomass ha^{-1} mm^{-1}, but after barley only 23.7 kg ha^{-1} mm^{-1} (Harris 1994). In similar studies at Breda and Tel Hadya, rotations of barley with vetch grown to maturity almost doubled the net offtake of nitrogen (and therefore protein) relative to barley-barley and fallow-barley sequences, an important consideration in production systems largely dedicated to feeding sheep (Jones and Singh 1995). Moreover, the growth stage of vetch at harvest (hay or seed production) significantly affects the soil moisture status, producing differences in the subsequent barley yield and rotational water use. In spite of the advantages of cereal-legumes systems over cereal-fallow and, more importantly, over continuous cereals, farmers generally tend to intensify their cropping with their staple crop first. Therefore, it is nowadays quite common in Syria to find fields where wheat or barley is grown nearly every year. This is, however, detrimental in the long run with regard to the sustainability of the production systems as well as efficient use of (rain)water resources.

In collaboration with ICARDA, a trial was conducted over six seasons in a clay loam soil in eastern Syria to test a no-tillage planter compared with the local technique. The objectives were to replace fallow with a barley-forage legume rotation, to increase barley productivity, to protect barley from the Ground Pearls and Mealy bug, and to provide green feed for sheep in the dry areas (SD 1997). Barley yield in the rotations with forage legumes was 15% higher than in continuous barley, but 14% less than in barley after fallow. Although the barley-fallow rotation was found to be the best with regard to yield in a given year, it was economically less interesting since only one harvest is obtained in two years.

In the same trial, barley yield using the zero-tillage planter was 9% greater than broadcasting the seeds and covering them by disc harrow, and 1.4% higher than using the local drill. This is promising with regard to energy-use efficiency, and lessens the disturbance of soil under reduced tillage. After five years, organic matter increased by 21% in rotations including legumes, and by 9% in the barley-fallow rotation. Under continuous barley, organic matter decreased by 7%, although the reason for this reduction is not clear since the roots are left in the soil. Total soil nitrogen increased by 32% in rotations including legumes, and by 17% in the barley-fallow and by 5% in the barley-barley rotations, respectively (SD 1997). No water measurements have been performed in these trials, but the efficiency of rainwater use can be estimated from the yields, as in other ICARDA trials (Jones 1996; Jones and Singh 1995; Christiansen et al. 1999).

Supplemental Irrigation

A completely different approach to increasing water-use efficiency in dry environments is supplemental irrigation (SI), defined as the addition of small amounts of water to rainfed crops during times when rainfall fails to provide sufficient moisture for normal plant growth (Perrier and Salkini 1991; Oweis 1997). Such additions, if well-managed, increase not only the utilization efficiency of rainfall, but also that of the irrigation water. When rigorously practised, supplementary irrigation follows the principle of > deficit irrigation=; the soil profile is not irrigated fully to field capacity, and the target is not maximum yield but rather a yield that optimizes water-use efficiency. The water source for SI can be underground or surface water available to the farmers. The most important considerations in management of SI are when and how much water to apply (Oweis 1997). Usually farmers tend to apply more water to their crops because of their immediate short-term production objectives. There is a need to transfer readily available research results to farmers to improve the efficiency in using scarce water.

Previous research results from ICARDA and collaborative studies with the Directorate of Irrigation and Water Use in farmers' fields showed substantial increases in rainfed crop yields in response to application of relatively small amounts of SI. Average increases in wheat grain yield under low (234 mm), medium (316 mm), and high (504 mm) annual rainfall at Tel Hadya station of ICARDA were about 400%, 150%, and 30% using SI amounts of about 180 mm, 125 mm, and 75 mm, respectively (Oweis 1997). The average WUE of rain in producing wheat in Syria and other dry areas of the region is about 0.35 kg grain m^{-3}, although with proper management and favorable rainfall (amount and distribution), this can be increased to 1 kg grain m^{-3}. However, research at ICARDA showed that each cubic meter of SI (at the right time and combined also with good management) could produce 2.5 kg of grain over the rainfed production (Oweis 1997).

The average wheat yield of 1.25 t ha^{-1} under rainfed conditions in Syria rose to 3 t ha^{-1} with SI. In 1996, over 40% of the rainfed areas were under SI, and over half of the 4 million tons of national wheat production was attributed to this practice (Oweis 1997). Much of this expansion has been based on the exploitation of groundwater, which varies locally in quality. Some aquifers supply brackish, even saline water. Others, initially fresh, are deteriorating. Thus, overuse of this precious resource should be prevented by reducing the amount of water applied through proper SI management techniques.

Oweis et al. (1998) reported the results of SI experiments during four seasons at ICARDAs Tel Hadya station. Wheat response to N and SI were related very closely. Under SI, yields were increased by N fertilization of up to 100 kg N ha^{-1}, whereas under rainfed conditions, crop response was only observed up to 50 kg N ha^{-1}. An addition of only limited irrigation (1/3 of full irrigation) significantly increased yields, but near maximum yields were obtained at 2/3 of full irrigation. The combined water-use efficiency of rainfall and SI in terms of crop grain yield ranged from 1.27 kg to 1.02 kg and 0.68 kg of grain per cubic meter of water at the 1/3, 2/3, and full SI levels, respectively, compared to the mean water-use efficiency of 0.7 kg grain m^{-3} under rainfed conditions. However, when calculating the water-use efficiency of supplemental irrigation only, it ranged from about 3.0 kg to 2.0 kg, and 0.8 kg of grain per cubic meter of water at the 1/3, 2/3, and full SI levels, respectively. This means that full irrigation yields as low a WUE as the rainfed crop.

The Directorate of Irrigation has also investigated net water consumption of wheat and other crops. Cham 3 (a durum wheat variety) irrigated with 5500 m^3 ha^{-1} produced 7059 kg ha^{-1} as compared to 3676 kg ha^{-1} under rainfed conditions (345 mm). This results in a WUE (combining rainfall and irrigation) of 0.79 kg grain m^{-3} under full irrigation, while the rainfed crop achieves a WUE of 1.07 kg grain m^{-3} (DOI 1996). Thus, in terms of improving water-use efficiency, there is no benefit in applying full irrigation. However, the Extension Directorate has recommended for wheat 2 irrigations with 750 m^3 for Zone 1 and 3-5 irrigations for Zone 2, depending on the season (Extension Directorate 1989). The total water requirement of wheat under sprinkler irrigation was determined at 5807 m^3 ha^{-1} for a grain yield of 6328 kg ha^{-1}, while under surface irrigation it was 9092 m^3 ha^{-1} for a yield of 5141 kg ha^{-1}, resulting in a WUE of 1.08 kg grain m^{-3} and 0.56 kg grain m^{-3}, respectively (DOI 1996).

Modeling

Field experiments are the best tools to assess the effects of production practices on crop yields and wateruse and fertilizer-use efficiency in a given area. However, they are usually conducted at specific sites for a short duration. To develop reliable results for analysis of the production risk, it needs a minimum of thirty years' data in most cases. In this respect, crop simulation models are possible alternative tools for this kind of studies, provided that they are preliminarily calibrated. Geographic information systems (GIS) are the tools that can be used to map soils and crop outputs, to extrapolate results for wider regions, and thus to direct research and development projects for the welfare of farmers. With this respect, various methods were tested to calibrate models using station-research results, and applying them in northwestern Syria.

CropSyst is a multiyear and multicrop daily time-step simulation model. It has been developed to serve as an analytical tool to study the effect of cropping systems management on productivity and the environment. The model simulates the soil water budget, soil-plant nitrogen budget, crop canopy and root growth, dry-matter production, grain yield, residue production and decomposition, and erosion. The management options include: cultivar selection, crop rotation (including fallow years), irrigation, nitrogen fertilization, tillage operations, and residue management (Stockle et al. 1994; Stockle and Nelson 1994).

In general, the model was able to track well changes in the green leaf area index (GLAI), biomass, ET, and N uptake throughout the season. Statistical analysis confirmed that CropSyst predicted these parameters reasonably well, showing a high index of agreement (d) and root mean square errors (RMSEs) corresponding to 9% (cumulative ET) to 25% (grain yield) of the observed mean values. The observed and simulated mean values of 16 data points of each cultivar were very close. CropSyst achieved a reasonable agreement between observed and predicted grain yields with an index of agreement of 0.92 for Cham 1, a durum wheat variety developed in collaboration between the Syrian NARS and ICARDA and widely used as a commercial variety by farmers (Pala et al. 1996b).

When the model was applied to northwestern Syria (Pala 1998), it was demonstrated that supplementary irrigation requirement decreases from about 400 mm in the 250 mm rainfall zone to 100 mm beyond the 500 mm rainfall zone, which is in line with previous results reported by Oweis (1997). Pala (1998) reported that yields increased linearly from about 0.5 t ha^{-1} in the 250 mm rainfall areas to about 5.5 t ha^{-1} with 530 mm of rain, and then leveled off with increasing amount of rainfall. This is in good agreement with a study on the assessment of environmental factors influencing wheat response to N fertilizer (Pala et al. 1996a). N requirements of wheat increased with increasing amount of rainfall up to 410 mm/and then leveled off also. This conforms to other studies in the region (Pala et al. 1992; Harris 1990). In 80% of the cases, yield was 0 t ha^{-1} , 1 t ha^{-1}, 2.5 t ha^{-1} , and 3.5 t ha^{-1} with 250 mm, 350 mm, 450 mm, and 570 mm rainfall, respectively, demonstrating that production of wheat is risky in areas with less than 300 mm of rainfall. This is understood well by the experienced farmers of the region; they therefore grow mostly barley which is more drought-resistant than wheat.

Using the same data set, SIMTAG, a wheat genotype simulation model developed at ICARDA (Stapper 1993), was tested for water and nitrogen effects on crop development, and the results were compared with the predictions of CropSyst (Pala and Goebel 1996). Cumulative biomass and evapotranspiration (ET) were estimated similarly by both models. However, the grain yield estimate was much closer (92% of agreement index) with CropSyst than with SIMTAG (72% of agreement index).

Testing and use of several other regression models simulating crop yield responses to water and nitrogen have not been mentioned here, but the results are available in the references given at the end of this paper.

Development Projects with Research Involved

In the Syrian steppe (the Bishri mountains), a project aiming at monitoring and combating desertification has been established as a technical cooperation among ICARDA and other national, regional, and international institutions (Syrian Soils Directorate, ACSAD, GORS, and GTZ). The main concern of the project with regard to optimizing soil water use is the testing of different techniques of rainwater harvesting for their applicability, success, cost-benefit ratio, transferability, and acceptance by the population.

In Mehasseh (120 km northeast of Damascus) operates another integrated watershed development project in the Syrian steppe, a collaboration between the Directorate of Irrigation and Water Use and the International Development Research Center (IDRC) and the United Nations Development Program (UNDP), with technical assistance by ICARDA. The objectives of this project in the very dry area are to improve surface and groundwater-use efficiency; to protect soil, water, and vegetation resources from degradation; to develop the natural resources (soil, water, plant cover) and organize their exploitation and management; to improve the production efficiency of sheep; and to study the economical and technical feasibility of water harvesting and water spreading techniques (Somi and Abdul Aal 1999).

The goals of the study on 'optimum water use at farm level' within the On-farm Water Husbandry Project in WANA (collaboration with ICARDA) are to find out practical and effective methods of water harvesting for sowing shrubs on slopes to reduce runoff and control erosion; to use techniques that increase the continued local exploitation of rainwater and prevent the degradation of natural resources; to activate surface runoff and construct microcatchments for water harvesting, considering cost-benefit ratios and erosion hazards; and to select methods of soil and water management for sustainable agricultural exploitation.

Future Research Activities

The increased production in the dryland areas in Syria is a solid step towards self-sufficiency. A considerable part of this increase can be attributed to the use of supplemental irrigation, particularly in wheat production. However, groundwater resources in Syria are being depleted at a scaring pace. To achieve sustainable dryland agriculture systems, the following steps should be taken with regard to supplemental irrigation as one of the effective methods to increase yields and water-use efficiency in the dryland areas of the country:

- Development of adapted supplemental irrigation methods, and their application in dryland regions;

- Identification and development of appropriate equipment for supplemental irrigation, based on the specific conditions prevailing in the dryland areas of different regions;
- Identification, development, and implementation of water harvesting, conveying, and storage techniques, considering the conditions prevailing in different dryland regions; and
- Development of suitable varieties of wheat and barley which can be grown under irrigation, and identification of the agronomic requirements of these varieties, such as optimum date of sowing and plant density.

Research on tillage and crop rotations carried out since 1991 in the arid and semi-arid regions have mainly focused on crop productivity. Measurements of water balance parameters need to be emphasized to enable investigations of soil-plant-water relationships; understanding of the principles behind optimization of soil water use is necessary for the development of management practices that can be applied.

The beneficial effects of reduced tillage and the use of crop residues on soil chemical and physical properties need further clarification. The positive effects of crop rotation systems to improve soil chemical and physical properties and to combat soil degradation should also be studied in long-term trials, with particular focus on the most efficient and effective water use. Further, there is an urgent need for an integrated approach to simultaneously optimize soil water and nutrient use by crops in dry areas for greater productivity and sustainability.

Reduced tillage and residue mulching are gaining momentum because of their beneficial effects on biological, chemical, and physical properties of the soil. The critical levels of different mulching materials to effectively reduce evaporative water loss under different climatic conditions and on different soil types must be determined. Cereal production areas in Syria have been largely expanded, and more sloped areas have gone under cultivation. However, in the dryland as well as humid areas, land is vulnerable to wind and water erosion. In cases where it is not possible to allocate land susceptible to erosion for grazing, no-till production seems feasible when considering the potential benefits of stubble residue to soil and water conservation. Consequently, research related to soil and water conservation through stubble management and direct seeding (zero-tillage) should be tested on different soil types under the dryland conditions of Syria, and be compared to conventional tillage practices, with particular regard to improved sustainability, energy and water-use efficiency. With regard to vertic soils, which are inherently fertile and productive when properly managed, the potentially beneficial effects of reduced tillage and stubble mulching should be further investigated. These soils with accentuated self-mulching properties and crust development, usually have low infiltration capacities and, consequently, low water storage because of their high clay content and structural degradation due to long-term conventional tillage.

Contour plowing may conserve 50% more soil moisture and soil than plowing up and down the slope. However, in order to put contour plowing into practice and conserve and utilize scarce and unevenly distributed rainwater more efficiently, field plot shapes, orientation, and sizes will have to be adapted, requiring sensitization of the farmers.

In the drier semi-arid climatic regions and on heavy clay soils, crop production using conventional tillage is only sustainable if practised extensively on a large scale. However, it is known that by reducing runoff and evaporation and increasing soil water storage using various mulching practices, precipitation-use efficiency (PUE) can be improved. These potentials have to be investigated in more detail. Similarly, the various water harvesting techniques to improve PUE, especially on marginal soils and under erratic and low rainfall, have not yet been sufficiently investigated in Syria.

The potential for water harvesting, especially in areas which receive an average annual rainfall of less than 200 mm, is promising. The ecological systems of this region are fragile and prone to degradation and desertification. However, they still have a reasonable potential for agricultural production if utilized properly. New systems will have to be developed and introduced, which allow at the same time sustainable development and preservation of the natural equilibrium in order to prevent further desertification.

Various water harvesting techniques, such as sowing in microbasins with optimum ratios of catchment (runoff) to cropped area (runon) have to be evaluated. These techniques, if adapted to local conditions, could be of great benefit in sustaining food production by small farmers who have to make a living on heavy clay soils under marginal rainfall. Further studies in water harvesting will have to consider rainfall distribution characteristics, efficiency of the collecting system, the potential for water harvesting as a means of artificial recharge, agricultural development strategies using water harvesting techniques, property rights issues of shared water and land resources, and the economic return of agricultural production using water harvesting technologies.

Conclusions

The basic principle of efficient soil water use for plant production lies in maximizing the gains and minimizing the losses of water. It was shown that the harmful effect of low and poorly distributed seasonal rainfall on crop production can be alleviated with proper soil and crop management techniques. Crop rotations which fit the local environment can already improve the water-use efficiency, production, and sustainability of the system to a great extent. Introduction of legumes into cereal-fallow and, most importantly, into continuous cereal production systems seems to be optimal for increasing biophysical as well as economic crop yields, associated with more efficient water as well as nutrient use. By leaving some of the seasonal rainwater in the soil profile, they benefit the following cereal crop. Increase in soil quality in cereal-legumes rotations will eventually sustain the productivity of the soil for better production in the long run.

Besides identifying optimal crop rotations, proper management of soils and crops is needed to reach maximal yields and resource-use efficiency. Timely cultivation and seedbed preparation at the right depth and using the appropriate implement has to consider the specific locality and the different agroecological conditions of the country. Timely tillage practices will allow sowing at the optimal date at adequate densities, which affects early stand establishment and thus competition with the weeds for light, water, and nutrients. However, minimum and no-till cropping systems, leaving most of the crop residues on the soil surface, were not entirely successful under Syrian conditions, but proved possible if the straw was grazed as it is often done in farmers' fields.

Nutrient management has proved very important in improving water-use efficiency of rainfed crops such as wheat, barley, and food and feed legumes. Increased soil fertility also increases productivity and water-use efficiency of the production system as a whole. Although the importance of weed control in improving water-use efficiency and crop yields has not been treated extensively, yield reductions of 30-80% (or complete crop failure in some cases) due to weeds have been recorded for rainfed field crops (Koudsieh et al. 1987; Solh and Pala 1990), and this is well understood by farmers.

In summary, proper soil and crop management were found to be very effective in increasing crop yield levels and improving water-use efficiency, particularly where chronically low and variable rainfall is a major problem for the farmers. Therefore, these research results need to be transferred to farmers more effectively and efficiently in order to fill the food and feed gap of the country.

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Optimizing Soil Water Use in Wheat Production Systems in Dryland Areas of Turkey

M Avci[1]

Abstract

Semi-arid areas cover about 55% of Turkey and are mainly found in the Central Anatolian Plateau. The main crop production systems are fallow/ wheat and legume/wheat. Wheat is generally prone to droughts, which severely affect the yields. Research on soil moisture use in fallow-wheat systems started in the 1930s. Its focus was on water interception and conservation techniques, and detailed research on rainfall interception led to practices which have been adopted by most of the plateau farmers. In the 1980s research focussed on the replacement of fallow by a crop in the rotation systems. In most areas, fallow can best be replaced in terms of yield by forage crops and economically by edible legumes. Characterisation of the other regions will identify fallow or continuous cropping target areas, and extrapolation of research results to them. Regarding technologies, the importance of terracing for moisture conservation increases with the degree of slope and the occurrence of erosive rainfall. Contour tillage and sowing were found effective only on steep slopes. Future research is needed on supplemental irrigation in order to increase the water-use efficiencies of the wheat and barley varieties especially developed for irrigation.

Resume

Les zones semi-arides de Turquie couvrent presque un tiers du pays et se trouvent principalement dans le Plateau Central d'Anatolie. Les systemes de production majeurs sont le ble/jachere et les legumineuses/ble. En general, le ble est generalement affecte par des perioues de secheresse qui affectent largement les rendements. La recherche sur l'utilisation de Veau de sol a commence depuis les annee's 30, Le point focal a ete l'interception de l'eau et les technologies de conservation de l'eau. La recherche detaillee

1. Central Research Institute for Field Crops (CRIFC), P O Box 226, Ankara, Turkey.

N. van Duivenbooden, M. Pala, C. Studer and C.L. Bielders (eds). 1999. Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia, and North and Sub-Saharan Africa. Proceedings of the 1998 (Niger) and 1999 (Jordan) workshops of the Optimizing Soil Water Use (OSWU) Consortium. Aleppo, Syria: ICARDA; and Patancheru, India: ICRISAT. pp 221-242.

sur l'interception de l'eau de pluie a abouti aux pratiques qui sont adoptees par la plupart des paysans sur le plateau. Dans les annees 80, la recherche a travaillee sur le remplacement de la jachere par une culture dans les systimes de rotation. Dans la plupart des zones, la jachire peut etre remplacie en terme de rendement par les cultures fourrageres, mais economiquement par les legumineuses vivrieres. Une caracterisation des autres zones permettra d'identifier les zones cibles de jachire ou de culture continue et l'extrapolation des resultats de la recherche vers ces zones. Concernant les technologies, l'importance de mise en terrasse comme mesure de conservation de l'eau augmente avec le degre de pente et l'occurrence de la pluviometrie erosive. On a observi que le travail du sol en bande de niveau et le semis sont seulement efficaces sur les pentes fortes. La recherche future doit se focaliser sur l'irrigation d'appoint afin d'augmenter l'efficacite de l'utilisation de l'eau des varietes de ble et d'orge specifiquement developpees pour l'irrigation.

Introduction

Turkey is located between latitudes 36°N and 42°N, and longitudes 26°E and 45°E. The inland area of the country is separated from the surrounding seas by a series of high mountains which prevent the clouds from penetrating into the central part, i.e. Central Anatolian Plateau and southeastern Anatolia (SA). Due to its geological and climatic conditions, Central Anatolia (CA) is very poor in vegetative cover, in contrast with the coastal and mountain areas that are rather rich in forests. It is a plateau divided by valleys, and is the most important region for wheat production in the country. The average elevation is 900 m, but in some places may reach 1600 m. About 90% of the agricultural lands do not receive adequate rainfall during the growing season. Because the rainfall is too limited to permit continuous cereal cropping, plateau farmers have adopted a crop-fallow production system as in many semi-arid areas of the world. Realizing the problems of dryland cereal production, the government is supporting agricultural research programs dealing with the tasks of optimizing the use of existing water and stabilizing cereal production.

The objective of this paper is to review research results related to optimizing water use and to identify issues for future research.

Characterization at the National Level

Climate

The semi-arid regions cover approximately one-third of the area of Turkey. Most of them are found in CA (55%), and are surrounded by dry-subhumid and humid patches. Only a few semi-arid areas are scattered outside the central zone (Fig. 1). The arid areas are located near the Syrian and Iranian borders. The temperature regime is mainly first mesothermal, i.e., somewhat warmer than cold (second

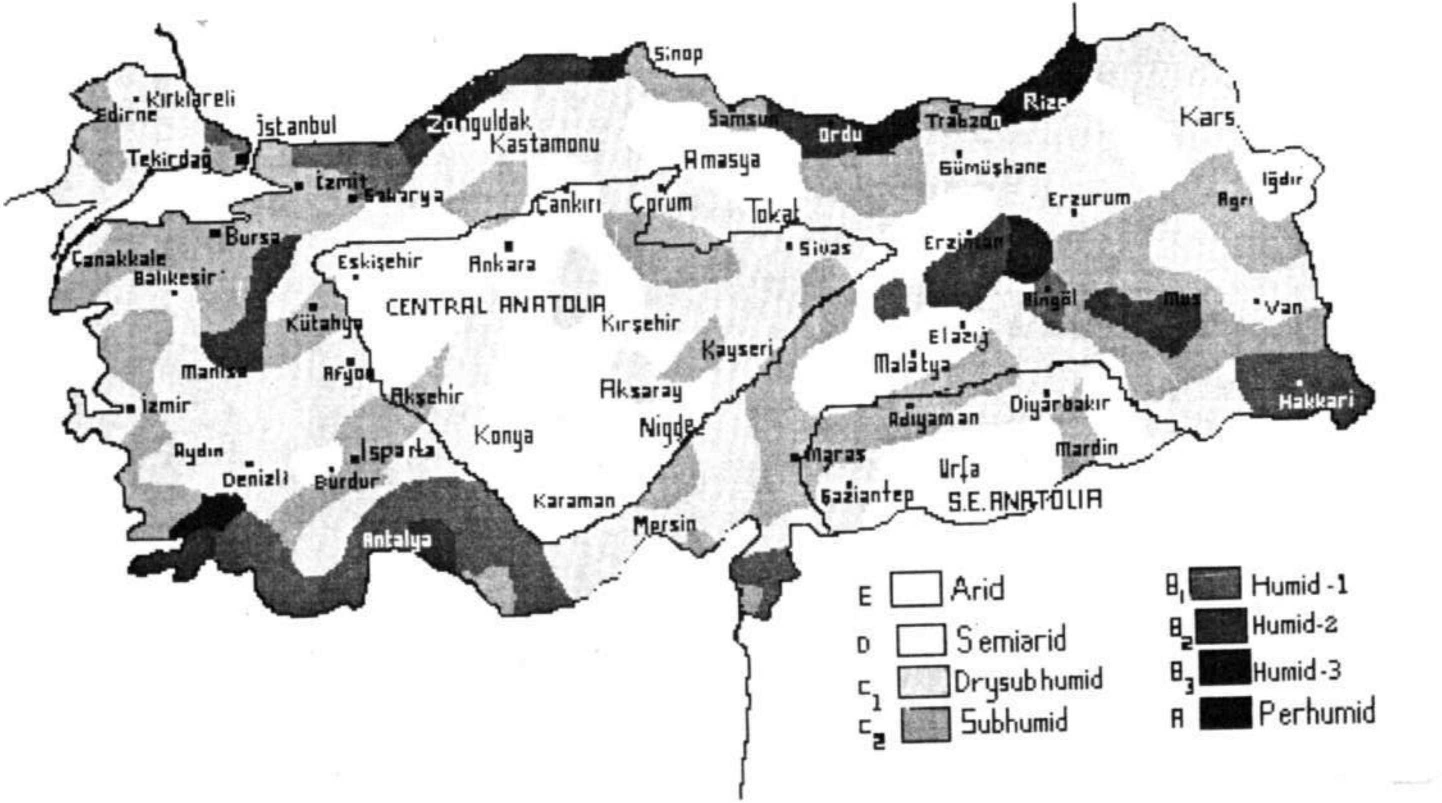

Figure 1. Climatic map of Turkey according to Thorthwaite's classification (Avci 1992).

microthermal) climate throughout the plateau and most of the country (Avci 1992). There is a small area of cold climate located in the eastern part of CA. Southeastern Anatolia is warmer than CA because of higher rainfall, and the climate varies from arid to very humid. Annual rainfall varies from 200 mm to 500 mm (Colasan 1960).

Soils

About 85% of the soils have a loamy or clay-loam texture. Most of them (90%, except in the Trace and Marmara regions) are alkaline (pH > 7), and are rich in $CaCO_3$ (58% of the soil contains more than 5% lime, except in the Black Sea and Marmara regions). Soil organic matter is low (0-2% in 70% of the soils) with the lowest range found in CA and SA. Most of the soils (66%) are deficient in phosphorus (P), requiring P fertilization for all crops; 18% of them have only a critical P level and need maintenance dressing; and the remainder (16%) have sufficient P for all crops. Almost all the soils have a sufficient or high potassium content. Most of the soils are limited in their water-holding capacity since the soil profile is just above 1 m above the calcareous parent material. However in SA, the soils generally are deep and have high water- holding capacities. These soils have a low water infiltration rate, but considerable upward movement occurs when evaporation takes place at the soil surface. Soil salinity and alkalinity are not serious problems (Ulgen and Yurtsever 1984).

Land Use and Crop Production Systems

Turkey has about 28 million ha of arable land, distributed among about 4.7 million agricultural holdings, of which 70% have 0.1-5.0 ha, the remainder owing up to 50 ha. The rural population has been gradually decreasing, being nearly 41% of the total population in 1991 (SIS 1994).

Wheat is the dominant crop in Turkey followed by barley, chickpea, lentil and, vetch. The main crop production system is wheat/fallow. Fallow is widely practised and covers 33% of the total cultivated area going up to 40% in wheat-fallow and barley-fallow systems (Durutan et al. 1990). Fallow is mostly practised by farmers who have 2-50 ha of land. Bare fallow lasts 14 months from the wheat harvest to sowing in the following year. Sowing is done in the period from mid September to mid October, and harvest in late July or early August. Until the first (primary) tillage (late March or early April), the field is left untouched with the wheat stubble remaining, to be grazed predominantly by small ruminants. Farmers having 2-20 ha of land own 62% of the sheep and goat population and 69% of the livestock in the region.

Winter legumes are sown about 2.5 months after the wheat harvest, and harvested in May. After burning the stubble, the field is plowed or disked and swept for seedbed preparation. Spring crops are sown with a cereal drill or broadcast in April (or early May) depending on the soil and weather conditions. The harvesting time differs for each crop: lentil and cumin in June, chickpea in late July (or early August), and sunflower in August (or early September), depending an the summer rains (Fig. 2).

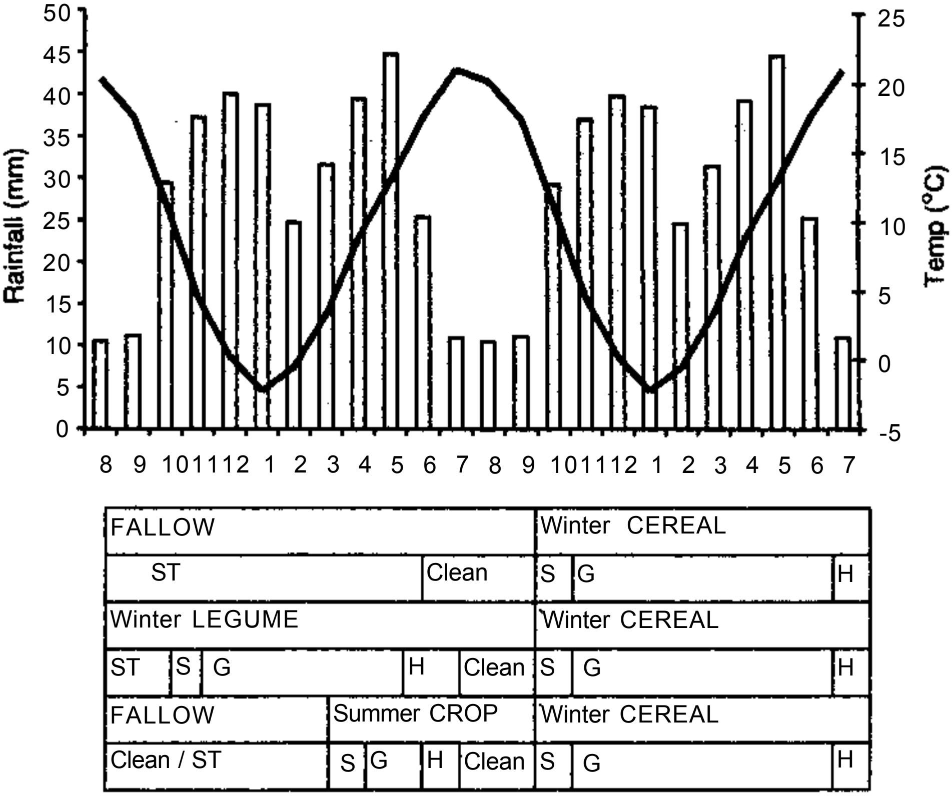

Figure* 2. *Climatic conditions and three cropping systems in Central Anatolia (S = sowing; G = growing; ST = stubble; and H = harvest).

The crop production systems are subject to some drought stress during their growing cycle. In CA, drought occurs during the early growth and grain-filling stages of wheat. Winter is usually very cold, retarding the growth of crops until March. Cold and drought are the main climatic stresses.

The number of holdings using fertilizer and chemicals is higher for cereal production than for food and feed legume production. Tractors and other farm equipment are owned mainly by farmers who have 10 ha or more. Farmers owning less rent or borrow tractors. Only 52% of the total cultivated area is cultivated with tractors owned by the farmer. Resource-poor farmers therefore face more problems relating to time-bound practices than resource-rich farmers (SIS 1994).

Water Resources

On average, the total renewable surface water potential of Turkey is roughly 95 billion m^3. The potential underground water supply is estimated at 12 billion m^3.

Currently, 27% of the surface water potential and 48% of the underground water potential are utilized for irrigation. The area that can be irrigated economically is 8.5 million ha. However, the actual irrigated land is about 3.67 million ha. Of this area, 33% is irrigated by using farmers' own facilities, the remainder by government investments on the irrigation conveyance system (DSI 1992).

Soil Moisture Utilization

Wheat-Fallow System

Rainfall Infiltration and Water Conservation in Fallow Phase

Fallow, considered an integral and essential part of the production system in the semi-arid areas for sustainable, stable, and risk-free production, has been studied since 1923. On the basis of the principles of water economy and nitrogen accumulation in the soil, Kirac (1937) proposed leaving the cultivated land fallow for 14 months and conducting the first tillage in early spring during the fallow period. This practice is still followed by most farmers of the wheat-fallow systems in CA. The best time is March (Table 1.) Gerek (1968) further specified that the best time is April for sloped and March for flat lands. Late tillage (plowing) in June lowered the wheat yield by half compared with timely tilling.

Berkmen (1961) also concluded that the primary tillage in fallow should be done when the soil moisture (tilth) is sufficient for tillage after winter, and that late-June tillage resulted in a 27% loss in wheat yield. If there was a need to have weeds in fallow for sheep grazing, the first tillage can be delayed until the end of May, but not beyond. Early tillage of fallow led to more stored moisture available at sowing time of wheat, higher grain yield and lower density of weed during the crop year (Table 2) (Karaca 1980; Pala et al. 1980; Durutan et al. 1989).

Different tillage and surface management techniques also affected rainfall infiltration and hence the soil water content (Table 3). Stubble cover and sand cover

Table 1. Effect of the timing of the first tillage on the amount of accumulated soil moisture (in a 180 cm profile) available at sowing time of wheat, and associated yield percentages of wheat (Kirac 1937).

	1930-1931 season		1932-1933 season	
Date of tillage	Moisture[1] (mm)	Yield (%)	Moisture (mm)	Yield (%)
March	225	100	147	100
April	206	99.5	158	106.5
May	197	77.0	93	86.5
June	110	44.0	66	52.0

1. The soil profile has a considerable amount of water below the rooting zone (< 1.2 m) which can move up rooting zone by capillary forces during summer.

Table 2. Effect of the timing of the first tillage (plowing) on average yield, soil moisture at sowing time (in a 1.2 m profile), and weed density in the wheat crop (Pala et al 1980).

Time of primary tillage	Yield (t ha^{-1})	Soil moisture (mm)	Weed density (plants m^{-2})
First week of April	2.74	329	13
First week of May	2.51	324	22
First week of June	1.87	292	50

were as effective on moisture storage as hand weed control and plowing in March. In addition, the effects of plowings at 15 cm and 20-25 cm depths were similar (Kirac 1937). After further research, Gerek (1968) recommended a primary tillage at a depth of 10 cm for slopes, and 15 cm for flat land.

Research carried out at Ankara indicated that plowing at 30 cm depth is advantageous when the March-June rains exceed the average (Berkmen 1961). The timing and depth of tillage seem to be more important in terms of soil moisture than the type of tillage implements (Unver 1978; Ayday 1996), but Karaca (1980) showed that the mouldboard plow (followed by the sweep) was the best for total water infiltration and infiltration rate. This was confirmed by Ayday (1996), who also found that contour tillage resulted in the most stored soil water. Kucukcakar (1987) showed that there was no difference between the implements in terms of runoff and soil loss. Demiroren and Kose (1986) tested the mouldboard plow, the reduced-mouldboard plow, and the Anatolian "saban" and sweep plow. The highest fallow efficiency (13%) was obtained with the mouldboard plow and the rodweeder + harrow combination at 60 cm soil depth. (Fallow efficiency expressed as a percentage, is defined as the amount of stored water in soil until sowing per 100 mm of rainfall recorded during the fallow period).

Kirac (1937) showed that weeds are the only cause of water loss from fallow in summer. Cultivation of fallow land, weed infested or not, resulted in a somewhat

Table 3. Impact of various tillage and surface management techniques on stored available soil water (in a 1.8 m profile) at the end of the rainy period[1] (mid June, 1932) (Kira 1937).

Types of management	Soil moisture (mm)
Stubble cover	159
Sand cover	153
No tillage + hand weed control	146
Plowing in March at 15 cm depth	139
No tillage + no weed control	132
Dry plowing at 50 cm depth	127
Soil dust (road dust) cover	95

1. Total precipitation during the experiment period was 726.2 mm.

Table 4. Soil moisture (%) at wheat sowing time at two soil depths (0-30 cm and 30-80 cm) as determined by different mulch types (applied in March) and weed control. (Average of period 1932-1934) (Kirac 1937).

	Cultivation with hoe		Hand weeding		Hand weeding + stubble cover	
Mulch type	0-30	30-80	0-30	30-80	0-30	30-80
Deep tillage (50 cm)	10.9	13.4	9.5	13.2		
Average tillage (15 cm)	10.9	13.5	9.7	12.9	12.9	13.9
Shallow tillage (8 cm)	10.1	12.9	9.6	12.3		
No tillage	6.8*	9.7*	8.9	12.4		

*= control.

higher moisture content in the 0-30 cm soil layer which was very important for NO_3-N accumulation and crop emergence in the fall. The depth of primary tillage was not important for accumulated soil moisture while surface stubble cover on tilled or nontilled soils increased moisture accumulation and shallow storage of water (Table 4).

Using various summer tillage implements in fallow in CA, Pala (1982) obtained no differences in moisture conservation and wheat yield. While no tillage provided 9.3% fallow efficiency the highest fallow efficiency, (24%) was obtained with tillage at 9 cm depth. Consequent increases were realized in wheat yields and amounts of conserved moisture.

The thickness of the soil mulch did not affect soil moisture. Although the soil moisture content of control (no summer tillage) was much less than the mulched systems, this difference did not affect wheat yield, despite fallow efficiencies between 8.6% and 22.8% in different years (Aktan 1984). The author concluded that the mulch formed was not effective enough to inhibit soil water evaporation and crack the soil under the mulch layer.

Various Techniques on Soil Water Status and Use

One category of techniques that influences soil water status and use relates to effects during the cropping period. These include fertilizer application and early sowing. Another category relates to physical techniques that affect soil water in every production system put in place. They include terracing, contour tillage and seeding, mulching, and miscellaneous techniques.

Water-use efficiency is defined here as crop yield per mm of water used. (ET = soil moisture in a profile of 1.2 m at sowing + precipitation in the crop year - soil moisture in the profile after harvest, hence WUE_{et}). Under nonfertilized conditions, it was 4.8 kg ha^{-1} mm^{-1} for durum wheat Kunduru 1149) and 6.0 kg ha^{-1} mm^{-1} for bread wheat (Gerek 79). N application (80 kg N ha^{-1}) increased WUE_{et} by an average of 22% in durum wheat and 29% in bread wheat (Isik et al. 1995). Ustiin and Ayla (1993) showed that under irrigation WUE_{et} of durum wheat can increase further when N is not limited (Table 5). Similar results were obtained by Kalayci et al. (1989) and Avci and Avcin (1993).

Table 5. Water-use efficiencies (WUE_{et}; kg ha^{-1} mm^{-1}) and wheat yield (kg ha^{-1}) influenced by N application (kg ha^{-1}) and irrigation; average of period 1985-1990 (Ustun and Ayla 1993).

	Rainfed crop		Irrigated crop	
N application rate	WUE_{et}	Yield	WUE,	Yield
0	6.4	2.2	5.3	3.2
50	6.7	2.4	4.5	3.4
100	*6.6*	2.5	6.7	4.8
150	7.6	2.7	6.8	5.0
200	6.7	2.6	7.0	5.4
250	*6.6*	2.5	7.0	5.3

Early sowing of wheat is another technique to raise yield, through a larger root system which leads to better use of spring and summer rainfall (Berkmen 1961; CRIFC 1988-1993). A deep-furrow drill (drilling seeds to depths of 12-15 cm) used in mid September resulted in 21% and 44% higher wheat grain yield than sowing by a drill with disc opener around mid October and mid November on fallowed land, respectively. The higher yields are caused by early establishment which allows development of the secondary root system before winter dormancy occurs, and advanced maturity by 1-2 weeks, thus reducing the stress of hot and dry weather. However, when the soil moisture was less than the critical level of 1.2 times the wilting point, it was considered that early sowing with a deep-furrow drill may cause some emergence and drought hazards. Eventually, it was concluded that the deep-furrow drill cannot be recommended to farmers yet, because it requires special skills (Anonymous 1977).

Terracing is an important technique of soil and water conservation on sloped lands, useful when vegetative and management techniques are inadequate (Dogan and Eriis 1997). However, 'Zingg' conservation bench terraces (a special terrace system for relatively flat lands) used to continuously cultivate wheat on a 3% sloped land were not economic because there was insufficient runoff, and sufficiently high yields were only obtained under high fertilization and weed control measures. Dogan (1978) observed on an 8%-l 1% sloped land that terrace channels stored more moisture than catchments of the terraces during all fallow and crop seasons. In general, the highest accumulation of moisture and the highest runoff from catchments to channels were obtained when the terraces had standard vertical intervals. To obtain optimum water accumulation in the catchments and channels, and higher wheat yield, he recommended vertical intervals (VI, in m) according to the equation:

$$VI = 0.305 * (C * S + CVS)$$

where,

C = Coefficient, depending on the region; 0.75 for Plateau

S = Gradient of slope of the field (%)

CVS = Coefficient as a function of cover and soil conditions, 3 for Plateau

Contour tillage and seeding in general contribute to soil and water conservation. Tested on a 12% sloped land in a dryland area of CA, Dogan and Kucukcakar (1986) determined that in only one out of the five years were significant runoff and soil losses recorded. In the same study, contour plowing accumulated 8.5- 23.6 mm more moisture in the 0-60 cm soil layer than slope up and down plowing, resulting in a 188 kg ha^{-1} higher yield. On a 10% sloped land, Kose and Sayin (1978) determined that April, May, and June were the months with the highest erosive potentials, and 19% of the average annual rainfall (365 mm) caused erosion. Compared with slope up and down plow contour plowing reduced runoff from 3.5% to 2.0% of erosive rainfall, and reduced, soil loss from 497 kg ha^{-1} to 252 kg ha^{-1}. Contour tillage on 9% sloped lands resulted in 57% less runoff and 80% less soil loss than slope up and down tillage (Ayday 1980).

Mulching systems also reduce runoff and soil loss. With soil and straw mulch, Karaca et al. 1988 and Guler et al. (1989) obtained some positive effects, but later results suggested that the soil mulch system was the most effective in terms of the characteristics investigated, and the straw mulch system the least appropriate (Table 6). Unver (1978) also showed that the soil mulch system was more effective on moisture conservation than the modified stubble mulch system. Increasing amounts of stubble mulch decreased wheat yield significantly, and were not effective for moisture or nitrate accumulation (Ilbeyi 1988). Burning stubble caused more runoff and soil loss in both contour and slope up and down tillage (Ayday 1980a).

Miscellaneous technologies that have been reported to have reduced soil erosion include inorganic fertilization (reduction 50-80%), sowing in fall (reduction 35-65%), use of winter crop (reduction 50-75%), and use of optimum length of slope (25-40 m) for effective soil and water conservation on 9% sloped and clayey or clay loam soils, with mouldboard plow in spring and rodweeder in summer.

Table 6. Impact of various soil and stubble mulch systems on soil moisture at sowing (120 cm profile), fallow efficiency, and weed density under dryland conditions in Central Anatolia; average of period 1976-1980 (Guler et al. 1989; Karaca et al. 1988).

Mulching and tillage system[1]	Soil moisture (mm)	Fallow efficiency (%)	Bromus density (culms m^{-2})
Stubble mulch + large sweep for all tillages	306	23	296
Modified stubble mulch + common sweep for all tillages	322	26	228
Modified soil mulch + mouldboard plow for first tillage + sweep + harrow for rest	329	27	44
Soil mulch + mouldboard plow for all tillages	336	31	18

1. All residue of wheat crop (1.5 - 3.5 t ha^{-1}) was left on the plots.

Continuous Cropping Systems

Water Conservation in Fallow Versus Cropped Land

Cagatay (1955) concluded that the water utilized by the crop for growth was not the water stored in the previous year, and that there wouldn't be any difference between fallow and cropped land in terms of soil moisture if 15-20 cm of soil was wetted by rainfall in the fall. The first attempt at continuous cropping systems in CA was made in the late 1970s. Ozbek et al. (1973) found that fallow in CA stored 18-22% of the average annual rainfall in the soil at sowing time (about 76-140 mm in a 1.8 m profile depending on the year and location). Most of it (80%) was in the zone of 30-90 cm. She observed no difference in moisture between cropped and fallow fields in March (except at some locations).

Yesilsoy (1984) showed that 80-100% of the soil moisture loss in a fallow field took place in the 0-90 cm zone of soil, and that spring and summer rains replenished the amount of soil moisture lost by evapotranspiration in spring. He therefore recommended replacing fallow-wheat with continuous cereal cropping in areas where the soil depth was less than 90 cm, and with shallow-rooted crops-wheat systems in areas where the soil depth exceeded 90 cm. However, intensification of rainfed agriculture by replacing fallow-cereal rotation with continuous cereal has several hazardous consequences in terms of buildup of noxious weeds, pests, and pathogens, besides accumulation of allelophatic compounds. The cereal cyst nematode *(Heterodera avena),* soil-inhabiting fungi such as *Cochliobolus sativus syn. Helminthosporium sativum,* the take-all disease pathogen (*Gaeumannomyces graminis* var *tritici),* and the wheat ground beetle (*Zabrus tenebroides)* can cause a considerable yield decline in the continuous cereal cropping systems of the WANA region (Harri's 1994). An evaluation of rotation research conducted under CA conditions for eight years showed that winter vetch (for hay), chickpea, spring lentil, and wheat can physically replace fallow when rainfall during the growing period is at least 360, 410, 420, and 770 mm, respectively (Avcin and Avci 1993). Or in other words, winter vetch in most semi-arid areas, and spring lentil and chickpea in the transitional zones which are more humid were able to replace fallow.

Moisture Utilization in Continuous Cropping System

Continuous cropping systems include summer crops (sunflower, safflower), spring crops (lentil, chickpea, and cumin), and winter crops (Hungarian vetch, winter lentil, and wheat) that are rotated with wheat in two-course rotations. Karaca et al. (1989) found that the total evapotranspiration of the wheat crops was affected by the residual soil water left by the preceding alternative crops, and WUE_{et} increased by about 5-15% when compared with the wheat-fallow system, except for safflower and wheat as alternative crops. (Karaca et al. 1989). Since Hungarian vetch (cut for hay) and winter-sown lentil were harvested earlier in the season, the soil moisture was high enough to start tillage for the next wheat crop, resulting in increased water-use efficiencies (Table 7).

Table 7. Economic yield and parameters of water balance and WUE_{et} in two-course rotation systems at the Haymana Experiment Station. TARM, Ankara, 1983-1988. (Karaca et al. 1989).

Rotation	ET[1] for 1st crop (mm)	WUE_{et} of 1st crop (kg ha^{-1} mm^{-1})	Soil water (mm)	Wheat yield (kg ha^{-1})	ET-wheat (mm)	WUE_{et} - wheat (kg ha^{-1} mm^{-1})
Sunflower- wheat	354 ab[2]	2.0 cd	203 d	2910 d	320 cd	9.5 ab
Winter lentil-wheat	310 cd	3.7 bcd	245 bc	3190 bc	358 b	9.8 a
Summer lentil-wheat	346 b	2.9 cd	210 d	3040 cd	329 c	10.0 a
Winter vetch-wheat	299 d	6.4 a	255 b	3300 ab	366 b	9.7 a
Safflower-wheat	369 a	2.7 cd	191 e	2500 e	309 d	8.3 b
Wheat-wheat	345 b	5.7 ab	209 d	1890 f	326 c	6.4 c
Cumin-wheat	322 c	1.7 d	235 c	3140 bc	355 b	9.3 ab
Chickpea-wheat	348 b	4.0 bc	209 d	3180 bc	326 c	10.2 a
Fallow-wheat	-	-	284 a	3410 a	399 a	8.9 ab
LSD(5%)	15	2.0	10	168	13	1.2
N	28	28	96	96	32	32

1. ET = Soil moisture in profile of 12 mat sowing + precipitation in crop year—soil moisture in profile after harvest.
2. a-d - significant difference at P = 0.01.

Meyveci and Munsuz (1989) obtained the following order with decreasing soil moisture for the wheat crop: (1) fallow, (2) winter legumes and cumin, (3) spring legumes and sunflower, and (4) wheat and safflower. In another experiment, the soil moisture values in the fallow phase of the rotations revealed that fallow efficiency (i.e., stored soil water as a percentage of the precipitation recorded during the fallow period) was 24% for the standard wheat-fallow system. In contrast, it was 3-13% for crop-wheat-fallow-wheat rotations, depending on the crop (Karaca et al. 1989).

Weed control during the preceding crop had an important positive impact on the yield of that crop as well as of the succeeding wheat crop. Weed control in the winter vetch crop grown for seed provided a 50-200% yield increase (average of 4 seasons, 1985 to 1988) in vetch. It also provided a 5-29% yield increase in the succeeding wheat. In case of vetch grown for hay, weed eradication increased the yield of succeeding wheat from 25-51% (Avci et al. 1996). Similar results were obtained in the wheat-spring lentil system. While weed control in the spring lentil increased the seed yield by 14-25%, the yield increase in the succeeding wheat was 10-20% (average of 5 years; Meyveci et al. 1993).

Supplemental Irrigation

Irrigation of wheat has been investigated for many years, with varying results for the different regions in CA (Table 8). In these studies, the average supplemental

Table 8. Number of supplemental irrigations for wheat varieties under different fertilizer application rates (kg N ha^{-1}), amount of supplemental irrigation water (mm), total water consumption (mm ET), and related average wheat yield in various studies.

No of S.I.[1]	Variety	N application	Time of application[2]	Amount	Total	Yield (t/ha)	Reference
2	Porsuk-76	65	1,2	179	460	5.6	Ertas 1980
2	Bezostia-1	140	1,2	237	584	4.7	Ogretir and Gungor 1989
2	093/44	60	-	262	460	-	Oylukan 1970
3		-	-	-	-		Koroglu 1957
3	Bezostia-1	60	1,2,4	300	-	4.4	Gungor and Ogretir 1980
3	Gerek-79	1 50	1,2,5	394	730	4.2	Uzunoglu 1992
3	Porsuk-2800	150	1,2,3	322	512	5.8	Aran and Kivanc 1989
3			1,2,4	259	398	6.0	Sevim 1988
3	Penjamo-62	120	2,3,5	435	728	5.1	Karaata 1987
4	Cakmak-79	200	1,2,3,5	435	777	3.2	Ustun and Ayla 1993
4	Yektay 406	150	1,2,3,5	393	690	3,3	Madanoglu 1977

1. S.I. = Supplemental irrigation.
2. 1 = Sowing; 2 - jointing; 3 = heading, 4 = anthesis; and 5 = milky ripe stage

irrigation accounted for 46%, 60%, and 57% of the total water consumption when there were 2, 3, and 4 irrigations, respectively. Oylukan (1973) recommended two irrigations, the first in fall and the second in spring, when there was not enough rainfall. Alptiirk (1970), however, recommended two irrigations in April and May. In the northern transitional zone of CA, one irrigation for wheat at heading stage was sufficient for an increase in yield of 800-1000 kg ha^{-1}. If the original time of supplementation was rainy, the irrigation should be delayed until the milky ripe stage (Gunbatili 1980). Wheat yield under supplemental irrigation increased by 25% (Oylukan 1972) and with fertilization 38% (i.e., compared to irrigation without fertilization). In future, instead of extensive field experimentation, crop simulation studies might be useful in determining the best method for a given year and region in the Central Anatolian Plateau.

Given that WUE_{et} under supplemental irrigation remains low (7.0 kg ha^{-1} mm^{-1} for Madanoglu 1977), there is scope for further improvements through breeding of wheat varieties for these conditions.

Farming System and Socioeconomic Factors Affecting Soil Water Use

Fallow-wheat has seemed an inefficient crop production system in most areas of CA and SA, and yield and economic returns from some legume-wheat or oil crop-wheat rotations have turned out to be 108% to 19% higher (Uzunlu and Ozcan 1987). Furthermore, economic conditions, in particular the high inflation rate, have forced farmers, especially small-holders, to turn to alternative crops instead of leaving their lands fallow. Thereby, they are able to save some money by refraining from tillage expenditures in a fallow year, and earn some cash from the alternative crop. Uzunlu (1992) indicated that the adoption level of the recommended wheat technology (e.g. timely tillage with proper implements at proper depth, timely sowing with drill at optimum density, improved varieties, optimum fertilization, and weed control) for the wheat-fallow system by CA farmers was about 59%. The underlying reasons for the nonadoption of new technologies were complexity of the technologies, lack of information, and cost of or nonavailability of inputs at the required time.

Farmers who have an insufficient amount of land (or 3-20 ha land, which cannot be irrigated) and equipment expect nothing from farming, because even though they have adopted some new technologies, improvements have not been realized. Eventually they migrate or want to migrate to large cities in developed regions or countries. However, they are reluctant to sell their assets, and thus the ownership regime of the land lingers almost unchanged for a prolonged time. Farmers who have 20 to 50 ha of dry land and a tractor and some implements are neither bound to the land nor can they abandon it. They can adopt new technology to some extent and hire land from the first group. Farmers who have 50 ha or more and considerable farming equipment are commercial farmers and are apt to adopt new techniques (Bayaner and Uzunlu 1993). As a consequence of these socioeconomic conditions, soil water use is strongly determined by the possible choices farmers can make and the availability of agronomic techniques related to water-use efficiency.

Yield Gap Analysis

In addition to the technologies designed to increase yield, some other management technologies exist. Firstly, wheat yield can increase by 21-44% when sowing is done with a deep-furrow drill in fallow areas (compared with the conventional disc drill). If the farmer can assess the soil moisture in the seed zone to be sufficient for sowing, this machine can provide a fairly good yield increase (Anonymous 1977).

Secondly, in winter legume-wheat rotations, weed control in the legume phase tremendously boosted yields of both crops. With weed control, yield increased 50-200% in seed vetch, and 5-29% in the following wheat (Avci et al. 1996). Similar results were obtained in the wheat-spring lentil system (Meyveci et al. 1993).

Although there has not been any research on direct drill or no-till, this technique seems to be cost efficient. Instead of three tillage operations in the fallow-wheat system, a one- (or may be two-) time chemical weed control will be sufficient in the no-till system. Results of research on the fallow-wheat system have indicated that the main and only cause of water loss from fallow was weeds (Kirac, 1937). This suggests that chemical fallow and direct drill will be a safe and good alternative to the conventional system in terms of water accumulation. In continuous cropping, the no-till system replaces two tillage and sowing operations. In the long run, the system will maintain the productivity of the field by leaving behind the crop residues and preventing soil erosion, especially in slope land. However, chemical use in fallow should be considered cautiously from the environmental point of view. Minimum tillage with sweep compared with conventional deep plowing can be an option in the continuous cropping systems of the lowland areas of WANA (Pala et al. 1998) and other parts of the world (Wilhelm et al. 1982; Allmaras and Dowdy 1985).

From the economic point of view, most of the continuous cropping systems were found to be better than the fallow-wheat system. The question then arises whether the remaining 4.5 million ha of fallow land should be allocated for continuous cropping. To answer this question, a detailed investigation should be conducted and the fallow boundaries determined for the whole country.

Discussion and Issues for Future Research

According to available research, only 8-20% of the average annual rainfall of 350 mm in CA is conserved in the soil for the wheat crop during the 14-month fallow period. In other words, 92- 80% of the annual rainfall is wasted in order to accumulate 30-100 mm of water in the soil, although in dry years this amount of conserved moisture plays an important role in the grain yield of wheat. In general, if the soil physical conditions related to water-holding capacity and intake of water are inappropriate and the amount of rainfall is below 410 mm, fallow is not a necessary practice and should be abandoned (Guler et al. 1984; Yesilsoy 1984). This paper has disclosed that soil moisture differentiation between continuous wheat and fallow-wheat systems has not been investigated in detail spatially and temporally. Research on this issue has dealt with the differences between the crop phase and the fallow phase of the fallow-wheat rotation as in the study by Ozbek et al. (1973). On the contrary, Cagatay's (1955) work was detailed, but comprised a relatively short period of an academic study of two seasons. Karaca et al. (1989) and Avcin and Avci (1993) compared continuous cropping including continuous wheat with the traditional fallow-wheat system with respect to soil moisture, but frequent soil moisture monitoring could not be performed. Therefore, the continuous-wheat and fallow-wheat systems should be compared in terms of soil moisture, and the areas where fallow practice is absolutely necessary should be determined by using relevant techniques including simulation models.

In continuous cropping, efficient water use was obtained in winter crops such as vetch and lentils, but the intensive weed density reduced WUE_{et} of these crops and the succeeding wheat as well. Future research on the control of weeds in these cropping sequences will help in increasing both WUE_{et} and crop production.

Further research is needed on the deep-furrow drill which enables early sowing of wheat and emergence in the fallow system, including the transfer to farmers' practices. By providing early crop establishment, practising clean fallow will attain its objective of accumulating sufficient moisture in the sowing zone for crop emergence by means of a created soil mulch. Hence, the aim of summer cultivation in the fallow phase of the traditional wheat-fallow system is to kill the weeds, which are the main cause of the soil water loss and also to bring the stored soil water up nearer the surface (0-30 cm). On an average, a 21-44% yield increase was obtained by the deep-furrow drill as compared to conventional disced drill. Researchers who have published the results of using this type of drill stressed the special skill required by farmers to use it (Anonymous 1977). We believe that farmers today have reached a substantial level of experience in machinery use and improvement in their farming practices.

Apparently, no research has been carried out on direct sowing and no-till, despite the fact that this technique has been practised since 1960 and has been gaining importance (Phillips and Phillips 1984; Allmaras and Dowdy 1985). Wheat-production areas in Turkey have expanded to the maximum extent. As a consequence, more sloped areas have been brought into cultivation. In those areas where soil erosion is severe, if it is not possible to allocate these lands for grazing, annual no-till cereal production seems feasible when applying wheat stubble residues that contribute to soil and water conservation. Terracing in CA works only on moderate slopes with erosive rainfall, while on steep slopes it conserves moisture: to a certain extent. Contour plowing conserved 50% more soil moisture and soil than up-and-down-slope plowing. In this context, farmer education, and legislation for optimizing farmers' field plot shapes, orientations, and sizes are key factors to put contour plowing into practice. Consequently, research related to soil and water conservation such as stubble management and direct sowing and zero tillage should be tested with emphasis on the economic analysis.

More than a sufficient amount of the work on supplemental irrigation has been carried out in both dryland areas and other regions of Turkey. Times of application and amount of irrigation water were determined at some research centres and extrapolated to other relevant regions by using calculated crop coefficients (Kc) (Anonymous 1982). However, the representativity of these stations for other areas has not been established. Suitable methods are required for the estimation of crop coefficients. This review has also revealed that there is an urgent need to identify suitable cereal varieties, wheat in particular, which can be cultivated under supplemental irrigation, and to determine their agronomic requirements (e.g. plant density, nitrogen requirements, etc.).

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Optimizing Soil Water Use in Zimbabwe

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Abstract

Zimbabwe has been divided into five Natural Regions (NRs) based on rainfall amount and variability. The dry-area production systems or semi-arid environments of Zimbabwe fall in NRs HI, IV, and V. These three NRs constitute about 83% of the country. Rainfall onset and length of growing period are unpredictable and highly variable, making crop production in the semi-arid areas risky and unstable. However, crop production by small-scale farmers in these areas continues to depend on the limited rainfall and its success depends on using management techniques that conserve and increase the total soil water available to crops. This paper is a review of past and current research on soil water-use efficiency and ways to improve it in low-rainfall dryland production systems. Gaps in the research on optimizing soil water use are identified (e.g. crop water use and crop water-use efficiency) and suggestions for further research presented.

Resume

Le Zimbabwe a ete classe en cinq regions naturelles (RN) sur la base de la quantite et de la variabilite de la pluviometrie. Les systemes de production en zone seche ou les milieux semi-arides du Zimbabwe se situent dans les zones classees comme etant RN HI, IV et V Les trois RN representent environ 83% de la superficie du pays. Le demarrage et la duree de la saison de culture sont imprevisibles et fortement variables, rendant ainsi la production aleatoire et instable dans les zones semi-arides. Toutefois, la production agricole des petits exploitants de ces zones continue de dependre d'une pluviometrie limitee, et son succes depend de l'utilisation de techniques de gestion qui conservent et accroissent la quantite totale d'eau disponible aux cultures. Le present document procede a une revue de Vetat

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de la recherche, passee et actuelle, sur l'efficience de l'utilisation de l'eau du sol et sur les moyens de l'ameliorer dans les systemes de production des zones arides a faible pluviometrie. Les points faibles de la recherche en matiere d'optimalisation de l'utilisation de l'eau du sol sont identifies (l'utilisation de l'eau des cultures et efficience de l'utilisation de l'eau des cultures) et des suggestions sont faites en vue d'autres recherches.

Introduction

Zimbabwe in southern Africa extends from latitude 15°30 S to 22°30 S and between latitudes 25°E and 33°E. The country has a total area of 39,075,700 ha. It has a diverse range of environmental conditions, which favor or limit particular types of farming, from the very intensive forms of production to the most extensive (Staples 1965). These widely varying conditions are caused by large variability in climate and soil types. As a consequence, especially rainfed agricultural production is very variable.

The agricultural industry comprises large-scale and small-scale (communal) sectors. About 70% of the population lives in the communal areas, where the average population density is 30 persons km^{-2}. In addition, most (74%) of the communal farmland is located in the semi-arid regions (Shumba 1994). This means that a large number of people are at risk in dry years. In order to relieve the population pressure in the communal areas, the government embarked on a resettlement program in the mid 1980s, which entailed conversion of some of the large-scale commercial farmland into communal farmland (known as resettlement areas).

Since water is a major limiting factor in Zimbabwe, research carried out in the domain of optimizing soil water use is being reviewed in this paper. In addition, new research priorities are identified.

Characterization at the National Level

On the basis of the rainfall amount and variability (Fig. 1), the country has been divided into five agroecological zones or Natural Regions (NRs) as defined by Vincent and Thomas (1960). The dry-area production systems or semi-arid environments fall in NRs III, IV, and V (Norton 1995). The three NRs constitute about 83% of the country, but only about 7% of that area can be cultivated (Table 1).

Table 1. Agricultural area and rainfall in NRs III, IV, and V of Zimbabwe (Anderson et al. 1993; Norton 1995).

Parameter	NR III	NR IV	NR V
Percentage of Zimbabwe's area	18.5	38.0	26.8
Total area ('000 ha)	718	1476	1041
Area of NR under Communal/Resettlement program (%)	55.2	56.1	46.9
Cultivable land (%)	7.2	7.3	6.5
Average rainfall (mm)	650-800	450-650	0-450

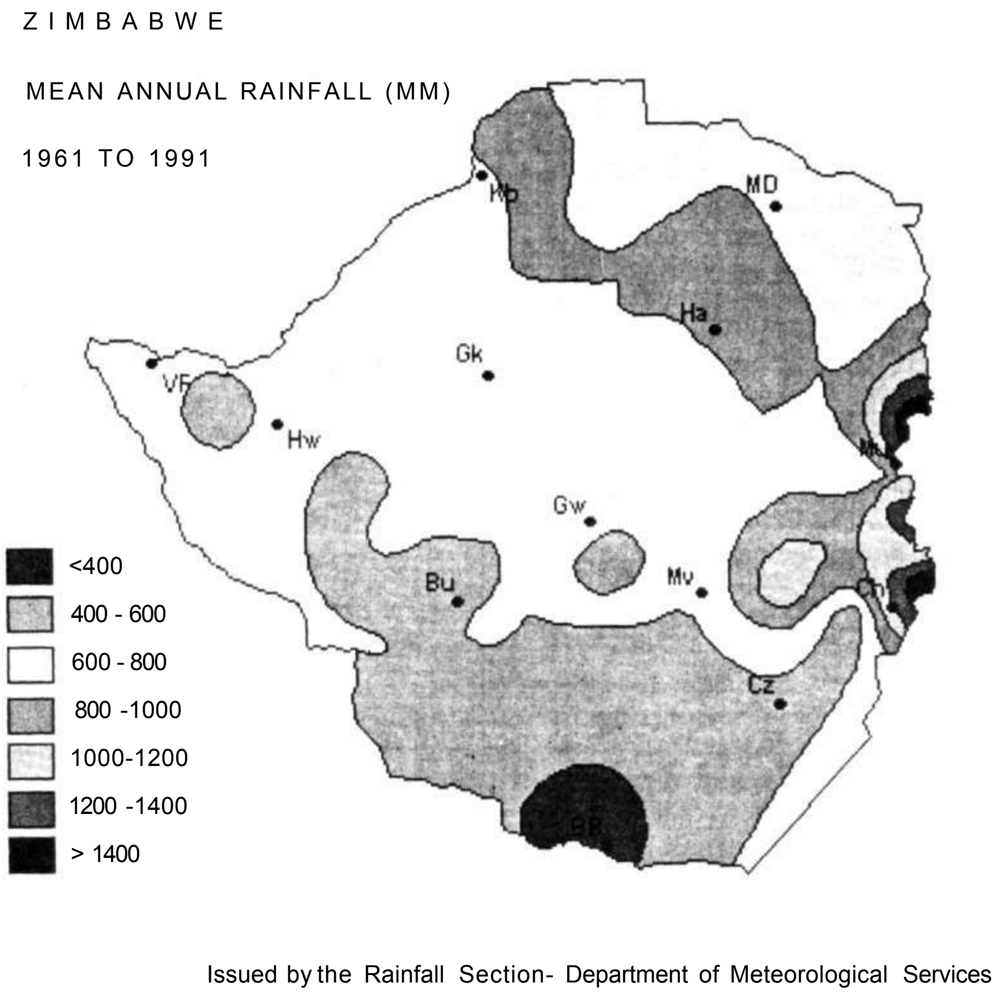

Figure 1. Mean annual rainfall (mm) during 1961-1991 in Zimbabwe (DMS 1992). BB = Beit Bridge; Bu = Bulawayo; Ch = Chipinge; Cz - Chiredzi; Gk = Gokwe* GW = *Gweru; Ha = Harare; Hw = Hwange; Kb = Kariba; MD* = Mr. *Darwin; MU = Mutare; Mv = Mvurwi; and VF =Victoria Falls.

Climate

Rainfall in Zimbabwe is seasonal, and occurs mainly in the period from mid November to mid March (DMS 1981). The annual amounts are markedly variable, particularly over the drier regions of the country (Table 1) and coefficients of variation exceeding 40% have been recorded (DMS 1981). In addition, periodic mid-seasdn drought spells occur, often in late January which can drastically decrease agricultural production (Lineham 1972). Therefore, rainfall is the main climatic constraint to dryland agricultural production in the three NRs.

The dry areas experience high temperatures, evaporation rates, and moisture deficits as illustrated for the main research stations in the three NRs in Figure 2.

Rainfall onset and length of growing period (LGP) are unpredictable and highly variable, making crop production in the semi-arid areas risky and unstable. For example, Hussein (1987) reported LGP mean median values of only 131 days for NR III, 121 days for NR IV, and 96 days for NR V Advising farmers on suitable sowing dates, crop varieties, plant populations, and time of maximum wetness is therefore difficult due to the uncertainties associated with the growing-season parameters. However, crop production by small-scale farmers in these areas continues to depend on the limited rainfall, and its success depends on using management techniques that conserve and increase the total soil water available to crops, as irrigation costs are prohibitive (Nyamudeza and Nyakatawa 1995).

Soils

Different types of soils occur in the semi-arid areas depending on the distribution of parent materials. They range from Vertisols to sands (Table 2). The soils are mostly shallow due to the prevalence of poor weathering and leaching conditions. Large areas of all three NRs consist of coarse-grained sands derived from granite, which have a low fertility and hence a low production potential in any environment, let alone in areas of marginal rainfall.

The semi-arid soils experience hyperthermic temperature and aridic moisture regimes as computed by Van Wambeke (1982; quoted by Anderson et al. 1993). Under these conditions, the total monthly rainfall of less than 50 mm is likely to evaporate and contribute nothing to soil moisture recharge. Very few of the soils in these NRs have, therefore, a moisture reserve sufficient to meet crop requirements during the growing season.

Crops

Despite the inadequacy of the rainfall, maize continues to be a favored crop in a common rotation of maize, groundnut, and millet (Mataruka 1985; Shumba 1984a). This situation is brought about by the necessity for people living in the communal farming areas to attempt to grow crops regardless of the poor quality of the land.

Sorghum and millet assume greater importance in NRs IV and V due to their drought tolerance. Details of crops grown in the semi-arid communal areas are given

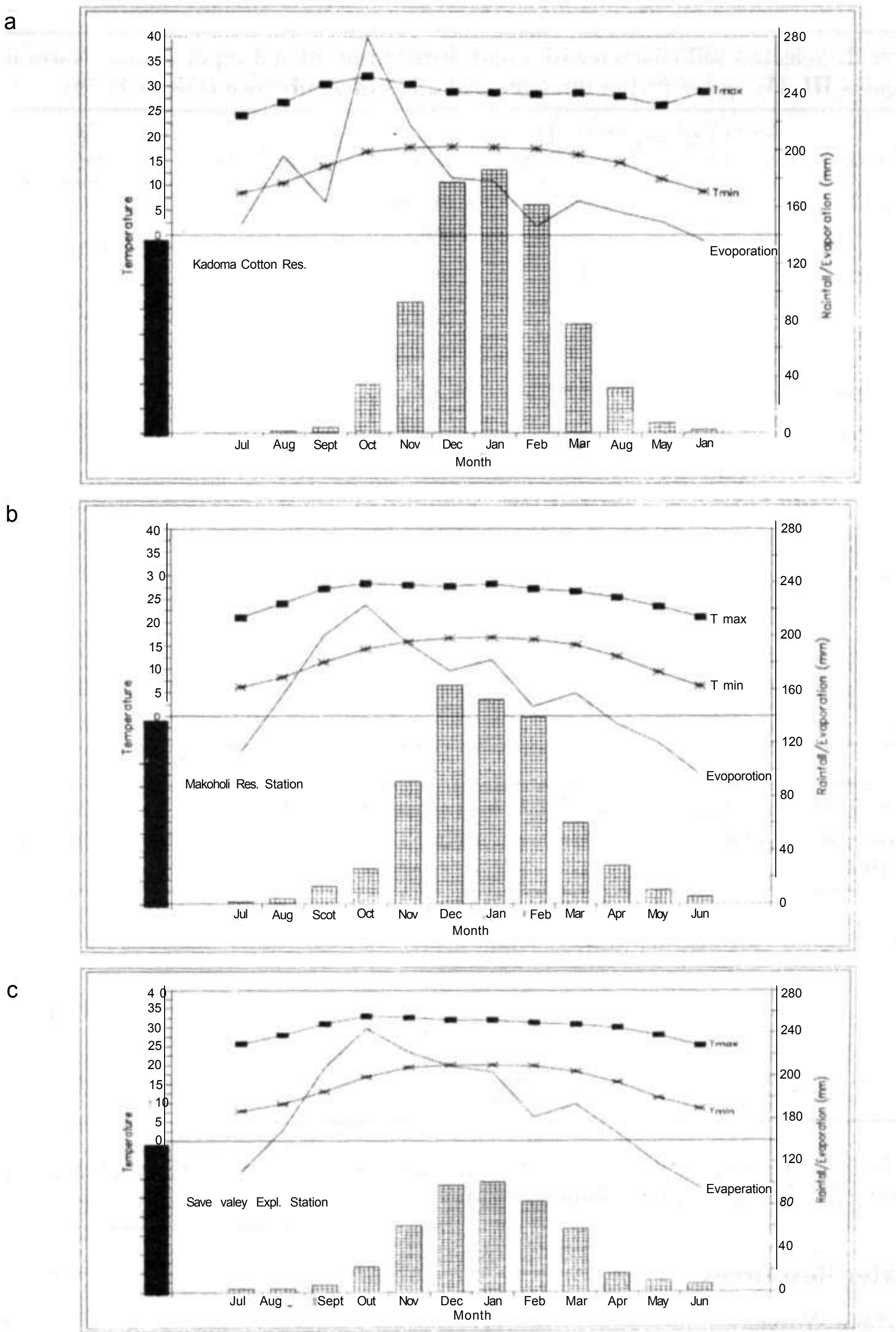

Figure 2. Average climatic data for research stations in the semi-arid areas in Zimbabwe: a) Kadoma Cotton Research Station in NR III; b) Makoholi Research Station in NR IV; and c) Save Valley Experimental Station in NR V (DMS 1981).

Table 2. Selected soil characteristics and distribution of soil types among Natural Regions III, IV, and V (%) in the semi-arid areas of Zimbabwe (DRSS 1979).

Soil type	Mean PWP[1] (mm 100 cm^{-1})	Mean FC[2] (mm 100 cm^{-1})	Texture[3]	Permeability	NR III	NR IV	NR V
Regosols	105	295	Kalahari sand	Very rapid	8	27	2
Vertisols	270	420	Clays	Very slow	2	1	9
Siallitic	140	250	Sandy loam to clay	Moderate	7	19	30
Fersiallitic	90	180	Mostly sand	Moderate	60	39	22
Paraferrallitic	110	190	Sandy to sandy clay	Moderately rapid	3	0.4	-
Orthoferrallitic	120	270	Loamy sand to clay	Rapid	2	0.2	-
Lithosols	na[4]	na	Variable	Variable	16	13	34
Sodic	na	na	Clays	Very slow	2	-	3

1. PWP = moisture content at 15 bars.
2. FC = moisture content at 0.1 bars.
3. The textural class was determined according to the Zimbabwean System of Soil Classification.
4. na = not available.

Table 3. Distribution of cropped land (% of total) in three Natural Regions (NRs) of Zimbabwe (average of three growing seasons, 1985/86 to 1988/89)[1]; (Anderson et al. 1993).

NR	Maize	Pearl millet	Sor-ghum	Finger millet	Cotton	Ground-nut	Sun-flower	Vege-tables	Beans	Fruit	Other
III	55	8	4	3	12	4	4	<1	<1	<1	9
IV	41	20	9	3	5	6	4	<1	<1	<1	11
V	26	20	37	2	3	3	3	<1	<1	<1	6

1. Figures are results of the statistical survey of cropping in the communal lands undertaken annually since 1985/86 by the Early Warning Unit for food security, Agritex, Harare.

in Table 3. The average yields are 1000 kg ha^{-1} for maize, 520 kg ha^{-1} for Sorghum, and 450 kg ha^{-1} for pearl millet (Shumba 1984a).

Water Resources

Surface Water

The potential of surface water is low because a small fraction (< 10%) of the low and unreliable rainfall appears as flow in the river systems and the rest is lost to evapotranspiration or to replenishment of groundwater (MWRD 1984). In addition, the variation in annual runoff is even larger with annual means of 4-300 mm and coefficients of variation of between 45% and 165% (MWRD 1984). These adverse features call for provision of storage reservoirs in order to meet water requirements throughout the year and over several years.

Groundwater

The greater part of the semi-arid areas is composed of ancient igneous (granite/gneiss complex) rock formations, where groundwater potential is comparatively low. Groundwater exploitation for domestic needs (including livestock watering and gardening) is through boreholes, which penetrate localized basins of rock decomposition. Better conditions prevail where granite-gneiss complex rocks are associated with the African erosion surface (Lister 1987). *Dambos* or *vleis* are also associated with this erosion surface and they often yield groundwater at shallow depths throughout the year (Anderson et al. 1993). They are important for primary water supply, winter grazing, and microscale irrigation.

Perennial water reservoirs are also associated with riverbed sand and alluvial deposits where they are primary sources for shallow wells sufficient for irrigation water supply.

Zimbabwe has been divided into six hydrological zones (denoted from A to F) depending on the river system. The semi-arid areas fall into zones A, B, E, and a part of C. The surface water potential of these zones is shown in Table 4.

According to MWRD (1984), groundwater is much cheaper to obtain as it is proximal to the point of use; it is also purer and evaporation losses are minimal. This is true for small-to-moderate supply systems. Shallow wells in particular have a low capital cost and low technology requirement, but are usually unreliable in the semi-arid areas due to fluctuations of the groundwater level in years of poor rainfall. The main water resources are boreholes and dams (Table 5), as hand-dug wells do not occur in any of the three NRs.

Water Management Techniques in Semi-Arid Areas

Two main water management techniques exist in the semi-arid regions of Zimbabwe: small-holder irrigation and use of *vleis* and *dambos.* Small-holder irrigation covers 5%

Table 4. Surface water resources (billion m^3) in four hydrological zones of Zimbabwe (MWRD 1984).

Zone	Mean annual runoff	Water use (%)	Water loss (%)
A	1756	10	90
B	1157	40	60
C	5638	22	78
E	5954	36	64

Table 5. Summary of primary water supplies in various districts in NRs IV and V (MEWRD 1985).

		Boreholes			
District	Communal land	Number	No. km^{-1}	Persons $hole^{-1}$	Population density (persons km^{-2})
Masvingo (NR IV)	Mshagashe SSCFA[1]	11	0.04	0[2]	0
	Mshawasha SSCFA	12	0.02	0[2]	0
	Mtilikwe	17	0.06	995	57.0
	Nyajena	47	0.08	982	74.0
	Nyanda	72	0.14	545	78.0
	Zimuto	31	0.11	437	47.0
	Zinyanigwe SSCFA	19	0.11	0[2]	0
	Total/Mean for district	209	0.08	622	49.0
Chiredzi (NR V)	Gonakudzi	39	0.13	0[2]	0
	Matibi 2	198	0.09	182	16.0
	Sangwe	63	0.10	303	30.0
	Sengwe	128	0.05	121	6.0
	Total/Mean for district	428	0.08	166	13.0

1 SSCFA = Small-scale commrcial farming area 2 Boreholes sunk tor game and livestock

of the total irrigated land in the communal areas of NRs III and IV (Manzungu and van Der Zaag 1996). For an average irrigator, the plot size varies from 0.5 ha to 2.0 ha (M. Rukuni, personal communication). Small-holder irrigation is considered capable of alleviating rural poverty in the country and it offers a chance to modernize peasant agriculture (Jayne and Rukuni 1994). This sector is mostly constrained by inadequate water supply, as most rivers flow only for six to eight months in a year and those that are perennial have low water flows at the time of peak irrigation water demand. In addition, the prospects for groundwater supply in the communal areas are poor, as the aquifers are either low-yielding or uneconomical as irrigation water sources.

Irrigated crop production involves the use of expensive machinery and other inputs. But as farmers rely on a single cash crop for their income, which according to Makadho (1994) implies great risk, they avoid taking up new technology. This risk avoidance by farmers has limited the expansion of this sector, although irrigated crop production in itself is less risky than dryland farming in semi-arid environments. In the southeastern part of the country (NR V), the Lowveld Research Station (LVRS) has carried out research on methods of low-cost, high-efficiency irrigation appropriate for use in semi-arid Africa (Murata and Vemedevan 1989). In 1989, a Collaborative project between the British Geological Survey (BGS), the Institute of hydrology (IH), and the, LVRS was initiated (Lovell et al. 1998). The project aimed specifically at developing groundwater resources for small-scale irrigation. The main objectives of the project are to assess the potential of collector wells for exploiting shallow aquifers and to carry out experiments and field trials on the design and management of different methods of low-cost, high-efficiency irrigation. The concept of low-cost, high-efficiency irrigation projects has been successful in developing community gardens using groundwater in the semi-arid areas. Although NR V is the driest region, irrigation development is confined to the large-scale commercial sector, which produces sugarcane, citrus fruits, and cotton. Small-holder farmers therefore cannot venture into irrigation, due to the high capital requirements and limited water resources.

Vleis or *dambos* are ecosystems that develop from a natural phenomenon whereby rainwater infiltrates into the soils high up in the catchment areas, percolates downwards and supplements groundwater reserve and then seeps towards low-lying areas over the surface of impermeable horizons (Mharapara et al. 1995). They are mostly found in NRs III and IV Soils in the *vleis* are fertile (with a high organic matter content and a high water-holding capacity) due to the anaerobic conditions. *Vleis* could therefore be an insurance against drought in moisture-stressed environments. Crop performances in *vleis* are quite encouraging. From studies carried out during the period 1983-1994, the average grain yield was 6219 kg ha^{-1} for maize and 2129 kg ha^{-1} for rice (Mharapara et al. 1995). Despite these high yields, *vlei* utilization has been legally confined to livestock grazing and isolated grazing in dry areas.

Socioeconomic Characteristics

The economic base of the communal areas in the Zimbabwean drylands is weak, and farmers have a limited access to resources. The arable landholdings in these areas are around 3 ha per family, and the farming methods employed are exploitative in nature (Mazhangara 1996). The crops produced are primarily for home consumption, and only a small surplus is marketed. In the Mutoko Communal Area (NR IV) in 1985, about 60% of the maize harvest was consumed and 40% was sold, and 90% of the millet and groundnut crops were used for home consumption or beer brewing while the remainder was marketed (Otzen et al. 1994). Inputs like fertilizer, pesticides, and implements are obtained at the local market through private businessmen but only a few farmers have the means to buy these inputs. Some farmers receive small quantities of inputs as gifts from their relatives.

Small-holder farmers in these areas realize low annual cash incomes, of which 50% come from off-farm sources (Shumba 1994). A survey by Govaerts (quoted by Otzen et al. 1994) showed that the average annual cash income for farmers in Mutoko in the 1984/85 season was US$ 442. Such low incomes limit the extent to which farmers can invest in agricultural production, e.g., the Chivi communal farmers (NR IV) were reported by Shumba (1994) to invest only 14% of their annual income of US$ 17.3 in agricultural inputs.

Review of Soil Water Studies

Soil Moisture Conservation

Research related to rainwater capture and infiltration in Zimbabwe started in 1957 when soil-tillage research was initiated (IAE 1988). The ongoing Conservation Tillage (Contil) for Sustainable Crop Production Systems Project was started in 1988 (Norton 1995). This is a collaborative project between the German aid agency Gesellschaft fur Technische Zusammenarbeit (GTZ) and the Institute of Agricultural Engineering (IAE), Agritex. Under this program, research is being carried out both in the subhumid north and in the semi-arid south. In a study it was found that cumulative infiltration in a mulch-ripping treatment was 40 cm after an hour, whilst under conventional till it was 30 cm (Nyagumbo 1998). Four years of data from tillage trials carried out at Makoholi (in NR IV) showed that mulch ripping is the best tillage system, especially in the drier seasons (Vogel 1992). However, because of the need to use mulch for grazing, tied ridging is used more than the mulch-ripping technique in conserving moisture and soil (Table 6). There were low soil and water loss/runoff values for tied ridging and mulch ripping than for conventional tillage.

The Contil project has been testing and developing conservation tillage systems in the semi-arid areas of Masvingo (NR IV) since 1988 (Chuma and Hagmann 1995). On-station research and adaptive on-farm research programs have been used. The project has investigated five tillage systems: (1) conventional inversion using a single-furrow ox-drawn mouldboard plow, (2) no-till tied ridging, (3) clean ripping into bare ground, (4) mulch ripping into stover mulch on the surface, and (5) hand hoeing into bare ground before the onset of the rains. Of these, only mulch ripping can be considered ecologically sustainable, due to its ability to maintain a high organic matter level of 2.6% in the topsoil (Chuma and Hagmann 1995). No-till tied ridging was rated second due to its soil and water conservation effect. It was noted that research work on quantification of crop water usage and crop water-use efficiency under various tillage systems was minimal and emphasis was placed mainly on crop yields, runoff, and soil loss.

Table 6. Summary of maize yield (t ha^{-1}), runoff (% of rainfall), and soil loss (t ha^{-1}) at Makoholi (Hagmann 1993).

Tillage system	Mean yield	Mean runoff	Mean soil loss
Conventional	3.67	6.73	2.1
Clean ripping	3.38	4.95	1.08
Tied ridging	2.89	0.91	0.08
Mulch ripping	3.59	2.15	0.6
Hand hoeing	2.41	7.73	1.17
Bare fallow	-	22.4	22.3

1. Seasonal rainfall totals were 415 mm In 1988/89; 742 mm in 1989/90; 343 mm in 1990/91; and 173 mm in 1991/92.

Results from eight years of work by the Cotton Research Institute showed that the tied-ridging system was the best technique for conserving moisture (Mashavira et al. 1995). Results also showed that tied ridges gave the highest seed cotton yield in the period 1991-94, although mid-season ridges gave the same yield as nontied ridges. This result is different from the scenario in Table 6, because cotton is more deep-rooted than maize and is therefore capable of abstracting deep-percolated water harvested by the tied-ridging system.

A collaborative project by the Department of Research and Specialist Services (DRSS) and the Silsoe Research Institute was started in 1989 (Norton 1995). Results so far indicate that cotton yields have improved due to tillage practices that conserve moisture (Mashavira et al. 1995; Norton 1995).

Adoption of conservation tillage by farmers has, however, been low, less than 1% of communal-area farmers and 5-10% of commercial farmers (Contil 1990). The reasons for this include shortage of labor, scarcity of draught animal power and of suitable equipment, and general noncompatibility with the wide range of technical and socioeconomic problems faced by communal-area farmers. The latter problems include high labor requirement for construction and maintenance, difficulties in sowing and weeding, poor crop establishment, and increased weed problems (Shumba 1984).

The tied-ridge technique has been developed by the LVRS to concentrate moisture and conserve soil in NR V This technology can enhance productivity, food security, and viability in dry-area production systems. Crop yields from this technique under researcher-managed on-farm trials increased (1982/83 and 1989/90 seasons) by an average of 25% for sorghum, 32% for cotton, and 46% for maize (Mazhangara 1996). The additional water in the soil due to the tied-ridge technique was the main reason for the increased crop yields (Table 7; Nyamudeza and Jones 1993; Nyamudeza and Nyakatawa 1995).

Table 7. Total soil water (mm) up to a depth of 0.75 m under tied ridges and on flat land from 8 days to 121 days after sowing (DAS) during the 1985/86 season (Nyamudeza and Nyakatawa 1995).

	DAS 8	22	36	50	53	64	79	93	107	121
Rainfall (mm)	89	0	34	33	45	80	85	8	27	0
Cumulative rainfall (mm)	89	89	123	156	201	281	366	374	401	401
Tied ridges	175	148	152	141	185	175	163	130	120	120
Flat	175	147	145	135	162	141	123	115	117	111
Difference	0	+ 1	+ 7	+6	+23	+ 34	+ 40	+ 15	+23	+9
SE difference	±6.6	±6.6	±7.2	±4.7	±6.9	±6.4	±6.0	±4.9	±5.8	±4.9
Significance	NS[1]	NS	NS	NS	**	**	**	**	**	NS
CV (%)	14	15	18	12	15	15	15	15	17	16

1. NS = not significant. ** p<0.001.

The tied-ridge technique also reduced the level of production risk (Mazhangara 1996; Nyamudeza and Nyakatawa 1995). The risk of farming in NR V is generally the highest due to inadequate and variable rainfall. The tied-ridge technique addresses this problem directly and food insecurity is reduced. The positive effect of the tied-ridge technique with regard to food security can be appreciated from the fact that grain yields were obtained from land mostly under this technique in the drought year of 1992/93. However, in the years with high and well-distributed rainfall, the benefits of the tied-ridge technique are reduced due to waterlogging (Nyamudeza and Nyakatawa 1995).

The technique is acceptable to farmers as an option to increase agricultural productivity in the semi-arid areas. Socioeconomic studies carried out in the Ndowoyo communal area (NR V), indicated that nearly 80% of the farmers viewed the tied-furrow technique favourably and they also viewed it as a good soil and moisture conservation technique (Mazhangara 1996).

Crop Research Related to Optimizing Soil Water Use

Agronomic research work by DRSS in the drier parts of the country has covered a wide range of topics over the years. However, few efforts have been directed toward water balance studies, while crop nutrition studies have had considerable attention. Sowing dates, rotations, intercropping, and soil surface management have been studied in terms of their influence on the water and nutrient balances. Work reviewed by Metelerkamp (1987) has clearly demonstrated the advantages of early maize sowing in NRs III, IV, and V, where the length and quality of the rainfall season are by far the most important constraints to economic dryland crop production (Table 8). Information on water use and water-use efficiency is not available to be related to crop yield, but recent work by Hikwa and Kangai (1992) at Matopos (NR V) has shown again the importance of early sowing on the grain yield of sunflower.

Maize water-use studies have been initiated in both semi-arid and subhumid areas of Zimbabwe. The effects of nitrogen fertilizer on yield and water-use efficiency of maize were investigated at two sites during the 1992-93 season. Results obtained at Makoholi (NR IV) showed that water-use efficiency improved from 1.6 kg ha^{-1} mm^{-1}

Table 8. Effect of time of sowing on maize and cofton yields (t ha^{-1}) (Metelerkamp 1987).

Crop	Date of sowing	Yield
Maize	15 November	3.9
	1 December	3.6
	15 December	1.9
Cotton	25 October	2.9
	8 November	2.4
	22 November	2.3
	6 December	1.8

to 4.9 kg ha^{-1} mm^{-1} while at Marondera HRC (NR II) it improved from 2.4 kg ha^{-1} mm^{-1} to 5.4 kg ha^{-1} mm^{-1} (Shamudzarira 1994).

While intercropping is widely practised in the drier areas, little or no research has been undertaken on the subject. Studies on maize/cowpea intercropping in the semi-arid areas indicated that sole maize outyielded intercropped maize by 120-700% in 1988/89 and by 25-77% in 1989/90. The yield reduction was associated with increased competition for moisture (Shumba et al. 1990). On the other hand, research on crop rotation has concentrated mainly on enhancing soil fertility rather than optimizing soil water use (Arnold 1922; Karigwindi et al. 1995).

Local breeding efforts over the years have concentrated on drought-tolerant maize with emphasis on early-maturing and high-yielding three-way hybrids (Shumba 1994). Breeding of hybrid maize started at the Harare Research Station in 1932 (Mashingaidze 1994). In the early 1970s, the short-season, three-way hybrids R 200 and R 201 were released. These hybrids, particularly R 201, proved successful and are still widely grown in the marginal rainfall areas of the country (Shumba 1984a).

Recently, early-maturing and high-yielding varieties of pearl millet and sorgum have also been developed in the country (Mushonga et al. 1991). However, adoption has been poor due largely to the shortage and limited distribution of the sorghum varieties (SV 1 and SV 2) and pearl millet varieties (PMV 1 and PMV 2) which are available for the marginal-rainfall areas (Mushonga et al. 1991).

A series of hybrid trials are sown in different ecological zones in order to screen for drought tolerance, yield potential, and disease resistance. Cooperation with the International Crops Research Institute for Semi-Arid Tropics (ICRISAT) in Bulawayo is necessary particularly in the areas of testing national and regional nurseries together.

Suggested Research to Optimize Soil Water Use in Communal Farming Areas

If soil water use is to be further optimized, research work should be intensified in the following three areas.

Soil Water Conservation Research

Although the benefits of conservation tillage in semi-arid areas have been demonstrated, future emphasis should be placed on (1) development of all types of machinery (tractor-drawn, ox-drawn, and hand-operated) to facilitate conservation tillage, (2) permanent water conservation systems; and (3) methods of handling conservation tillage in wet seasons to minimize yield decreases.

Crop Improvement and Management

A reestablishment of crop research is required in the communal areas of Zimbabwe. Such research has so far not been adequately carried out. In order to optimize soil water use, crop research should focus on crop improvement and crop management.

Crop improvement could focus on screening germplasm for drought tolerance and nitrogen-use efficiency at sites with low rainfall and low fertility. Linkages with organizations like ICRISAT and CIMMYT will be useful as they carry out research on crop improvement, soil fertility, and risk management. Work is particularly needed to improye the important millets, and to develop more drought-tolerant maize varieties. Variety testing and improvement by itself is not enough, but must be linked with climatological factors on a far more detailed basis than is the case now. In selecting crop species and cultivars for dry areas, decisions have to be made whether to emphasize yield stability so that the farmers are guaranteed some acceptable but probably modest yield in all but the very worst years, or maximum yields in good years. There is also a need to compare crop varieties with different morphological and phenological characteristics with respect to water-use efficiency. If this research work is done with simulation models, time and funds could be saved.

Improvement of the existing cropping systems is required to increase production and stability, especially in relation to variations in rainfall. Management-related crop research could focus on the following aspects in relation to soil water dynamics: crop rotation, residue management, intercropping (shallow and deep-rooted crops), weed control, crop density, effects of fertilizer/manure and other amendments on crop water use.

Socioeconomic Research

In most instances, research work should involve farmers so that their knowledge, perceptions of water inadequacy problems, and their production objectives and priorities could be incorporated. The involvement of technical and socioeconomic scientists and extension specialists in farmer-participatory research activities is also called for.

Concluding Remarks

It is well-documented that the majority of the communal farmers in NRs III, IV, and V contribute very little towards the national food reserves, and that these farmers experience food shortages, particularly during the drought years. It is the low level and unpredictable nature of rainfall that affects Zimbabwean farmers' ability to produce enough food for subsistence and for cash (Huchu and Sithole 1994). There is therefore a big challenge facing scientists to develop relevant improved water management strategies and technologies in such dry environments in order to alleviate rural poverty in particular and boost the Strategic Grain Reserves (SGR) in general. By engaging in applied and generic research and adaptive and participatory research, Zimbabwe can close the gaps in the understanding of cropping for efficient water utilisation and transferring this knowledge to the farm level.

The only opportunity Zimbabwe can use to address the gaps in the efficient utilization of soil water research is through its participation in the activities of the Optimizing Soil Water Use (OSWU) Consortium. The issues of water-use efficiency can be better tackled through a coordinated global OSWU Consortium approach so that all research need not be done in Zimbabwe. The country stands to benefit from and contribute to the OSWU Consortium in the following ways:

- Through the exchange of information and experiences of scientists working across the two dry ecoregions (Sub-Saharan Africa (SSA) and West Asia North Africa (WANA));
- The OWSU Consortium will assist Zimbabwe to gather spatially referenced databases and use these in simulation'models. The comparative advantages of institutions within the OSWU Consortium will be used in designing the structure of the databases and train others within the region to use it;
- Zimbabwe will see increased capacity in its national research systems to identify and render advice on appropriate management systems for enhanced water-use efficiency in dry-area cropping sequences; and
- The research activities of the Consortium will help scientists to develop guidelines for national and regional policies to promote efficient and acceptable water-use management techniques within the development of dry-area agriculture.

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Part B. Expert Opinions, Case Studies, and Linkages

Development of Water Management Technologies for Rainfed Crops in Burkina Faso

B Ouattara, V Hien, and F Lompo[1]

Abstract

This paper briefly reviews the main characteristics of the physical environment that determines the water supply of rainfed crops as well as their consequences for the production systems in Burkina Faso. The water management techniques relate to techniques developed so far for soil preparation at the scale of a field (plowing, earthing-up, tied ridging, weeding, Zai, etc.) and to antierosion devices at the scale of a village or a watershed. There exist no blueprints for techniques to save water at the field level Each one needs to be adapted to the particular pedoclimatic and socioeconomic conditions of the land user. The generated technology can often be combined into a technical sequence for soil tillage. The choice of these technologies will depend on the objectives. Techniques combating erosion, starting with rock bunds and contour earthen bunds for community application, are widespread in the central and northern parts of Burkina Faso. Along with techniques of Zai, half-moons, etc., they are used to rehabilitate degraded soils. Finally, the runoff water collection system for complementary irrigation appears at this time to be the surest means of securing agricultural production under the harsh climatic conditions in the country.

Resume

Ce chapitre fait d'abord un bref rappel des principales caracteristiques du milieu physique qui conditionnent l'alimentation hydrique des cultures pluviales ainsi que de leurs repercussions sur les systemes de production au Burkina Faso. Les techniques de gestion de l'eau qui y ont ete developpees se rapportent aux techniques de travail du sol a l'echelle de la parcelle de culture (labour, buttage, billon cloisonne, sarclo-binage, zai, etc.) et a la

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confection de dispositifs de lutte anti-erosive a l'echelle de bassin versant ou du terroir. Il n'existe pas de recettes 'passe-partout' en matiere d'economie de l'eau a la parcelle. Chacune doit etre adaptie au contexte pedo-climatique et socio-economique de l'agriculteur. Les technologies generees peuvent toutefois Stre combinees sous forme d'itineraires techniques de travail du sol dont le choix dependra des objectifs vises a travers leur mise en oeuvre. Les techniques de lutte anti-erosive, a partir de la confection des cordons pierreux ou des diguettes en terre isohypses, constituent quant a elles des pratiques communautaires tres repandues dans le Centre et le Nord du pays. Associees aux techniques de zai, de demi-lunes, etc., elles sont utilisees pour la rehabilitation des sols degrades. Enfin, les systemes de collecte des eaux de ruissellement a des fins d'irrigation de complement apparaissem a l'heure actuelle comme une des voies les plus sures pour securiser les productions agricoles soumis aux lourds poids des alias climatiques

Introduction

In Burkina Faso, as in other intertropical African countries, insufficient rainfall and/ or poor temporal and spatial distribution of it limits crop production. The periods of drought that have marked the last two decades clearly demonstrate that this phenomenon is especially severe in the semi-arid zones that are further characterized by low soil fertility levels (in general, shortage of phosphorus, low organic matter content, degraded structure, crusted surface, etc). In addition, the low quantity of rain that does fall may be lost through runoff because of surface characteristics that limit infiltration. Many efforts have been made by research and development organizations to improve crop yield (Nicou et al. 1990; Hien et al. 1992). However, one has to recognize that classical intensification techniques (such as fertilization, animal traction, improved varieties) have not always guaranteed good agricultural production under the prevailing harsh climatic conditions (Dugue 1986).

In areas of heightened climatic risk, such as the Sahel and the Sudanian Zone (Fig. 1), a range of actions are taken for soil and water conservation. These include techniques to control runoff water (stone lines, contour earthen bunds, soil tillage, etc.) and microreservoirs to collect water for supplementary irrigation.

This paper, after a genera! description of the biophysical conditions obtaining in Burkina Faso, analyzes the different production systems and summarizes the various actions taken in the domain of water management of rainfed crops.

General Biophysical Characteristics at the National Level

Climate

The topography of Burkina Faso is relatively flat with an average altitude of 400 m. The exceptions, however, are the sandstone mountains in the southwest and the

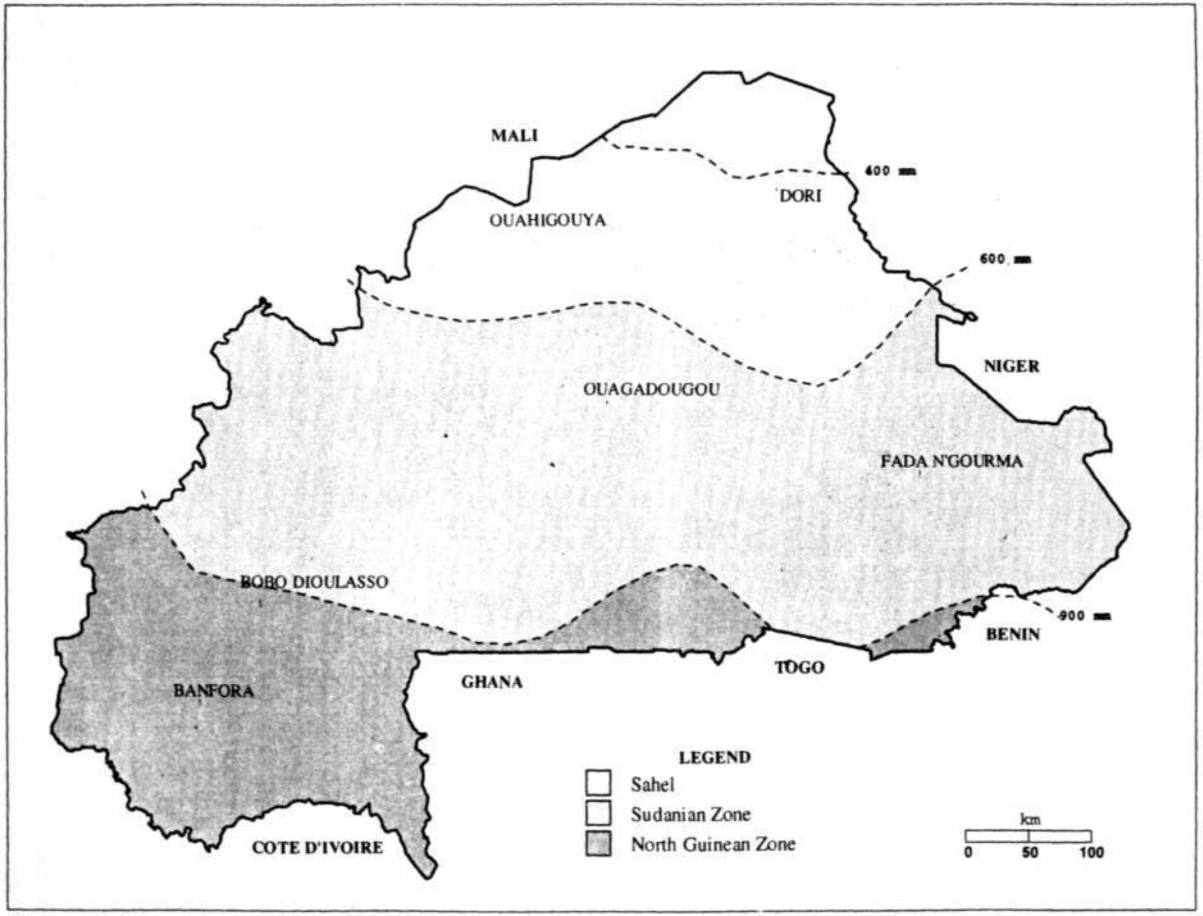

Figure 1. The agroecological zones of Burkina Faso.

Table 1. Frequency distribution of annual rainfall (mm) in the three agroecological zones of Burkina Faso during the period 1970-1990 (Some 1989; 1997).

Probability	Southern Sudanian Zone	Northern Sudanian Zone	Sahelian Zone
8 years out of 10	940.0	686.5	262.7
5 years out of 10	1042.7	719.6	340.1
2 years out of 10	1205.3	791.6	408.3
Average for the period	1070.8	742.7	328.3

birrimian hills in the northwest made up of a vast impluvium on which runoff starts. The hydrological network is characterized by numerous water courses and temporary lakes upon which water and agricultural management depends.

The general climate is Sudanian, characterized by alternating dry and rainy seasons. The rainy season lasts from three to six months, lengthening from the north to the southwest. The average annual rainfall follows this same spatial pattern: from 300 mm in the Sahel to 1200 mm in the Southern Sudanian Zone. For agriculture, the frequency distribution of rainfall is more revealing than the average annual amount (Table 1).

The interannual rainfall variability is coupled with an equally large intraannual variability characterized by (1) an unreliable beginning to the rainy season, (2) a frequent early end to the rains, and (3) the existence of various "rainfall holes" during the cropping season (Some 1989; Nicou et al. 1990). This very erratic and variable rainfall necessitates the use of water collection and conservation techniques in order to secure agricultural production. Implementation of these techniques most particularly concerns the Sahel and the Northern Sudanian Zone.

Soils

From the various soil classifications carried out in Burkina Faso, eight main soil types (French system) have been identified: (1) 'sols ferrugineux tropicaux' (39% of the area), *(2)* 'sols peu evolues' (26%), (3) 'sols hydromorphes' (13%), (4) 'sols bruns eutrophes' (6%), (5) 'sols vertiques' (6%), (6) 'sols halomorphes a structure degradee' (5%), (7) 'sols mineraux bruts' (3%), and (8) 'sols ferralitiques' (2%) (ORSTOM 1967, 1968, 1969). The agricultural lands predominantly comprise sols ferrugineux tropicaux.

Soils constitute a kind of 'food storage' for plants, and their capacity and functioning are largely linked to their physical and hydrodynamic characteristics. However, this paper will not elaborate on those aspects that control crop water supply. The amount of usable soil water is proportional to the clay content and the volume of rootable soil (e.g. determined by the presence of substratum or plinthites). In a soil profile of 1 m, the useful water reserve is around 100 mm in 'sols ferrugineux' and 'sols ferralitiques'. It practically doubles (236 mm) in 'sols bruns eutrophes', which are rich in clay. The texture and structure of soils also control the amount of infiltration. For example, measurement of hydraulic conductivity at saturation in 'sols ferrugineux tropicaux' resulted in a recording of 33 mm h^{-1} on cultivated soils with a loamy-sandy texture and with a large structure and 72 mm h^{-1} on sandy-clayey soils under long-term fallow for 30 years with *Andropogon* grass (Ouattara 1994).

Under the given climatic conditions, the level of crop water supply is predominantly a function of the intrinsic physical soil characteristics, but it can be greatly influenced by the use of appropriate agricultural technologies (especially soil tillage practices). For example, on the 'sols ferrugineux tropicaux' of the Central Plateau of Burkina Faso, with equal levels of organic and mineral fertilizer (5 t ha^{-1} of manure every 2 years, 100 kg ha^{-1} NPK, and 50 kg ha^{-1} urea), sorghum grain yield and water supply varied according to the water conservation technologies used:

- Direct sowing: 625 kg ha^{-1} with a water supply of 330 mm (real evapotranspiration, RETR);
- Plowing before sowing: 1250 kg ha^{-1} with 360 mm RETR;
- Plowing + tied ridges: 2600 kg ha^{-1} with 420 mm RETR (Ouattara et al. 1993).

The quantity of water consumed as measured by RETR is somewhat overestimated, because of the high evaporation rate from soils in the tropics. Nevertheless, it gives an order of magnitude of the impact of using water conservation techniques, in this case for a sorghum crop. Future research activities of INERA will aim at better quantifying the losses of productive soil water (part of transpiration by the plant) and at identifying techniques that reduce the high loss of water for the crop by soil evaporation.

Characteristics of Production Systems at the Agroecological Zone Level

The agroecological conditions, the diversity of available crops (varieties), and socioeconomic factors largely determine the production systems. We exclude in the following the Sahel where rainfall in eight out of ten years is below 400 mm. Traditional transhumance livestock production with a tendency for settling characterizes that zone. The agropastoral region of Burkina Faso is divided into the Southern Sudanian Zone, the sub-Sahel, and the Northern Sudanian Zone.

Southern Sudanian Zone

The Southern Sudanian Zone is the wettest part of the country. It is characterized by:

- a relatively abundant annual rainfall (900-1200 mm);
- a dense hydrological network that allows installation of large-scale irrigation schemes for rice cultivation, and traditional exploitation of inland valley bottoms;
- a large diversity of food crops (sorghum, maize, millet, rice, fonio, grain legumes, tuber crops, etc.);

- an important cash-crop sector (cotton, rice, fruit, and vegetables) that allows for an open-market economy in the region;
- an animal husbandry system in transition such that the western and southwestern part of the country seem to be becoming agropastoral regions. The region is home to more than 54% of the nation's draught animals mostly concentrated in the cotton-producing areas (INERA 1994a).

In terms of water management techniques at the field level, ridge tillage[3]/4or sometimes tied ridges[3]/aremains the traditional technique to combat not only runoff but also waterlogging due to the high rainfall. This technology is mechanized only in the cotton-producing zone.

The exploitation of the inland valley bottoms for rice production remains an activity essentially reserved for women. Unless these valley bottoms are otherwise managed, the traditional water collection system is used by making small basins with small earthen dikes (Thiombiano 1996).

The western and southwestern regions of the country, due to their geographic situation, benefit from a pedoclimatic environment favorable to agriculture and animal husbandry. Possessing important agricultural reserves, it is the destination of an important number of migrants coming from the north, resulting in a competitive attitude and socioeconomic competition that favors intensification of agricultural production (INERA 1994a).

Sub-Sahel and Northern Sudanian Zone

This zone includes the Central Plateau, and the eastern and northwestern parts of the country (Fig 1) with an annual rainfall between 500 mm and 800 mm. The prevailing pedoclimatic conditions (insufficient and/or irregular rains, low soil fertility) seriously limit agricultural development. The cropping systems have remained traditional and are essentially oriented toward food crops, mainly sorghum and millet with low external inputs (INERA 1994b). Secondary crops that enter into the commercial circuit are cowpea, groundnut, and maize. Vegetables are becoming more and more important in agricultural production due to the increase in the water reservoirs. Sedentary small ruminants and cattle raising usually in collaboration with Fulani herdsmen characterize the animal husbandry system.

In terms of water management for rainfed crops, this zone is known for a remarkable development of a range of water and soil conservation techniques (stone lines, earthen contour-bunds, application of Zai, etc.) due to concerted actions of research institutes, nongovernmental organizations (NGOs), and the national agricultural service.

Water Management Techniques for Rainfed Crops

The techniques developed in Burkina Faso comprise water-saving techniques at the field level, water and soil conservation works, and supplementary irrigation using collected runoff water.

Water-Saving Technologies

Water-saving techniques for rainfed crops aim essentially to serve three goals: (1) increasing water infiltration into the soil and decreasing runoff, (2) facilitating plants to use water stored in the soil, and (3) promoting better conservation of water infiltrated in the soil. Many soil preparation techniques have been developed for animal traction as well as for mechanization, but we only present those that can be realized with animal traction. They have been tested for six to seven years under different pedoclimatic conditions to determine their effects on the water balance and yields of the main cereal crops (sorghum, millet, maize) (Nicou et al. 1990). A short evaluation of these techniques follows.

Plowing

Plowing can be used for broadcast and deep (12-15 cm deep) soil tillage. By loosening the ground, it promotes rainwater infiltration and rapid crop establishment due to rapid root growth. This results in efficient use of rainwater and reduced lixiviation (Ouattara et al. 1993). However, the effects of plowing remain only for one growing season. The tiths quickly fall in due to the sandy texture of the soils with low clay contents. Moreover, annual plowing might result in the destruction of the soil structure in the long run (Ouattara et al. 1998).

Plowing also appears to be a basic water-saving technique with yield increases ranging from 25% to over 100% when compared with nonplowed conditions. Plowing is indispensable even for maize cropping in areas receiving more than 800 mm of annual rainfall. However, it can also have adverse effects such as rapid vegetative growth, which is detrimental to the formation and filling of grains, especially when dry spells occur during the flowering and grain-filling stages of the crop. Plowing needs to be associated with application of organic matter (Sedogo et al. 1994).

Ridge Tillage

Ridge tillage consists of the construction of raised earth in rectilinear shapes before sowing. Sowing is done on top of the ridge. Constructed across slopes, it is a good water and soil conservation technique. However, this method of cultivation can jeopardize crop establishment in areas with irregular rainfall because the ridge dries more quickly. Ridge tillage can increase yields by over 50% and can replace the need for plowing in heavy-rainfall areas, where it is traditionally practised to insure better drying of the soil and to prevent waterlogging (Nicou et al. 1994).

Hilling

Hilling is done during the growing period from the first weeding onward by putting earth from between the sowing rows around the stems of the plants. Following a plowing, this permits good control of weeds and increases the benefits of plowing by promoting root growth. Maize, however, does not necessarily benefit from this additional practice (Nicou et al. 1990).

Tied Ridges or Tied Hills

The technique of tied ridges or hills consists of making small dikes at regular intervals (every 1-2 m) in the furrows. Runoff is almost eliminated and all the water is captured in the furrows for infiltration. This technique is the most reliable method to increase crop yield. The date of tying the ridges or earth-hills can be delayed until rains are heaviest, because the partitioning is only essential for the elongation/ flowering stage of the crop. Partitioning is generally done by hand which demands much work from farmers: between 25 md ha^{-1} and 30 md ha^{-1} (ICRISAT 1982; IITA-SAFGRAD 1985). It is thus necessary to search for ways to mechanize this operation. IITA and ICRISAT have developed useful prototypes (Cloisonneuse IITA and Oeuf de Mathlon, respectively), but they require further improvement (Nicou et al. 1991).

Soil Scarifying

Soil scarifying is carried out to break up the soil (when dry) or to crush the topsoil (when wet) without inversion. This technique breaks up crusted soil and creates a rough soil surface that promotes rainwater infiltration. The dry variant provides an alternative to plowing. It is used as a water and soil conservation technique to rehabilitate degraded land (locally called 'zippela'). Research has developed a tine tool (Tine IR12) on a strong stem base set at a sharp angle. The required force of traction is equivalent to that provided by a pair of oxen carrying out flat plowing in wet soils (Son 1995).

Tine tillage in wet conditions is carried out with pliable tines (Canadian, body weeder, etc.). Repeated hoe weeding in the course of the cropping season between rains reduces soil evaporation by breaking up the capillary rise. Therefore, it is a good water conservation technique in areas with low rainfall (less than 600 mm). The increased grain yield from repeated hoe weeding is equal to that of plowing.

Comparison of these Five Technologies

Table 2 summarizes the expected effects of the five water conservation techniques and the problems encountered when they are applied. It appears that the different tillage operations can be combined with one another to meet site-specific needs as determined by pedoclimatic and socioeconomic conditions.

Erosion Control Measures

The combined effect of the unpredictable climatic conditions and demographic pressures in the central and northern parts of the country is the primary reason for the continuing degradation of the land, sometimes resulting in completely bare soils. Efforts have been made by NGOs and agricultural development organizations to stop this process. The problem is being addressed by managing the agro-sylvo-pastoral areas against erosion by constructing, for example, contour earthen or rock bunds, Zai, mulching, and half-moons.

Table 2. Efficiency[1] of various water conservation techniques and constraints in their application.

Characteristic	Plowing	Ridge tillage: Open	Ridge tillage: Tied	Hilling: Without plowing	Hilling: With plowing	Tied hilling: Without plowing	Tied hilling: With plowing	Tine tillage (IR12): Dry	Tine tillage (IR12): Hoe weeding
Improvement of infiltration and reducing runoff	++	++	+++	++	++	++	+++	+++	+
Facilitate use of water in soil	+++	+	+	+	++	+	++	+	0
Allows conservation of infiltrated water	++	0	+	0	++	0	++	0	+
Facilitates weed control	++	+	+	++	+++	+	+++	0	++
Reduces crop failure yield	++	+	++	+	++	+	+++	++	++
Constraints in the application of the techniques	Equipment for animal traction Time required to complete Effect on cropping agenda	Proper placement perpendicular to slope Problem for mechanized sowing High labor requirements when done by hand Weeding difficult		Planting lines perpendicular to slope Dates of earthing-up in dry zone High labor requirements when done by hand Cutting of roots		High labor requirements for sectioning Weeding required when plowing is not done		High traction power needed	Valid especially at start of growing cycle Various weedings needed with high rainfall

1. 0 = no action; + = low efficiency; ++ = efficient; +++ = very efficient.

Contour Earthen Bunds

Contour earthen bunds were the first form of field management started by the European Soil Restoration Group (GERES) around 1963-1964. This project ended in failure because of the use of heavy machinery (tractors) and the lack of participation of the population concerned. Since then, populations are committed to use simpler tools such as levels, picks, shovels, wheel barrels, and carts to construct these bunds. Results of the National Development Project showed increased yield of about 25% in a year with a deficient rainfall (496 mm), but only 13% with high rainfall (Ky-Dembele, and Zougmore 1994). This lower increase is caused by waterlogging due to problems in evacuation of excess water in this system of earthen bunds. Compared with rock bunds, earthen bunds do not filter well. Hence, construction of earthen bunds is only recommended for zones where rocks are not available. In case earthen bunds are chosen, it is recommended to make excess water facilities of 2 m width with stones and/or plants. The earthen bunds can be further stabilized by sowing low shrubs *(Piliostigma reticulata, Guiera senegalensis,* etc.) or perennial plants such as *Andropogon gayanus* depending on the needs of the population (firewood, fodder, medicinal plants, etc.).

Rock Bunds

Constructing rock bunds is the most practised technique to combat runoff and erosion. Three types are used in Burkina Faso: (1) a stack of stones embedded in the earth (locally PDS: Pierres Dressees associe au Sous-solage), (2) a three-stone system (locally FEER: Fonds de l'Eau et de l'Equipement Rural), and (3) a single row of stones.

Rock bunds, like earthen bunds, can be further stabilized with the plants mentioned earlier. Research results suggest a spacing of 33 m between the rock bunds on a slope with a gradient of less than 3% (INERA and IRBET 1995). Under these conditions, the runoff coefficient exceeds 50% without bunds, while it is 10% on a managed plot. Crop yields improve as well, but are a function of the amount of rainfall (Table 3) and location relative to the rock bunds (van Duijn et al. 1994). There is a marked effect of the nutrients in the deposited soil on the upstream side of the bunds (van Duijn et al. 1994). In order to achieve the best results from these techniques, it is necessary to carry them out together with other cultural techniques (land preparation, fertilization, etc.).

Table 3. Yields of sorghum (kg ha^{-1}) without fertilizer application as a function of application of rock bunds and type of rainfall at Kirsi (INERA 1994c).

Treatment	Dry (470 mm)	Normal (663 mm)	Wet (870 mm)
Without stone bund	119	562	71
With stone bund	249	972	432
Increase (%)	109	73	500

Various NGOs and development projects support financially or materially the farmers in their combat against runoff and erosion in the central and northwestern regions of the country. A mobilized population often does the work keeping the common interest in mind. The cost of constructing antierosion barriers is a function of the means used and the organization of manual labor. The management of one hectare of land, assuming that 300 m ha^{-1} of rock bund involves between 80 and 160 md, may cost about 250 FCFA km^{-1} (= 0.41 US$ in 6/99) (Some 1997).

Zai

Zai ('water pocket') is an ancestral practice developed in Yatenga (northwestern Burkina Faso) to regenerate the most degraded parts of the field. They consist of holes with a diameter of 0.15-0.20 m and a depth of 0.10-0.15 m. In general, the density is about 12,000-15,000 holes ha^{-1} depending on the crop chosen. Holes can be made in staggered rows moved from one year to another. The excavated soil is put on the lower side of the hole in the direction of the slope. In the hole, organic matter (manure, compost) is put, at the rate of an adult-sized hand (corresponding to about 3-4 t ha^{-1}) and subsequently mixed with a limited amount of soil. Sowing is done at the beginning of the rainy season. Generally, sorghum is the preferred crop because it resists better than millet the possible temporary hydromorphic conditions in the hole.

Compared to nontreated fields, crop yield doubled when the Zai technique was applied. For instance, in Donsin village the average grain yield in the Zai treatment was 1200 kg ha^{-1}, with a maximum of 4000 kg ha^{-1} (Kabore quoted by Maatman et al. 1998).

Zai construction is, however, hard work, and is more and more being done by hired labor (5 FCFA $hole^{-1}$). This implies, for example, for a sorghum field with a sowing density of 0.8 ' 0.8 m a cost of 80,000 FCFA ha^{-1} (about 130 US$ ha^{-1}). To reduce the amount of work to make the holes, the animal-drawn rake IR12 (mini-tooth) has been developed (Son 1995). This tool is used on dry ground in alternating directions, and the hole is made at the intersection of these scratches. In general, oxen are used for traction, except in the Central Plateau where donkeys are used. This improved Zai technique has been named "mechanized Zai".

Through a modeling exercise, Maatman et al. (1998) concluded that the combination of Zai and rock bunds is of high potential. They also suggest that Zai could be an appropriate technique for women to increase their crop yields since their fields are generally small and low in fertility.

Straw Mulching

Straw mulching can be carried out on bare soil or together with Zai. Its thickness should be at least 5 cm to be effective in reducing erosion, improving water retention, and developing biological activity. However, the main problem for this technique is the lack of sufficient available straw, which is equally used as fodder, building material, and fuel. Therefore, grass and weed clippings are used on exceptional terrain being fallow or used as pasture.

Half-Moons

The half-moon technique was only recently introduced, after its success was proven in Niger (INERA and IRBET 1995). The technique consists of making a hole in the form of a half-moon, with the removed earth put on the downhill side. The half-moons are always positioned on the slope with their widest points at the same level. They have a diameter of 4 m, and placed 4 m apart in a staggered pattern.

On the Central Plateau (Passore), on-farm experiments with half-moons are being carried out by a collaborative project of CES/Agroforestry and the International Program for Arid Land Crops (IPALAC). Sorghum grain yield was so spectacular (exceeding 1 t ha^{-1}) that farmers started applying this technology themselves immediately without further incentives. Consequently, the area of managed land in the village has increased by about 60%.

Supplementary Irrigation Techniques

Experimentation with supplementary irrigation was started in 1985 by CIRAD (Centre International de Recherche Agricole pour le Developpement) in collaboration with INERA and CIEH (Centre Interafricain d'Etudes Hydrauliques) as a reaction to the large droughts of 1983 and 1984 that affected the whole country, especially the Sahelian zone. The objective was to optimize the infiltrated and stored runoff water during the rainy season, and to secure the harvests of cereal crops through supplementary irrigation. In addition, the technique had to be acceptable for extension (rightly priced for development organizations and easy to carry out for farmers) and targeted to the sub-Sahel. The experiments were carried out in periods of 2-3 years with regard to the socioeconomic problems experienced. Table 4 presents the main characteristics of four types of supplementary irrigation techniques tested in the sub-Sahel: the GERES reservoir, 'boulis' reservoirs, experimental individual microreservoir, and farmer's microreservoir.

Using the GERES reservoir and its irrigation systeir together with 286 mm of annual rainfall (by itself insufficient to meet crop water requirements) resulted in a maize grain yield of 3 t ha^{-1} . The disadvantage of this system, however, is the current land tenure system; it was constructed collectively, but only the traditional landowner used the irrigated land (Dugue 1986).

The boulis reservoirs are constructed downstream of a ravine. They are holes of about 3-4 m depth and have a diameter of 50-60 m. Generally, they are not far from the village, but since their use is not primarily irrigation (Table 4), the location is not selected according to irrigation criteria. In one case, a tube was placed under the dike of the boulis, and provided irrigation water by gravity. The irrigated field was cultivated with maize by a group of farmers and the grain yield was about 2 t ha^{-1} The field was not well-maintained, and it appeared that farmers invested more in their own field (Dugue 1986).

Construction of both types of reservoirs thus seems not very useful. Unless carried out at the community level with clear commitments and substantial benefits for all or when the required funds are available for the embankment work, farmers prefer the individual exploitation rather than the collective one.

Table 4. The different complementary irrigation models used in the sub-Sahel region of Burkina Faso.

Reservoir	Topographic location	Capacity and period of stock	Type of pumping-out and installation costs	Purpose
GERES	Between two hills where water flow is important	15,000-25,000 m^3; June - Feb/ April depending on rainfall	Pipe dug under the dike; 150,000 FCFA (1985[1])	Livestock watering; irrigation by flooding downstream (0.25 ha with maize)
Boulis	Zone with high runoff	2,500 - 3,000 m^3; June - December	Manual or PVC pipe or trap; NC[2].	Livestock watering; domestic use; brick fabrication; supplementary irrigation
Experimental micro-reservoir	Runoff area	100 m^3; end June-end September	Chain or motor pump + PVC pipe and trap (gravity); 200,000 FCFA	Supplementary irrigation experiment with sorghum, maize and gombo (0.2 ha)
Farmers' microreservoir	Runoff area in a small gully	15 m^3; end June - end September	Manually + PVC pipe + funnel + canals of clay; 15,000 FCFA	Irrigation of maize and pigeonpea (0.05 ha)

1. Corrected for devaluation in 1994.
2. NC = Not calculated. Only manual labor required and simple tools.

With regard to the mentioned constraints of reservoir construction through collective work, research on individual microreservoirs was initiated (Dugue 1986), one experimental one and another for farmers (Table 4). At the experimental site, sorghum (IRAT 204; 90-day growing cycle) was cultivated, but no second crop was grown because of the longer sorghum growth cycle. Supplementary irrigation increased yield on average by 67% (Table 5). The greatest absolute gain (1046 kg ha^{-1}) occurred using tied ridges, and corresponds to an additional gross revenue of 52,300 FCFA (86 US$). However, the low soil fertility level of the field (after more than 30 years of cultivation without fertilization) lowered yield from the varietal potential despite fertilization conforming to extension service recommendations (100 kg ha^{-1} NPK + 50 kg ha^{-1} urea). Ridging increases the effectiveness of irrigation because the furrows serve to direct the water and seeding is done on the sides of the ridge. Two technical problems with this irrigation system were noted: (1) lack of waterproofing to reduce seepage, and (2) manual pumping of water at a rate of 4-5 m^3 h^{-1}, which is too low to irrigate the entire area in a single day.

The farmer's microreservoir requires 25 man-days for construction. Irrigation is applied through two PVC tubes placed under the dike and fitted with wide funnels

Table 5. Yields of sorghum (kg ha^{-1}) under different management practices in 1985 at Sabouna with 600 mm of rainfall (Dugue 1986).

	Direct sowing	Plowing	Tied ridges
Without irrigation	810	1114	1654
With irrigation (92 mm)	1250	2060	2700
Increase (%)	54	85	63

(40 cm in diameter). Water is provided manually by two persons with buckets. Downstream, a third person directs the water flow into the earthen canals. Maize is sown in a fish-bone pattern. This type of irrigation system requires field use planning by farms, in which they are not yet well experienced. Nevertheless, it seems satisfactory, because it is quick at low cost and allows farmers to also have some other crops. The increase in gross revenues for this small area is not very large (10,000-15,000 FCFA; 16-25 US$; Dugue 1986).

These several projects reviewed carried out in Yatenga show the various possibilities for intensification of crop production through supplementary irrigation. It is, however, still necessary to carry out further both technical and socioeconomic research before giving recommendations for models of complementary irrigation that are cheap and easy to use by farmers.

Research in the Field of Optimizing Soil Water Use

A large number of studies have been carried out, but only a few on the water management techniques of rainfed crops in Burkina Faso. At this time it would be better to place the emphasis on correcting the shortcomings of existing technologies before embarking on further research activities in this field. Thus, a first research area could be to focus on mechanization (animal traction) of various land-preparation techniques, such as tied ridging. Therefore, a review of existing technologies is needed.

Secondly, to overcome the large intraannual and spatial rainfall variability, supplementary irrigation based on efficient use of runoff water becomes more and more important. As indicated earlier, further experimenting is needed before large-scale application becomes feasible.

A third research theme will be to identify integrated techniques that address both soil fertility and efficient soil water-use aspects.

The INERA Department of Natural Resources and Production Systems Management (GRN/SP) will carry out the research activities.

Conclusion

The water management techniques for rainfed crops developed in Burkina Faso aim partially or totally at controlling the circulation of rainwater at the soil surface (land preparation, antierosion measures). The primary goals are to increase rainwater infiltration by reducing runoff to benefit crops or to improve the stocking for supplementary irrigation in reservoirs on downstream parts of the terrain that is not suitable for crops. Although certain of these technologies need further improvement through research, it appears that Burkina Faso has a range of experience which it could share with the other OSWU member countries that have similar agroecological conditions. In the same way, the OSWU Consortium will allow INERA to gain from other experiences and to improve its adaptive research on the existing techniques.

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Optimizing Soil Water Use from a Watershed Perspective

C Batchelor[1]

Abstract

Sustainable and profitable agricultural development in dryland areas requires technologies and practices that make efficient and productive use of water resources and enabling environments that encourage adoption of these technologies. There is a wide range of technologies that can be used by farmers to make more efficient and productive use of soil water at the field and farm scales. However, it is argued in this paper, that consideration should be given to the impact that these technologies may have at the watershed scale. In particular, it is argued that water that is considered as being lost at the field and farm scales can have important uses and value, elsewhere in a watershed. Hence, improving the efficiency of water use in one part of a watershed can have important equity implications by reducing water availability to other potential users. Many institutions and international agencies are showing considerable interest in integrated watershed management (IWM) as a practical means of improving the management of water resources, reducing environmental degradation, and promoting sustainable agricultural development. This paper outlines some of the main components of IWM and discusses how it might be used in dryland areas to design and implement programmes that lead to improved utilization of soil water at the watershed scale. Recommendations are made for IWM-related research that could be undertaken by the OSWU Consortium. In particular, the case is argued for using interdisciplinary modeling techniques that make use of belief and decision networks.

Resume

Le developpement agricole durable et rentable en zones seches requiert des technologies et des pratiques qui font une utilisation efficience et productive des ressources en eau ainsi qu'un environnement favorables qui encouragent

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encouragent l'adoption de ces technologies. Il existe une gamme variee de technologies susceptibles d'etre utilisees par les paysans pour faire une utilisation plus efficiente et productive au niveau des champs. Toutefois, dans le present document, on argumente qu'il faut examiner l'impact que ces technologies peuvent avoir au niveau des bassins versants. En particulier, on estime que l'eau que l'on considere comme etant perdue au niveau des champs peut etre mieux exploitee ailleurs dans un bassin versant. Ainsi, l'amelioration de l'efficience de l'utilisation de l'eau sur une partie du bassin versant peut avoir des implications importantes en terme d'equite, par la reduction de l'eau disponible a d'autres utilisateurs. De nombreuses institutions et agences internationales accordent un interet a la gestion intigree des bassins versants (GIB), comme moyen pratique permettant d'ameliorer la gestion des ressources en eau, en reduisant la degradation de l'environnement et en encourageant un developpement agricole durable. Le present papier fait etat de quelques uns des principaux volets de la GIB, et traite des moyens de son utilisation en zones seches pour concevoir et executer des programmes qui permettent une meilleure utilisation de l'eau du sol au niveau des bassins versants. Des recommandations sont faites pour la conduite de recherches dans le domaine de la GIB qui pourraient etre entreprises par le Consortium sur l'Optimisation de l'Utilisation de l'eau du sol (OSWU). En particulier, il s'agit d'utiliser des techniques de modelisation interdisciplinaire qui s'appuient sur des reseaux de croyances et de decisions.

Introduction

Soil water problems in dryland areas have received considerable attention. Many excellent reviews exist of research related to soil water management (e.g. Morse 1996; Syers 1997), soil degradation and resilience (e.g., Lal 1997) and interactions between soil water and soil nutrients (e.g. Gregory et al. 1997). Good reviews also exist of farmers' adoption of measures aimed at optimizing soil water use. For example, Reij et al. (1996) describe 27 case studies in which a range of different soil and water conservation practices were promoted and adopted in different parts of Africa. Despite our understanding of soil water problems and encouraging (but often localized and much quoted) examples of farmers improving soil water use, crop yields in dryland areas remain at low levels.

Although it is extremely difficult (if not impossible) to obtain meaningful estimates of potential crop yields for a given set of physical and socioeconomic conditions, there is a general agreement that there is a large gap between yields achieved on research stations and those achieved by farmers. For the semi-arid Sahel, Rockstrom (1997) reported potential yields of millet and sorghum of approximately 2 and 2.5 t ha^{-1} respectively. Farmers' yields in the region generally average 500-600 kg ha^{-1} but can easily drop to 150-300 kg ha^{-1} on degraded land. This yield gap is generally explained by differences in cultivation practices, choice of cultivar, fertilizer use, and soil and water management practices. Although soil water is a critical factor, the extent to which yield gap can be attributed to inefficient soil water use varies within fields (Brouwer and Bouma 1997), from field to field, and from season to season.

The main challenge facing the Optimizing Soil Water Use (OSWU) Consortium is to assess the extent to which soil water is the cause of low yields in dryland areas and to evaluate strategies and farming systems that can lead to more sustainable and profitable agricultural production. This paper reviews and discusses some important issues and factors that can influence improved soil water use and crop production at the watershed scale.

Optimizing Soil Water Use at the Watershed Scale

The bulk of research associated with optimizing soil water use in dryland areas has been carried out at the small plot and field scales. Whilst this research has generated a wealth of important and useful information, scaling up plot- and field-scale information to the watershed scale has presented a number of problems, many of which result from the traditional approach that has been taken to defining and estimating water losses and water-use efficiency at the plot and field scales. This traditional approach does not recognize that, at the watershed scale, water that has been "lost" at the plot or field scales can often be reused (e.g. water "lost" as deep drainage can be abstracted from aquifers and reused) (Seckler 1996). In addition, the traditional approach does not recognize that additional water captured or harvested in one part of a watershed may be at the expense of alternative uses or users in other parts of the watershed. A "whole watershed" approach to water use considers the efficiency and productivity with which water is used at different places in a watershed by different users and the degree to which different uses degrade water quality. Ultimately, watershed water-use efficiencies should be calculated (and optimized) not only in physical terms but also in economic, social, and environmental terms (Wallace and Batchelor 1997). Seckler (1996) suggests that opportunities for improving watershed water-use efficiency or productivity lie in four directions: (1) increasing output per unit of evaporated water; (2) reducing losses of usable water to sinks; (3) reducing water pollution; and (4) reallocating water from lower valued uses to higher valued uses.

Another direction that could be added to this list is maximizing the recycling of evaporated water within large watersheds or across continents. Recycling of moisture by vegetation across continents and within large watersheds is an important hydrological process (Savenije 1994). Salati and Nobre (1992) suggest that half the rainfall in the Amazon Basin originates from forest evaporation and not evaporation from the oceans. With regard to crop water use, current theory suggests that crop water use during dry seasons (primarily from irrigated crops or deep-rooting vegetation) implies a loss of recycling capacity, as water evaporated during the dry season is less likely to enhance rainfall. However, water use by crops (rainfed and irrigated) during "wet" seasons is likely to be recycled.

A commonly-held view is that central governments have failed to manage natural resources effectively; that people at the local level know better how to handle the resources that they exploit; and that resource users have stronger incentives to manage resources with care than government officials (Engberg-Pedersen 1995). Although there is some truth in this argument, it is clear that some level of regulation and management is needed at the watershed level (or if more appropriate at the village or administrative district levels) if the wider objective of equitable access to water resources is to be achieved. Perry (1997) notes with some concern that there are two apparently contradictory trends in the management of water resources. One trend involves using river basins as the framework for analysis and management, implying intervention and regulation at levels above farms, small watersheds, districts or even states. The other trend is towards local management, decentralization, and decision making at the lowest possible level. In theory, this apparent contradiction can be overcome, or at least accommodated, within programs of integrated watershed management.

Integrated Watershed Management

Many institutions and international agencies are showing considerable interest in integrated watershed management (IWM) as a practical means of improving the management of water resources, reducing environmental degradation, and promoting sustainable agricultural development. IWM programs that are having some success comprise the following components: (1) an overall natural resource management strategy that clearly defines the management objectives; (2) a range of delivery mechanisms that enables these objectives to be achieved; and (3) a monitoring schedule that evaluates program performance.

IWM programs are based on the principles that:

- Decision-making and action take place at the lowest level, whether it be at the farm, watershed, district or river basin levels. Wherever possible, stakeholders are involved both in decision making and in resulting activities (at the local level, stakeholders include farmers, community groups, and local institutions, while at the national or basin levels, stakeholders can include national governments, government departments and agencies, farmers organisations and NGOs);
- Delivery mechanisms and enabling policies are established that provide long-term support to programmes of environmental recovery and sustainable development; and
- Rural development is considered to be process-oriented rather than target-oriented.

Implementing Community-Based Integrated Watershed Management

In the past, a failing of many watershed management strategies has been that, while they have been able to articulate the right aspirations for the management of resources, they have not been able to bring about improvements in resource management at the watershed scale (Blackmore 1994; van Zyl 1995). One of the main reasons for this has been the lack of delivery mechanisms artd enabling policies that generate interest and prompt the participation of local institutions and communities. Arguably, the best examples of IWM being put into practice come from Australia (Blackmore 1994; Campbell, 1994a). In Australia, IWM and the Landcare system have encouraged farmers and other local stakeholders to work together with government in seeking solutions for a wide range of rural problems (Campbell 1994a). The Landcare system combines elements of community and environmental education, action research, and participatory planning. More than 2000 voluntary Landcare community groups are currently working to develop more sustainable systems of land and water use supported by a national 10-year funding programme. Some groups have already created a climate of opinion (or consensus) that is more favorable to the adoption of resource-conserving practices and some have achieved notable successes in land management improvements particularly suited to group action, such as controlling rabbits and weeds.

Although Landcare has achieved notable successes, the program is not without problems (Campbell 1994a,b). There has been evidence of frustration building up as a result of the bureaucracy, politics, and paperwork associated with Landcare, particularly with project funding. Frustrations have also built up as a result of the lack of appropriate expertise and resources available to tackle major environmental problems, and as a result of the amount of poor resource management still occurring. Another problem is related to the changes in attitude required by professionals involved in Landcare. Many professionals have little training in interpersonal skills and, more importantly, they find it hard to be accountable to local people. A key constraint, therefore, remains the existing institutional cultures, which are yet to be oriented towards genuine community involvement and self-reliance (Pretty 1995).

The delivery mechanisms that are being used with relative success in Australia involve the allocation of large amounts of public funds. It is a simple fact that few countries in semi-arid areas have the same political will and financial resources as Australia. An alternative and less costly approach to initiating community and local-level involvement in IWM is being evaluated in south-east Zimbabwe (Batchelor et al. 1996). A key hypothesis behind this approach is that a first community-based productive water point can provide an ideal initial step towards other community-based activities aimed at reducing environmental degradation and promoting sustainable development. In this context, productive water points are considered to be community-based water points that are designed and implemented to provide water both for domestic use and for income-generating activities such as small-scale vegetable production. Evidence to date suggests that the immediate benefits from productive water points are sufficient to encourage communities to overcome the inevitable leadership and organizational problems that are associated with first community-based activities. Evidence to date also shows that productive water points have a positive impact on the wider farming and livelihood systems (Waughray et al. 1997). Research in Zimbabwe is now evaluating enabling policies that facilitate the scaling up of these village level activities as part of program of IWM.

Scope for Improving Soil Water Use from a Watershed Perspective

As stated earlier in this paper, the main opportunities for improving water productivity or efficiency from a watershed perspective lie in four directions. The scope for increasing output per unit of evaporated water is immense at both the field and watershed scales. Figure 1 presents data from Niger which shows that nonproductive soil evaporation from rainfed millet is typically in excess of one-third of the seasonal rainfall. Hence, if areas of watersheds that are not producing useful vegetation are taken into account, nonproductive evaporation in dryland areas will generally be well in excess of one-third of the annual rainfall.

Different strategies for reducing surface runoff and harvesting rainfall have been used to improve crop production. However, from the watershed perspective in dryland areas, surface runoff represents a much smaller loss of usable water to a sink (e.g. the sea) than is the case for soil evaporation. Figure 2 presents data from the Romwe Catchment Study, which is located in south-east Zimbabwe. Although these data are from three years of relatively high rainfall, it can be seen that runoff from the watershed as a whole was always less than 10% of annual rainfall and in the driest year reported, it was only 0.5% of the annual rainfall. Runoff from sub-catchments within the Romwe Catchment, was influenced strongly by soil type and land use. Runoff was highest from the cropped areas with grey duplex soil and lowest from the cropped areas with red clay soil. Although water-harvesting measures can reduce the variability of in-field soil water availability, in the case of the Romwe Catchment they are likely to be of most benefit to crop production in the areas of grey duplex soil. In general in dryland watersheds, the quantities of runoff that can be harvested is

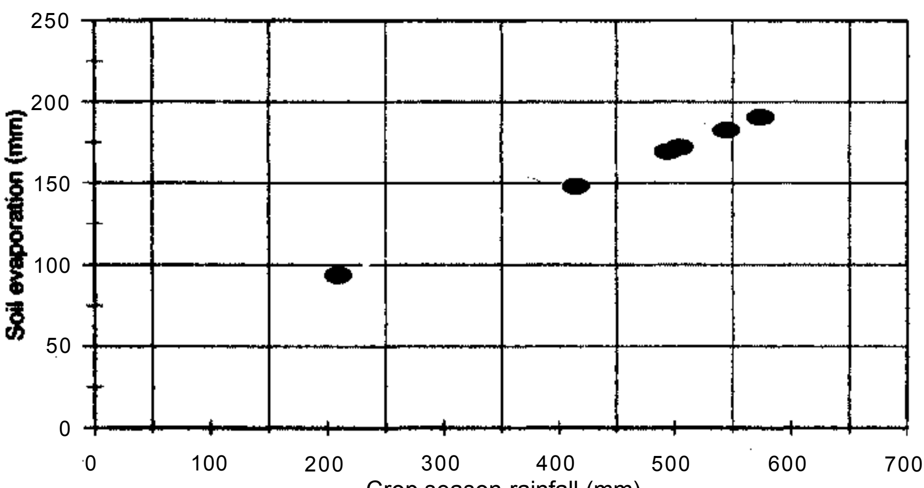

Figure 1. Cumulative seasonal evaporation from soil in millet crops as a function of rainfall (Wallace and Batchelor 1997).

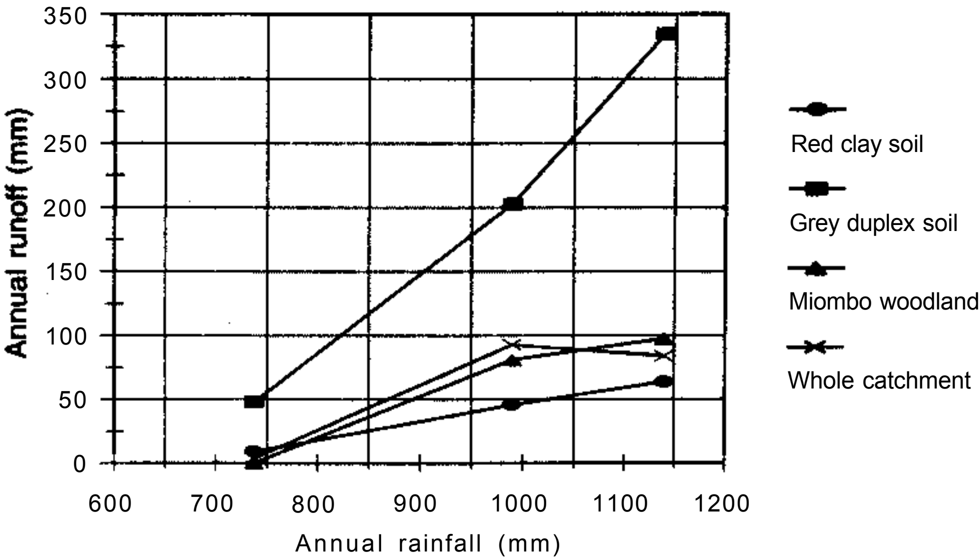

Figure 2. Annual runoff plotted against annual rainfall for the whole Romwe Catchment and three sub-catchments within the Romwe Catchment representing an arable area with red clay soil, an arable area with grey duplex soil, and an area of miombo woodland with steeper slopes (Lovell et al. 1998).

limited. Hence, decisions have to be made on criteria that lead to the most appropriate location, design, and management of water harvesting systems. Selection of these criteria will depend on whether the aim of the water harvesting systems is to, say, maximize agricultural productivity or, alternatively to improve the access to water resources of different social groupings.

Figure 3 summarizes data from a number of studies of drainage beneath millet fields in the Sahel. This figure shows that, for traditionally-managed millet fields on sandy soils, drainage can be a substantial component of the water balance when annual rainfall is in excess of around 300 mm. In contrast, there is no significant drainage below fallow-savannah lands in the Sahel even when rainfall reaches 450 mm (Allen and Grime 1995; Gaze 1996). Water harvesting strategies can be used to reduce deep drainage (e.g. by spreading surface runoff) or to increase deep drainage (e.g. by concentrating runoff). In dryland areas, water harvesting to improve crop production is rarely compatible with water harvesting to improve groundwater recharge. Surface management practices such as tied ridge and furrow, which harvest rain where it falls, are of benefit to rainfed crops but the same practices, by preventing surface redistribution and concentration of rainfall, can substantially reduce groundwater recharge. In years of low or evenly-distributed rainfall, there will be a trade-off between the benefits to individual farmers of improved crop production through in-field water harvesting and the benefits to pastoralists and the wider community of enhanced groundwater through water harvesting using, say,

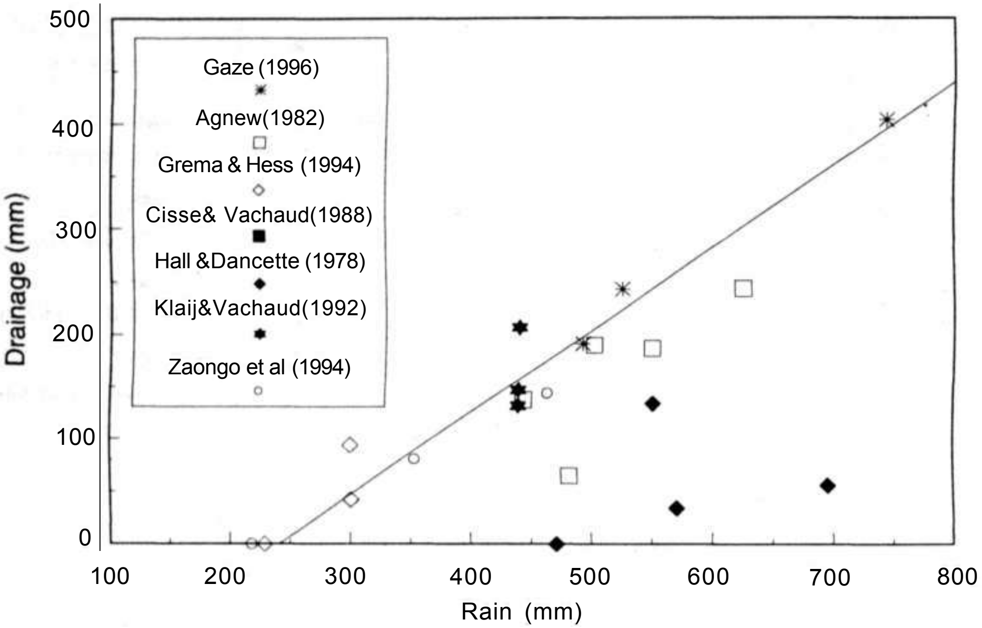

Figure 3. Comparison of estimated drainage below millet on sandy soils in the Sahel (Gaze 1996).

more widely spaced contour bunds (Lovell et al. 1998). Figure 4 presents data from the Romwe Catchment Study that shows the relatively small influence of contour bunds on infiltration in arable areas with red clay soils following a large rainfall event.

Problems related to water pollution are rarely taken into account when considering strategies for optimizing soil water use. There are, however, a number of problems or potential risks that should be considered when selecting the most appropriate design, location, and management of water harvesting systems. For example, systems that lead to rising groundwater levels can cause soil salination and deterioration of the quality of domestic water supplies. For example, concentrating rainfall and increasing drainage rates may lead to rapid transport of nitrates and other agrochemicals into aquifers and water courses. In each example, there may be a net decline in the productive use of water from the watershed perspective.

In most dryland areas, there is scope for improving the efficiency or productivity of water use by reallocating water from lower valued to higher valued uses. In terms of optimizing soil water use, this may involve using water harvesting systems that enable water to be stored, either in small reservoirs or as groundwater. This stored water can then be used immediately as supplemental irrigation of higher valued crops such as vegetables or subsequently during dry seasons or periods of drought when many crops will attract a higher value. Alternatively, harvested rainfall might be used for a range of relatively higher value domestic or nonagricultural uses. Rockstrom

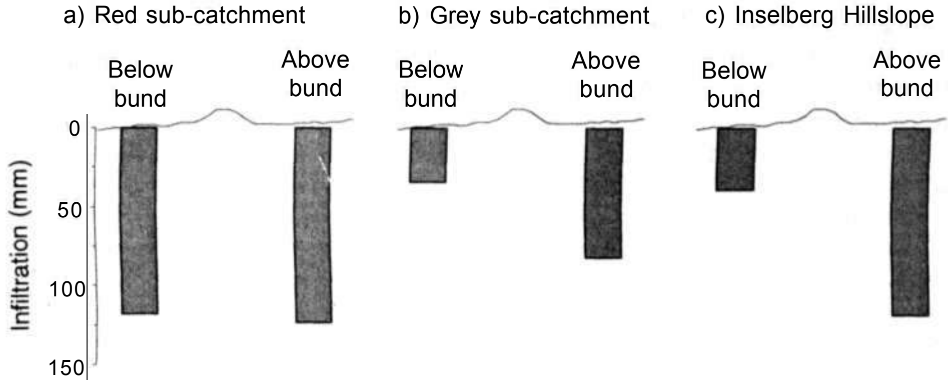

Figure 4. Infiltration above and below contour bunds at three sites in the Romwe Catchment in Zimbabwe following a 141 mm rainfall event in February 1995 (Butterworth 1997).

(1997) discusses the potential for using water harvesting to provide water for supplemental irrigation in the Sahel and concludes that there are substantial volumes of surface water that could be used more productively in semi-arid zones, at least during years of average rainfall.

Farmer Uptake of Strategies for Optimizing Soil Water Use

Numerous environmentally-benign technologies have been shown to have the potential to improve agricultural sustainability, production levels, and efficiency of water utilization in semi-arid areas. These include contour farming to reduce runoff and soil erosion, mulching, minimum tillage, crop mixtures and rotations that ensure continuous soil cover, terracing and bunding, integration of livestock and arable cropping to maintain soil fertility, agroforestry, integrated pest management, and water harvesting (Cleaver and Schreiber 1994; Reij et al. 1996). It should be noted that many of these technologies have been known and practised in certain areas for millennia. This being the case, it has to be asked why it is that the adoption of these technologies is not more widespread. To researchers, politicians, and resource "managers", it seems obvious that farmers should adopt these technologies. However, the perceptions of farmers are usually very different and very dependent on the physical, social, economic, and institutional circumstances under which a farmer operates.

Key reasons for the nonadoption of these technologies appear to be the fact that farmers have not demanded them, that there is often a poor fit between the technologies and resources available to farmers and, in many cases, the technologies lead to increased risks, at least in the short term (Cleaver and Schreiber 1994). A recent review of technologies acceptable to resource-poor farmers points out that combining practices into a farming system must take account not only of physical factors such as soil type, slope and climate, but also the available resource inputs, especially cash and labor, and the farmer's objectives (Stocking, 1993). The objectives of the commercial farmer are usually to maximize yield and income, but the subsistence farmer is likely to be more interested in improving food security by reducing risk of crop failure, or improving the return on inputs of seed, fertilizer and labour, or improving the quality of life by reducing drudgery, particularly in the case of women farmers (Hudson 1995).

In the last few years, there has been an increasing volume of research that has questioned the general view of most policy makers that soil erosion and environmental degradation are major problems in dryland areas of Africa (e.g. Tiffen et al. 1994; Leach and Mearns 1996). This research puts emphasis upon Boserupian processes of agricultural intensification as opposed to the pessimism which has previously prevailed in many studies of African peoples, their livelihoods and their environment (Murton 1997). The often-quoted study in the Machakos region of Kenya by Tiffen et al. (1994) suggested that, from the 1960's, a major transformation of the farming landscape took place with huge voluntary investment in conservation works resulting in falling erosion rates, increased environmental rehabilitation and a boost for agricultural productivity. The reasons that were identified included: increasing population densities and resultant land scarcity combined with improved access to the growing market of Nairobi. Other reasons were the access to information through informal networks that, along with formal extension advice, enable farmers to try out a range of conservation measures. More recent research in the Machakos region by Murton (1997), confirmed some of the earlier findings with regard to environmental transformation and the adoption of soil and water conservation measures. However, Murton (1997) suggests that the earlier findings do not tell the whole story. Although agricultural production per capita may have risen over the district as a whole, this has not been true for all people or all places.

Another example of the interaction between population pressure and agricultural intensification has been observed on the Jos Plateau in Nigeria (Cleaver and Schreiber, 1994). The Kofyar people initially lived as subsistence farmers on the Jos Plateau. As population density on the escarpment increased, farming systems were intensified with increasing reliance on agroforestry, terracing, and manuring. When population pressure on the plateau outpaced the ability of the farming system to sustain the increased numbers, the Kofyar obtained permission from tribes in the Benue River plains to clear lowland forest and farm there. The migrants abandoned the intensive farming techniques they had practised on the plateau and adopted instead an extensive forest-fallow farming system focused on cash cropping and market-oriented animal production. Cleaver and Schreiber (1994) suggest that it should not be surprising that this process is observed in certain areas of developing and developed countries. If there is no land constraint, and if land is free or very cheap, it makes sense from the farmer's perspective to extend the use of land and minimize the use of other inputs that include capital and labor. If, however, land becomes more scarce, there is an obvious incentive for individual farmers to intensify agricultural production and to take better care of the limited land available to them.

Unfortunately, the intensification process observed in Machakos and on the Jos Plateau is not seen throughout Sub-Saharan Africa. In fact, sluggish agricultural growth and severe environmental degradation are the norm throughout the region. Cleaver and Schreiber (1994) hypothesise that, in most of Sub-Saharan Africa, rapidly increasing population over the last twenty to thirty years has overwhelmed the slowly evolving rural traditions of farming, livestock production, fuelwood provision, land allocation and utilization, and gender-specific responsibilities in household maintenance and rural production systems. This has led to and accelerated degradation of natural resources which, in turn has contributed co a low rate of agricultural growth. In short, a range of complex interlinked factors has prevented agricultural intensification from taking place and, as a consequence, natural resources are being depleted.

Although the policies of governments or other financing organizations alone will not lead to the uptake of water-efficient technologies, policies can play an important role in encouraging the uptake of improved technologies or practices. Using 20 detailed case studies and field and community level data from more than 50 projects, Pretty (1995) has identified some of the common elements needed in the successful implementation of sustainable agricultural practices and concludes that policy formulation is a key area. For sustainable agriculture to succeed, policy formulation must not repeat the past mistakes of coercion and control; rather it should concentrate on creating enabling environments that promote productive use of local resources, skills, and knowledge.

Conclusions and Recommendations for Future Work

Research intended to increase production by improving soil and water management in dryland areas should not focus solely on agronomic, plant physiological, and soil water experimentation. Integrated and multidisciplinary research programs are needed to determine other factors that may be crucial to the adoption of a new technology and the impact that it may have on a range of spatial and temporal scales. Interdisciplinary modelling techniques using, for example, Bayesian Belief Networks have huge potential in providing a clearer insight into the impact of new technologies and, in many instances, explaining reasons for lack of widespread uptake. Belief networks provide a method of representing relationships between variables even if the relationships involve uncertainty, unpredictability or imprecision. Links between variables can be established deterministically or probabilistically using field data or, if more appropriate, expert opinion. By adding decision variables (variables that can be controlled) and utility variables (variables we want to optimize) to the relationships of a belief network, it is possible to form a decision network. This can be used to identify optimal decisions. The theory and methods of construction of belief and decision networks have been described by a number of authors (e.g. Spiegelhalter et al. 1993). Batchelor and Cain (1998) provide examples of interdisciplinary data analysis of water management systems using belief networks.

The case for undertaking soil and water management research at a range of temporal and spatial scales is strong. To date, the bulk of such research has been carried out at the plot and field scales over relatively short time scales. It is recommended that more off-station soil and water management research be carried out at range of scales, that includes the watershed scale, and that the emphasis of this research should be on the productivity of water use and on distinguishing between "real" and "paper" water losses (as defined by Seckler 1996). Research at the watershed scale should also study interactions between the management of arable land and the rest of the landscape, which may be used for grazing livestock, forestry, housing, and a range of nonagricultural uses (Morse 1996). Apart from short-term variability in rainfall, longer systematic trends have been observed in many areas (e.g. in Zimbabwe by Lovell et al. (1998)). Research is needed over comparable periods of time to account for these trends and other natural climatic phenomena such as severe droughts. Soil and water management research should also consider the potential impact of climate change and the possible need to include risk factors in the design of water systems (Downing et al. 1997).

Fanington and Lobo (1997) identify some of the main factors that influence the scaling up of village level activities (such as water harvesting) to the watershed level in India. Similar research is recommended for the Sub-Saharan Africa and WANA regions. A main emphasis of this research could be to assess the potential for promoting strategies that optimize soil water use within the framework of integrated watershed management (IWM). Further detailed investigation is warranted into the potential of using productive water points as a first step towards (or delivery mechanism for) programs of IWM that include a range of options for optimizing soil water use.

Economic, social, and institutional factors have an enormous influence on farmer demand for new technologies and the potential impact of new technologies on farming and wider livelihood systems. Studies are warranted to assess the factors that have led to the adoption of improved soil and water management practices (in many cases the readoption of indigenous soil practices). These studies would benefit from using environmental and resource economics to provide information on the relative market and nonmarket values of water in dryland areas.

Morse (1996) has identified and listed a number of researchable issues relating to soil and water management at the field scale. One issue that does not appear on this list is the inherent danger of using point measurements of soil hydraulic properties or soil water content and potential to represent large areas (i.e. fields, watersheds, etc.). The high spatial variability that is typical in dryland areas poses major problems when developing and using crop production or hydrological models (Gaze 1996). Models developed using a belief network as a framework may provide a good approach to tackling and describing this variability.

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Cropping Systems and Crop Complementarity in Dryland Agriculture

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Abstract

Dryland agriculture under rainfed conditions is found mainly in Africa, the Middle East, Asia, and Latin America. In the harsh environments of Sub-Saharan Africa (SSA) and West Asia and North Africa (WANA), the factor which ultimately limits crop yield is availability of water. A variable supply of water due to seasonal differences in precipitation leads to correspondingly variable crop yields. However, research has shown that good soil and crop management practices can considerably increase the efficiency with which the limited amount of water available from precipitation is used. That is, more production per unit area can be gained from each mm of precipitation if crops are well-established and adequately fertilized, weeds are controlled, and appropriate crop rotations used. These activities should be considered together with proper management of the soil if production is to be sustained and resources to be conserved in the long term. Both will be responsible for higher production with improved water-use efficiency.

The WANA production systems are dominated by cereals, primarily wheat in the wetter and barley in the drier areas, in rotation with mainly food legumes such as chickpea and lentil, which occupy, however, only 10-15% of the area sown to cereals. Fallows are inefficient in storing a sufficient amount of water. Continuous cereal cropping is becoming the main production system, but is found to be unsustainable. Crop production takes place under limited, variable, and chronically deficient precipitation. Precipitation occurs mainly during the winter months, so that crops must often rely on stored soil moisture when they are growing most rapidly in the spring months. Soils of the region are predominantly calcareous, frequently phosphate-deficient with variable depth and texture determining the maximum amount of water that can be stored and hence the effective length of the growing season.

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The SSA production systems are generally characterized by cereal/ legume mixed-cropping dominated by maize, millet, sorghum, and wheat. The major constraints to production are low soil fertility, insecure rainfall, low-productive genotypes, and lack of appropriate institutional support. The soils are structurally weak, are easily compacted, have low water-holding capacities, and are susceptible to both water and wind erosion. Soil management with conventional tillage systems appears suitable. Several improved genotypes, which are both stress-tolerant and tailor well under more productive cropping systems have also been identified.

Resume

L'agriculture pluviale dans les regions seches se retrouve principalement en Afrique, au Moyen-Orient, en Asie et en Amerique Latine. Dans ces conditions environnementales contraignantes de l'Afrique sub-saharienne (SSA), de l'Afrique du Nord et de l'Asie de l'Ouest (WANA), la pluviometrie est le facteur qui controle en fin le rendement des cultures, dependant, la recherche a demontre que des methodes de gestion appropriees du sols et des cultures peuvent considerablement accroitre l'efficience de l'utilisation des quantites limitees des eaux de pluies disponible. Ainsi, il devient possible d'accroitre la production par unite de surface pour chaque mm de pluie si les cultures sont bien mises en place et fertilisees, les adventkes sont contrdles et des rotation de culture avantageuses sont utilisees. Ceci doit egalement etre accompagne par une gestion judicieuse des terres afin d assurer la durabilite de la production et la conservation des ressources a long terme. Ces deux aspects resulteront en une augmentation des rendements et une meilleure efficiente de Vutilisation de Veau.

Les systemes de production de la region WANA sont domines par les cereales, principalement le ble et l'orge dans les zones plus humide et plus siche, respectivement en rotation avec des legumineuses a vacation alimentaire tel que le poids chiche et le lentille qui occupent seulement 10-15% de la surface plantee en cereale. Les jacheres ne permettent pas se stocker efficacement l'eau. La culture continue de cereale tend a devenir le systeme de production principale mais il a ete montre que ce systeme n'est pas durable. La production agricole a lieu dans des conditions de pluviometrie limitee, variable et chroniquement deficitaire. Les pluies tombent principalement durant le mois d'hiver, de telle sorte que les cultures doivent generalement s'appuyer sur l'eau stockee dans le sol au moment de leur developpement le plus rapide pendant le printemps. Les sols de la region sont domines par les sols calcaires, generalement deficient en P, et dont la profondeur et la texture variable conditionne la quantite maximale d'eau qui peut etre stockee dans le sol et donc la duree effective de la saison de culture.

Les systimes de production de l'Afrique sub-saharienne sont caracterises par des systemes de culture mixtes ciriales/legumineuses domine par le mais, le mil, le sorgho et le ble. Les contraintes principales pour la productivite de ces systemes sont le faible niveau de fertilite des sols, la pluviometrie aleatoire, les varietes a faible productivite, et l'absence manque de support institutionel adequat. Les sols saheliens sont mal structures, se compactent facilement, ont une faible capacite de retention en eau, et sont sensibles a l'erosion hydrique et eolienne. Lamenagement des sols avec des methodes conventionnelles de travail de sol semblent etre approprie. Plusieurs varietes ameliorees, tolerantes a la secheresse et adaptees aux systimes de culture plus productifs ont egalement ete identifiees.

Introduction

Across wide tracts of Sub-Saharan Africa (SSA) and West Asia and North Africa (WANA), water scarcity is a major factor limiting agricultural production. For millions of resource-poor dryland farmers, small total rainfall amounts and erratic, unreliable distribution constrain the achievement of stable, sustainable production systems providing satisfactory, low-risk livelihoods. However, even where water is very scarce, particularly in the driest areas, a surprisingly small proportion of the available water is actually transpired by the crop. Non-productive losses include surface runoff, deep drainage, evaporation from the soil surface and deep cracks, and transpiration by weeds. Viable farm-level techniques are needed to reduce those losses and so increase the proportion of available water transpired by the crop. The development of water-efficient cultivars may help in this, but in many situations major contributions may be anticipated from improved soil, crop, and cropping system management.

Crop production systems are characterized by their production objective, with yield being determined by climate, the degree of exploitation of natural resources (including human resources), and management. Rainfall in combination with temperature, soils, and socioeconomic factors are the major determinants for the multiplicity and complexity of the systems. In the drylands of SSA, rainfed food crop production systems are mainly based on pearl millet, cowpea, maize, and wheat, and to a lesser extent on sorghum and groundnut. In WANA, these systems are mainly based on barley, wheat, lentil, and chickpea. In both regions, integration with livestock is important for nutrient cycling and fertilization of the soils* During the last two decades, the annual increase in the output of the current production systems (e.g. 0.7% for millet; World Bank 1984) could not meet the increase in food demand (2.8%, Club du Sahel 1991). The WANA region has become the largest food importing region in the developing world, though it was a net food exporter less than 40 years ago, as a result *pf* a rapidly growing population but a less than 1% increase in agricultural production (Oram 1988). Considering that the production increase is primarily due to expansion of cultivation to marginal and fragile environments, the impact of research and extension on intensification of crop production systems has been limited. *Piiri* (1985) estimated that to meet regional food demands in the early 21st century, about 75% of increased production will have to come from increased yield per unit area. FAO (1987) also estimates for the WANA region that only 7% of the overall increase practicable in crop production can be achieved by expanding the cultivated area, a further gain of some 21% is thought possible from more intensive cropping, through fallow replacement and multiple cropping, leaving 72% to be achieved by increasing productivity. Hence, technologies to increase outputs and input-use efficiencies (e.g. water and nutrient-use efficiencies) are required that fit in the land-use system of resource-poor farmers, and conserve the natural resource base. In general, in addition to soil fertility management, two main agronomic strategies have been identified to intensify crop production systems: (1) soil and water management, and (2) cropping system management.

This chapter reviews the present status of research on cropping systems and crop complementarity in dryland agriculture in the light of increasing soil water-use efficiency.

Dryland Agriculture and its Traditional Crop Production Systems

In SSA, the main production systems are based on maize, millet or sorghum, and wheat. Most of the millet is grown in the region with average rainfall ranging from 400 mm to 900 mm with high variability. However, yield is more determined by rainfall distribution than annual rainfall *per se.* The significant features of rainfall variability in West Africa are the persistence and extreme magnitude of variability (Nicholson 1981). The average length of the growing period (LGP) in the millet-growing regions ranges from 60 days to 150 days. Studies on environmental risks, using long-term daily rainfall data, other weather parameters, and information on soils, have shown that the probabilities of drought are high during the crop-establishment and grain- filling phases (Sivakumar 1989). In West Africa, millet and cowpea are mainly grown on coarse-textured arenosols, luvisols, and regosols containing more than 65% sand and less than 18% clay. Whereas soils in the Sahel are more susceptible to wind erosion, water erosion predominates in the Sudanian Zone. In both agroecological zones, as the soil dries there is a tendency toward compaction of the upper horizon (i.e., hard setting or crust formation) causing problems with crop establishment and harvest of root crops (Stroosnijder and Hoogmoed 1984; Cooper et al. 1987a).

In traditional West African crop production systems, two main categories of millet are grown: a short-duration (70-100 d), photoperiod-nonsensitive type, and a long-duration (120-170 d), photoperiod-sensitive type. In the Sahel, millet is mostly grown as a sole crop, or as an intercrop with low populations of a legume. Intercropping enables the spread of risks over two contrasting crops, spreads labor peaks, and allows exploitation of the long rainy season during good years. Legumes, essentially cowpea and sometimes groundnut, also contribute to the maintenance of soil fertility through their N-fixing capacities. In both production systems, millet is sown in hills after the first rains in mid June/July with virtually no prior land preparation, at densities of 5,000-10,000 hills ha^{-1}, depending on the expected rainfall and the soil type. Because of crop establishment problems—mainly due to prolonged dry spells—repeated sowing is common. Weeding is done by hand. Generally, external inputs such as fertilizers or pesticides are not applied. Farmers apply a similar technology for cowpea cultivation. Yields are low, generally ranging from 100 kg ha^{-1} to 600 kg ha^{-1} millet grain, and for cowpea from 50 kg ha^{-1} (intercrop) to 250 kg grain ha^{-1} (sole crop) (Shetty et al. 1998). The latter are, however, at least as much grown for fodder as for grains. In the higher rainfall areas of the Sudanian Zone, photosensitive, late millet varieties are sown in June-July which mature on residual soil moisture, and are harvested in November-December. Maize and sorghum or short-duration millet are sown earlier in the season, and millet is grown as a secondary intercrop.

In WANA, 125 million ha of rainfed agricultural land receive between 200 mm and 600 mm mean annual rainfall with high variability in space and time. The soils of the region are diverse, and seven major soil groups account for 86% of the rainfed agricultural land in this region (Kassam 1981). Calcareous soils, formed from limestone residuum, predominate in the region with very variable texture, depth, slope, and stoniness. Calcium carbonate with its important role in the chemistry of soils causes generally high pH, thereby decreasing the availability of micronutrients (Fe, Mn, Cu, and Zn) or increasing B availability up to toxicity levels for crops. It also affects the availability of phosphate by fixation (Harmsen 1984). The organic matter levels are generally low, and in some soils, silty and sandy ones in particular, structural stability is poor which allows surface crusting due to rainfall, resulting in serious problems in seedling emergence and causing surface runoff (Cooper et al. 1987a).

The cropping systems are based on cereals, mainly wheat and barley, but with small areas of oats, rye, and triticale in some countries (FAO 1995). This system is integrated closely with livestock production, mainly sheep and goats (Cooper et al. 1987a). Wheat is the main cereal in the wetter areas (>ca.350 mm) where it is grown in rotation with either fallow or a range of other crops including barley, faba bean, chickpea, and lentil as winter-sown species, or melon, sunflower, and sesame sown in spring. Barley occupies the drier rainfall zones (<ca.. 350 mm) and is being extended into ever more arid areas to replace the now degraded vegetation of native steppelands. It is rotated with fallow, or increasingly grown in continuous barley systems, and used mainly for animal feed (Harris 1995). Introduction of forage legume production in rotation with barley has proved successful but the adoption rate is still low because of the socioeconomic conditions of the farmers (Osman et al. 1990). Barley and wheat are sown in November, and harvested between mid May and mid June in the lowlands. They are sown in October and harvested between mid July and mid August in the highlands. Lentils are sown in December-January and chickpea in early March, and harvested in mid May to mid June in the lowlands. In the highlands, both crops are sown in late March-early April and harvested between June and July lentils earlier than chickpea. All winter-sown crops are, because of their small canopy and low evaporative demands in the winter months, increasingly

exposed to drought in the spring or early summer when the evaporative demand is high, mostly at flowering and grain-filling stages, and are largely dependent on the stored soil moisture to complete their growth cycles (Cooper et al. 1987a). Intercropping of cereals or legumes between young olive trees (until fruit production) is becoming a common practice in the wetter areas because of the economic considerations of farmers.

For both regions, the importance of legumes for nutritious food and feed, their contribtition to subsequent cereal productivity through biologically fixed N, for breaking disease and pest cycles, and conserving farming resources and promoting sustainable agriculture has been documented by several researchers (Beck and Materon 1988; Summerfield 1988; Osman et al. 1990; Bationo et al. 1991; Harris et at. 1991; Hafner et al. 1992; Muehlbauer and Keiser 1994). Soil degradation, in the form of soil erosion and loss of soil organic matter and essential nutrients, is an increasing problem in both regions. Legume cultivation to increase soil organic matter, to fix nitrogen and spare soil mineral N, to eliminate cereal diseases, and to provide more flexible weed-control options offers a means of alleviating soil degradation in the face of inevitable crop intensification in dry areas. The integration of legumes in the cropping systems can reduce soil erosion substantially (Zougmore et al. 1998).

Strategies to Optimize Water-Use Efficiency

Recent agricultural research has resulted in innovations which can enable farmers to overcome many of the constraints that previously limited their crop yields. Mechanization of farm operations, proper and timely tillage, sowing date, plant geometry, new crop varieties, use of fertilizers, pesticides, and herbicides in suitable crop rotations can all help farmers in both increasing and stabilizing their production. However, in most rainfed farming systems, the major constraint that the farmers cannot influence remains the low and erratic precipitation. Within this context, innovations in soil and crop management are sought by agricultural scientists to make maximum use of the water available for crop growth. These will be discussed in brief in the next sections.

Soil and Water Management

Efficient capture of rainwater by soil requires that the infiltration rate equals the rainfall intensity for the entire duration of a storm. Otherwise, the excess water ponds on the soil, runs off, and is lost to the soil-crop water economy at that place. The occurrence/severity of runoff is a function of rainfall quantity and intensity, land slope, soil and surface characteristics, and plant cover. Of these, only the last two are potentially subject to control, although land slopes can be modified by building terraces. Most research on infiltration problems has concentrated on soil characteristics and how the limitations they impose on infiltration, either directly by surface sealing (or crusting) or indirectly by slow subsurface percolation, may be ameliorated. Surface crusting and restricted infiltration are also widespread problems in dry areas that may limit tillage opportunities. Technotegies to increase water availability affecting physical soil characteristics comprise mainly tillage and antierosion measures.

Tillage

Tillage operations (form, depth, frequency, and timing) and the management of crop residues are important in moisture conservation, particularly in dry areas. In rainfed agriculture in semi-arid regions, conventional tillage has mainly four purposes: (1) to prepare a seedbed, (2) to promote infiltration, (3) to conserve water within the soil profile, and (4) to prevent wind and water erosion. Where the land has been untitled since the previous harvest, in all but the lightest soils it is necessary to wait until the early rains have cumulatively moistened the soil sufficiently to permit the entry of an implement; a particularly vicious circle can arise where the crusted surface of 'hardsetting' soil resists infiltration and promotes the runoff of much of the heavy early-season rainfall. Research-derived recommendations to cultivate after harvest or before the next fains to assist infiltration are often inapplicable: one problem is the indigenous practice of *in situ* grazing of residues (maize, sorghum, and millet in SSA, barley and wheat in WANA), another that the power available for tillage is inadequate to match the natural strength of the dry soil. For the driest environments, it may be advantageous to rethink the cropping pattern and its relation to the tillage requirements for water infiltration and weed control. Currently, most staple cereals (overwhelmingly the predominant crop) continue extracting soil moisture beyond the end of the rainy season, so that after harvest many soils are unworkable until the next season. One solution is to give priority to the basic needs of the tillage operation (rather than those of a particular crop), and to increase the flexibility of the cropping system by introducing new varieties and species of shorter growth cycle (Jones 1987). The underlying logic in all cases should be soil management to optimize the provision of water to crops most able to utilize it productively.

Increasing the surface area of soil exposed to radiation and wind by deep plowing increases the loss of water through evaporation. Maintenance of the soil structure is the basic requirement for any package aimed at recuperating and maintaining the productivity of soil. Conventional or clean tillage has a long traditional and historical basis in rainfed cropping areas of the world. However, conservation tillage, which requires that stubble residues remain on or near the soil surface, is becoming more widely used (Bolton 1991). The no-tillage system is a powerful point of entry to solve the problems of soil erosion, soil fertility, and soils with low water-holding capacity (Lal 1976). Crop yields from no-tillage agriculture are usually as high as or higher than yields from crops produced by conventional tillage (Campbell et al. 1984). However, no-till systems might create other challenges that *need* to be coped with, such as weed and pest infestations.

Tillage research in the semi-arid areas of Southern Africa has been related to compaction and water conservation. Controlled traffic and deep tillage resulted in higher maize yields and dry-matter production, improved water-use efficiencies and improved rooting (Bennie et al. 1982). Berry and Mallett (1988) and Mallet et al. (1987) obtained better, or the same yields, with no tillage compared with conventional tillage.

In West Africa, millet soils are characterized by low surface porosity, poor structure, susceptibility to crust formation, and low water-holding capacities. Tillage incorporates organic matter, better controls weeds, improves moisture conservation, enhances root proliferation, thus increasing fertilizer-and water-use efficiency. Tillage, combined with other inputs such as fertilizer and improved cultivars, showed synergistic effects, which varied per year and cropping system. Nicou and Charreau (1985) reported an average yield increase of 22% with tillage from 38 experiments. In a millet-cowpea rotation, ridging and P fertilizer input increased biomass production by 10% for millet grains, 21% for millet straw, and 27% for cowpea fodder, but reduced cowpea grain yields (-8%; Klaij et al. 1994). In another experiment, tillage resulted in a 76-167% millet yield increase (Fussell et al. 1987; Klaij and Hoogmoed 1993).

Except on sandy soils, ridging is traditionally practised in Nigeria, Mali, Senegal, and Niger, and hilling or mounding in the Seno plain in Mali. Ridging reduces bulk density, concentrates fertility and organic matter, stimulates seedling growth and establishment, and may help reduce wind erosion (Fussell et al. 1987; Klaij and Hoogmoed 1993). Where infiltration rates are low, tied ridging leads to higher infiltration by reducing runoff.

Large-scale adoption of primary and secondary tillage methods may only be realized through the acceptance of animal traction to replace hand labor, which also reduces the labor requirement, especially for ridge plowing. In Southern Africa the rapid mechanization of the commercial sector from the 1930s onward has meant that little research on tillage using animal draught has been carried out (Morse 1996). Farmers' application of animal traction is, however, limited by the availability of the traction source, fodder availability, and equipment. Still, the use of animal traction seems a practical means to increase farmers' efficiency and improve conditions for intensified crop production (Shetty et al. 1998).

Within the WANA region, it is a regular practice to plow with a disc or moldboard to a depth of 20-30 cm each year, and then to prepare the seedbed with either a harrow or tine implement (Tully 1989; Cooper et al. 1987a). Several reasons for deep plowing are given by regional scientists and farmers: (1) increased water and soil conservation through prevention of runoff, (2) increased root growth, (3) disruption of a plow layer in the soil, and (4) weed control through deep burial of weed seeds (Durutan et al. 1991).

Many of the soils used for cropping in the region are self-mulching clays which are plastic when wet, and crack extensively when dry (Cooper et al. 1987a). Compaction and plow layers can develop on such soils if they are worked with heavy equipment when they are too wet (Hodgson and Chan 1984; McGarry 1984). This is mainly a problem on irrigated land; with the relatively light equipment used in the WANA region, it will cause no major problem in rainfed agriculture.

Within the region, deep tillage with moldboard in the spring of a fallow year is recommended for control of grass weeds in cereal crops, e.g. on the Anatolian Plateau of Turkey. This has an additional advantage of increasing surface roughness which enhances infiltration of rainfall late in the season. When followed by a shallow secondary tillage at the end of the rains, the practice leads to greater storage of soil water and increased wheat yield through soil mulch serving as an isolation layer at 8-10 cm of the soil surface (Durutan et al. 1989).

However, conservation tillage must be integrated with other elements of the system such as crop rotation (or sequence), because crop and pest interactions, fertilization, timeliness of operations, and other factors need to be considered for successful adoption of conservation tillage. For example, with crop rotation as part of the conservation tillage system, moldboard plows and discs can be used in segments of the rotation when the danger of erosion is slight or nonexistent. Noninversion-type equipment can be used in other parts of the rotation when needed to meet conservation objectives. Systematic and greater use of no-till methods is also facilitated in rotations (Allmaras et al. 1985).

In the long term, tillage can be expected to cause breakdown of the surface structure and increased crusting. In soils where the surface structure is inherently weak, cultivation rapidly leads to surface degradation, reduced infiltration, and failure of crops to emerge through the solid crusts which form. There are many such soils in the region and widespread evidence of the ensuing problems can be seen, particularly toward the drier margins of the cropped area (Cooper et al. 1987a). If these same soils are cultivated when they are dry, the lack of structure renders them very susceptible to wind erosion. Again, observations in the region suggest that this is a problem, but its severity is unquantified (Bielders et al. personal communication).

Where arable land in dry areas is cropped every year, interseason management may significantly affect soil moisture. Postharvest control of weeds, by tillage or grazing, is important whenever residual moisture is left in the soil profile by a crop that might have been shallow-rooted, short-cycle, or harvested premature. Even in the absence of weeds, soil mulching prepared by plow, sweep and harrow tillage moldboard and sweep, creating a dry soil surface layer with little or no stubble remaining on the soil (Guler et al. 1991), may prove beneficial in some situations. In the USA, systems utilizing zero-tillage, reduced-tillage, and/or crop residue retention treatments have been credited with reducing evaporation, as well as improving infiltration and reducing erosion (Bolton 1991; Papendick et al. 1991). However, such results have proved hard to reproduce in northern Syria (Jones 1997). Over six years of continuous barley and vetch-barley rotations, any effect of zero tillage, with retention of stubble and straw, on the dry-season soil moisture economy was negligible. The small improvements in crop performance, occasionally observed may reflect a marginal reduction in evaporation in young plant stands drilled directly into the standing stubble. Pala et al. (In press) reported that the general trends in soil water change are the same for all tillage practices. However, zero-tillage and minimum-tillage treatments leave more water at harvest compared with deep-tillage practices and are more energy-efficient, but no yield differences were observed. It should be noted, however, that these results were obtained for crop rotationsin the lowlands of West Asia. In the highland areas of the region, deep tillage during fallow has resulted in a higher infiltration rate and moisture storage, resulting in increased fallow-use and water-use efficiencies as well as associated yields (Durutan et al. 1989 and 1991).

Erosion Control Measures

In SSA, common water erosion control measures comprise stone bunds, stone lines, Zai, microcatchments, and rows of (leguminous) trees or perennial grasses (Roose 1989; Manu et al. 1994; Ouattara, Hien et al. in these proceedings). Small-scale amendments, using hand labor or simple mechanization, are often proposed for such measures. Numerous reports from SSA over many years have described ways to manage the soil surface to counter the effects of high-intensity rainfall on crust-prone surfaces and so prevent runoff. These include crust-breaking techniques, mainly employed soon after sowing to assist crop emergence and, more widely, various systems of ridging, on or slightly off the contour, often with transverse 'ties' at intervals across the furrows that restrict flow and create a pattern of infiltration basins (Dagg and Macartney 1968; Jones and Wild 1975; Stroosnijder and Hoogmoed 1984; van der Ploeg and Reddy 1988). However, improved infiltration may lead to higher nutrient losses through leaching, particularly in sandy soils.

Cropping systems also play a role in reducing soil erosion. For example, in Burkina Faso, a mixed crop of sorghum and cowpea reduced runoff by 20-30% and 5-10% compared with sorghum and cowpea alone, respectively, resulting in a reduction in soil erosion of 80% and 45-55%, respectively (Zougmore et al. 1998). In South Africa, Haylett (1960) found soil loss to be 44 times higher under continuous maize cropping compared with natural veld.

In addition, the strips between fields can also be of importance, e.g. strips of Vetiver grass *(Vetiveria zizanioides* and *V. nigritana)* found in Burkina Faso, Kenya, Mali, Nigeria, Tanzania, Tunisia, and Zimbabwe (Vietmeyer and Ruskin 1993). Other grasses that may be found in such strips include *Andropogon* spp. and *Panicum maximum.* Hedgerows of shrubs or small trees are also being planted as observed in Kenya (Kiepe 1995) and Senegal (Perez et al. 1998). Besides their positive effects on soil and water conservation, and reducing soil erosion, these strips contribute to the farmers' income (e.g. through weave activities, fodder for animals, traditional medicine, etc.). Hence, research should focus on integrated site-specific management, i.e., combining fertilization, crop and variety, and crop management (Shetty et al. 1998).

Similar systems are currently under test in WANA, for instance in Morocco (Boutfirass, El Gharous, El Mourid et al. in these proceedings). Larger-scale alternatives include contour strips (Carter et al. 1988) and various bunding and terracing systems. The latter may possibly be more appropriate in the wetter environments where soil and water conservation efforts focus more heavily on prevention of massive soil erosion. This is increasingly becoming a problem, particularly in the wetter hilly areas of northern Syria, where olive plantations have substantially expanded in the last decade. Therefore, a project on 'Stabilization of marginal steeplands' has recently been initiated by ICARDA in collaboration with the Syrian Olive Bureau with participation of farmers to reduce soil erosion through an integrated soil and land management approach and tree management techniques (LMP 1999).

Evaporative losses from crops, weeds, and soil surface are partly a function of wind speed and, in dry conditions, appreciable savings of water may be achieved by reducing the wind flow through a crop. In Niger, windbreaks of neem trees increased millet yields by approximately 20% (Long and Persaud 1988), while in Nigeria, *Eucalyptus* trees increased yields by 50% (Onyewotu et al. 1998). In addition, windbreaks may have another beneficial effect through control of wind erosion. Nevertheless, windbreaks are rarely part of indigenous systems (except for the traditional parkland system in the Sudano-Sahelian Zone which might yield similar effects); and if small farmers are to adopt them, they must be seen to have intrinsic economic value additional to any conservation role, as demonstrated by Jones and Harris (1993) for fodder shrubs and trees (*Acacia* and *Atriplex* spp) in WANA. Though potentially important, in neither SSA nor WANA is this innovation likely to make a quick impact.

Cropping System Management

During the last decades, attention has been paid to the design of more productive and stable systems through improved cropping system management. This comprises various aspects, such as the use of appropriate crop varieties, improved cropping patterns, relay-cropping, and cultural techniques. The suggested technology packages vary with agroecological conditions and farmers' objectives.

Crop Varieties

The identification of appropriate crops and cultivars with optimum physiology, morphology, and phenology to suit local environmental conditions, especially the pattern of water availability, is one of the important areas of research within cropping systems management for improved water-use efficiency.

Because rainfall in SSA has been below average in recent years and the probability of drought is high at the beginning and end of the growing season, the short-duration varieties developed must be useful to mitigate the effects of drought periods. Such cultivars—-with higher harvest indices—perform particularly well when grown under better conditions and management, and are considered an important component of management strategies in the drought-prone areas of West Africa. However, many of these cultivars are susceptible to insect pests and bird damage. Breeders should aim at well-adapted cultivars with higher yield potential, tailored to the specific agroclimatic conditions (Shetty et al. 1998).

In the WANA region, the principles are not very different from those in SSA. Breeding and selection for improved water-use efficiency, and use of genotypes best adapted to specific conditions can improve soil water use and increase crop yield levels. Breeding programs have similar goals: improvement of crops that are tolerant to cold, drought, and heat; are resistant to diseases and insects; have vigorous early growth; and are of good quality and high-yielding. Seasonal shifting, i.e., development of crop varieties that can be grown in winter under a lower evaporative demand, represents an additional challenge for breeders aiming at using scarce water more efficiently, since traits such as winter hardiness and disease resistance of the cultivars have to be improved. Development of crop varieties for early-growth vigor has been a major concern of winter-cereal breeders in WANA for many years (Ceccarelli et al. 1991). Early and complete canopy establishment to shade the soil and reduce evaporative loss from the soil surface can significantly improve the WUE of winter-rainfall crops in Mediterranean conditions and also, apparently, of summer-rainfall crops over much of the semi-arid tropics (Durutan et al. 1987; Gregory 1991).

Durutan et al. (1987) reported from on-farm trials that the highest-yielding wheat variety with recommended cultural practices provided 48% more grain yield (5.5 t ha^{-1}) than a local variety under recommended practices (3.7 t ha^{-1}), while the increase was about 650% compared with the local variety under local practices (0.85 t ha^{-1}). Pala et al. (1996a) reported that Cham 1, an improved durum wheat variety, provided between 3% and 86% grain-yield increase compared to Hourani, a local durum cultivar, under different water and nitrogen regimes in three distinct seasons. However, these results also show that improved cultivars may not render increased yields unless cultural practices are applied in an appropriate and timely manner.

Intercropping

Greater efficiency of resource utilization is expected from intercropping and mixed-cropping in a wide range of environments (Willey 1979; Francis 1989). However, these generalizations do not necessarily hold true in the more extreme environments. If rainfall is infrequent, evaporative losses from the usually dry soil surface may be relatively unimportant; and if water rather than radiation is limiting, intercrops grown beneath a cereal canopy—supposed to utilize low-intensity radiation that would otherwise be 'wasted'—may in fact compete heavily with the cereal for the limited water available. This has been demonstrated in Botswana, where intercropped cowpea had the same effect as weeds; in dry years, even very low populations were able to devastate the adjacent rows of sorghum (Rees 1986b). The rooting patterns of the intercrop, which are complementary in relatively moist conditions, may severely handicap the other crop component when rains are light. In wet years at Sebele, small grain-yield advantages from intercropping could be recorded, but over a run of years, intercropping greatly increased yield variation and the risk of total crop failure (Jones 1987). Such results, however, contrast strongly with the report of Swinton and Dueson (1988) that subsistence farmers in Niger practise forms of intercropping that exhibit high complementarity between component crops and reduce the risk of crop failure.

In West Africa, millet is often intercropped with cowpea, sorghum, maize, and groundnut. It has been shown that these traditional production systems have a total yield advantage and are more stable than sole cropping (Fussell and Serafini 1987; Shetty et al. 1987). Hence, management strategies to intensify millet systems must consider these advantages of intercropping which include profit maximization and risk minimization. In Mali, it has been shown that short and early millet cultivars sown about 2 weeks later than groundnut resulted in optimum productivity. The system maintained about 80% of the sole-crop groundnut yields plus about 40-50% of the sole-crop millet yields, yielding a Land Equivalent Ratio of 1.3-1.5. One significant observation was the reduced *Striga* infestation in millet/groundnut systems (N'tare et al. 1989).

In the southern Sahel, ruminant livestock are becoming increasingly dependent on crop residues for feed. The poor quality of millet stover has prompted the need for alternatives. Legumes other than cowpea could provide an important protein source. Recent studies have indicated that the perennial legumes *Stylosanthes hamata* (L.) Taub and S. *fruticosa* (Retz) Alston are particularly well-adapted to short rainy seasons (Garba and Renard 1991). *Stylosanthes* sown between millet rows at the rate of 4 kg ha^{-1} establishes and sets seed before millet is harvested. In India, yield improvement of pearl millet after *S. hamata* is equivalent to an application of 20-50 kg N ha^{-1}. After harvest, animals are allowed to graze the stylo and millet stover. In normal rainfall years, a production of 1.7 t ha^{-1} of dry matter could be obtained from stylo, and in good years, up to 5 t ha^{-1}. The millet/stylo association uses water efficiently, its efficiency exceeding largely that in a millet/cowpea system (Shetty et al. 1998).

Relay Cropping

Relay cropping, the practice of growing a short-duration, fast-growing secondary crop, usually a legume, after the principal cereal crop, is a well-known strategy in tropical regions. In the southern Sahelian zone, favourable rainfall years do occur and these must be fully exploited, ensuring use of any stored soil water. The need for such a strategy is greatest on sandy soils with low water-holding capacities and subject to high rates of evaporative loss. It is, however, difficult to predict whether or not the coming rainy season is likely to be favorable. Hence, recent efforts have been made to predict the essential characteristics of the approaching rainy season and tailor crop management decisions to them.

Analyzing long-term daily rainfall data for several locations in West Africa, Sivakumar (1988) concluded that rainy-season potential can be predicted from the relation between the date of onset of the rains and the length of the growing season. Stewart (1989) showed for the Sudano-Sahelian Zone that the duration of the rainy season can be reliably predicted from the date of onset of the rains, but suggested that detailed crop-specific, farm-level recommendations need more research. For instance, the average length of the growing season in Niamey is 109 days (Sivakumar et al. 1992), but if the onset of the rains is early, it may exceed 110 days (88% probability) or 130 days (49% probability). Experimentally, it was shown that this longer growing season could be exploited by growing a relay crop of cowpea for hay after a short- duration (90-100 days) millet crop (Sivakumar 1993). It avoids the competitive effects inherent in intercropping systems, while maintaining the advantages of rotating cereals with legumes. The economic feasibility of relay-cropping systems, however, are yet to be determined (Shetty et al. 1998).

Cultural Techniques

Timely cultural techniques, such as sowing with the first substantial rains, early weeding and thinning are important for increased use of soil water, and consequently, good yields. They also have synergistic effects with improved soil management practices, improved cultivars, and higher crop density (Fussell et al. 1987). In the intercrop production system, adjusting cowpea sowing time to the millet's growth cycle and the probable length of the rainy season is a technique that might increase cowpea yields (N'tare et al. 1989).

In the rainfed farming systems of WANA, the limited and variable moisture supply almost always defines the ceiling of crop production potential (Acevedo et al. 1991). Nevertheless, any husbandry technique that facilitates rapid canopy development and enables the crop to cover the soil surface, to shade out weeds, and also to reduce wind speed through the crop may, in most circumstances, be expected to increase crop competitiveness and water-use efficiency. Thus research results in WANA (Cooper and Gregory 1987) and also, for instance, under similar conditions in Australia (Hamblin et al. 1987) have emphasized the importance of achieving early crop cover through management practices. Practices that particularly contribute to this are: early sowing; selection of varieties with rapid early growth (under cool conditions); adequate fertilization; and adequate plant population and close spacing (Gregory 1991).

Sowing Date

Within the concept of improved WUE, water transpired by crops should be increased relative to evaporation from the soil surface. Transpiration efficiency is a function of the atmospheric saturation deficit, i.e., relative dryness of the air (Gregory 1991). Therefore, directing biomass production into periods of lowest atmospheric demand confers an advantage (Acevedo et al. 1991; Loss and Siddique 1994; Gupta 1995). This so-called "seasonal shifting" can improve the water-use efficiency of crops to a great extent, and allow for better use of limited (rain) water and/or large water savings in crop production (Seckler 1996). Timely sowing on the basis of a scientific method rather than a traditional method increased millet yields in Nigeria by 20-40% (Onyewotu et al. 1998).

In the winter-rainfall environment of WANA, despite temperature limitations to growth, it pays to sow early (late fall, early winter) so that as much as possible of the crop's growth cycle is completed within the cool, rainy winter/early spring period (Cooper and Gregory 1987). It has been calculated that in northern Syria, each one-week delay in sowing after the beginning of November will reduce wheat yields by 4.2% (Stapper and Harris 1989). Similar considerations lie behind the attempts to persuade WANA farmers to move from spring to winter sowing of chickpea (Silim and Saxena 1991). Yield increases of 30-70% have been reported from comparisons of winter- and spring-sown chickpea in favor of the winter-sown crop (Keatinge and Cooper 1984; Silim and Saxena 1991; Pala and Mazid 1992a). Likewise, early sowing of lentil in mid November increased seed yield by 20-25% compared with late sowing in early January (Silim et al. 1991; Pala and Mazid 1992b). Winter sowing results in the development of plants with a larger vegetative frame capable of supporting a bigger reproductive structure, leading to greater WUE and increased productivity (Cooper and Gregory 1987). Keatinge and Cooper (1983) reported that the water-use efficiency of winter-sown chickpea may be more than 100% higher than in the traditionally spring-sown crop. Similarly Brown et al. (1989) reported that the water-use efficiency of chickpea in northern Syria increased from 8.8 kg DM ha^{-1} mm^{-1} of evapotranspiration for spring-sown chickpea to 15.7 kg ha^{-1} mm^{-1} for the winter-sown crop.

Whether or not there is any analogue of this strategy for West and East African environments is not clear. Potential evapotranspiration is minimal between November and February. However, this period falls outside the rainy season and few if any soils have the moisture storage capacity to permit exploitation of this characteristic. For southern Africa, these months are July and August. It may make sense, however, to use this time to grow crops other than sorghum or millet where irrigation water is available.

Early sowing depends on the tillage/crop rotation system employed. In the highland areas of WANA, proper fallow tillage practices as well as sufficient precipitation will permit timely stand establishment of early-sown crops and result in higher yield by extending the period of vegetative growth under cereal-fallow rotation systems (Pala 1991). Delaying the sowing date will prevent crop germination and seedling establishment because of a rapid drop in air temperature starting generally in November. In the lowlands of the Mediterranean regions, where continuous cropping prevails as pure cereal or cereals-legume rotations, mid November was found to be an optimum sowing time for cereals (Photiades and Hadjichristodolou 1984; French and Shultz 1984; Keatinge et al. 1986; Acevedo et al. 1991) with 200-250 kg ha^{-1} yield decrease for every one week's delay from the optimum.

Crop Density Improvement

Economic crop yields arise from plant densities that minimize inter- and intrarow competition, which widely depends on environmental conditions (Bolton 1981). Cereal grain yield is the product of three components: (1) heads per unit area, (2) kernels per head, and (3) kernel weight. The seeding density, plant distribution, and genotype in a given area have substantial effects on these components. Increasing the seeding density can increase the heads per unit area, but may reduce the other two components (Darwinkel 1978; Joseph et al. 1985). Among yield components, there is compensation which tends to minimize yield loss when one component is reduced, but such compensation may not be complete. In the case of legume crops, the optimum plant density depends upon environmental conditions and the genotype. A sowing density of 300-450 germinable lentil seed m^{-2} generally resulted in the highest yield under Syrian conditions (Saxena 1981; Silim et al. 1990). The effect of increased seeding density was more apparent at the earliest sowing date, which also resulted in a higher yield, decreasing when the sowing date was delayed. Tall and erect chickpea varieties respond better to increased plant population than the spreading types (Singh 1981; Keatinge and Cooper 1984). The yields of these genotypes at a density of 50 plants m^{-2} are increased significantly compared to 33 plants m^{-2} though the lower plant density appears to be optimum for a wide range of environments (Saxena 1981).

N'tare et al. (1989) concluded from their millet/cowpea intercrop experiments that millet yields were not greatly reduced by increasing cowpea densities when soil moisture and fertility were adequate. Bationo et al. (1990) observed that low plant density in farmers' fields is the primary reason for low crop response to applied fertilizer. Manu et al. (1994) demonstrated on-farm the yield-increasing effect of increased millet population under adequate nutrition. In addition, low plant densities can give rise to below-optimal crop WUE because the ratio of soil evaporation to crop transpiration may be increased. Wallace et al. (1988), working on sparse millet crops in Niger, estimated that about 36% of the seasonal rainfall of 562 mm could be lost as direct evaporation from the surface. Higher plant density may, therefore, increase WUE and yield (Gandah 1988).

However, while the densest populations of sorghum at Sebele, Botswana, produced the most dry matter (per unit area and per mm of rain), they used up the available soil moisture sooner between the infrequent rainstorms. Thus, they became stressed earlier than did sparser crops, such that flowering was often delayed or failed completely (Rees 1986a; Jones 1987). Even where flowering occurred, intense competition in the denser populations kept individual plants very small, and with decreasing size the transfer of dry matter into the grain became rapidly less efficient. The greatest water-use efficiency of grain production was achieved by the sparser populations, which left much of the soil surface exposed to solar radiation. This finding applies not only to sorghum; commercial farmers in the dry parts of South Africa learned many years ago to grow their maize in rows 2-3 m apart. Van Averbeke and Marais (1992) found that the maize plant population for optimum yield decreased from 60 000 plants ha^{-1} with 650 mm water supply to 10 000 plants ha^{-1} when 240 mm water is available. Similarly, olive growers in the dry areas of WANA (e.g. in southern Tunisia with a mean annual rainfall of 200 mm) plant trees at very wide spacing, such that the canopy cover probably never exceeds 25%. Frequent tillage between the trees controls weeds and may also conserve soil moisture through a 'dry-mulch' effect.

Soil Fertility Management

Improved fertility improves water-use efficiency (Fussell et al. 1987; Klaij and Vachaud 1992; Brown et al. 1987; Cooper et al. 1987b; Cooper 1991) and can, therefore, stabilize production in poor rainfall years, and enable crops to exploit favorable rainfall in good years. Improved soil fertility also means improved yields. Farina (1989) shows an increase in national (South African) dryland maize yields from 0.8 t ha^{-1} to 2.0 t ha^{-1} over the period 1946-1987 with an increase in NPK application from about 10 kg ha^{-1} to 100 kg ha^{-1}. Venter (1979) found over 34 localities that maize yield losses can be reduced by 84% by increasing soil P levels from 5 to 25 mg kg^{-1}.

Given the inherent low fertility of many dry-area soils, judicious use of fertilizer is particularly important. Extensive work in Niger (e.g. Klaij and Vachaud 1992; Payne et al. 1991), Syria (Cooper et al. 1987a; Shepherd et al. 1987; Jones and Wahbi 1992; Matar et al. 1992; Pala et al. 1996b; Ryan 1997), in Turkey (Kalayci et al. 1991), and Tunisia (Mechergui et al. 1991) has demonstrated the benefits of appropriate fertilization on water-use efficiency and therefore on production and yield stability of millet in SSA and of winter-sown crops, especially wheat and barley, in WANA. In deficient soils, seedbed phosphate (usually together with a small dose of nitrogen) enhances the rate of leaf expansion, tillering, root growth, and phenological development, ensuring more rapid ground cover and canopy closure, and earlier completion of the growth cycle before rising temperatures increase the atmospheric demand (Gregory et al. 1984; Gregory 1991). The results also confirm the observation that in WANA responses to nitrogen are more important in wet years and locations, while in dry years and locations, responses to phosphate are dominant (Cooper 1991; Jones and Wahbi 1992; Pala et al. 1996b). Similar effects of fertility on the efficiency of water use have been reported for sorghum and millet in the Sahel (Onken et al. 1988). Small additions of N and P fertilizer increased yields, particularly of sorghum. All farmers in semi-arid environments face limits to crop and animal productivity. Yet, the use of fertilizer, labor, and other inputs can still make a difference for farmers wealthy enough to secure such inputs. For example, it has been found in the marginal regions of Burkina Faso and Ethiopia that the average grain output from the wealthier farmers can be twice that of the poorer farmers cultivating adjacent fields in the same communities (Webb and Reardon 1992).

Weed Control

Weeds compete with crops for water, nutrients, and light, resulting in lower use by the crop and therefore lower yields. However, the main effect of weed control is to increase the water supply available to the crop, although it also interacts with factors such as early sowing, which affects transpiration efficiency, and mulching, which reduces soil evaporation (Amor 1991). Weed control also interacts with management factors such as tillage, sowing date, seed density, fertilizer application, and crop rotations to improve efficiency of soil water use (Reinersten et al. 1984; Cornish and Lymberg 1986; Koudsieh et al. 1986; Tanji et al. 1987; Durutan et al. 1991).

Weed problems are dynamic, depending on changes in the farming systems applied. In minimizing the competition between the current weeds and crops for water, it is important that an integrated approach to control of weeds is adopted. Rather than relying on only one method, several possible alternatives should be used in a systematic manner, thus increasing the chance of developing economic and sustainable farming systems which are also efficient in water use (Amor 1991). The components of integrated weed control may include preventing weed infestation by using clean seed, proper and timely cultivation, crop competition, early crop development, crop rotation, grazing, hand weeding, herbicide use, biological control, etc.

Crop Rotations

There is increasing concern about the deterioration of integrated crop/livestock systems because of the high pressure put on these systems by the ever-rising demand for food and feed. Continuous cereal systems are increasing parallel to the increasing demand for human and animal consumption in WANA (Harris et al. 1991; Jones 1993; Harris 1994).

Cereal-fallow and continuous cereal cropping are the predominant crop rotations in WANA, but including legumes in the rotation has proved to be beneficial for sustainable crop production. For example, soil organic matter content was found to be lower under continuous wheat and wheat-fallow than under wheat-legume systems (Masri 1996). The decline in yield under continuous barley constitutes a major problem, but the causes of the poor productivity are not clear (Harris 1994). Intensification of rainfed agriculture by replacing fallow-cereal rotations with continuous cereal has several hazardous consequences in terms of the buildup of noxious weeds, pests, and pathogens, besides accumulation of allelophatic compounds. The cereal cyst nematode (*Heterodera avena),* soil-inhabiting fungi such as *Cochliobolus sativus* syn. *Helminthosporium sativum,* the take-all disease pathogen *(Gaeumannomyces graminis* var tritici), and the wheat ground beetle (*Zabrus tenebroides)* can cause a considerable yield decline in continuous cereal cropping systems of WANA (Saxena et al. 1991).

The major beneficial effect of legumes is generally attributed to their addition of fixed N to cropping systems. However, other effects such as increased cereal yield, improved water-use efficiency and soil physical parameters, and interruption of disease and pest cycles are also important (Beck and Materon 1988; Saxena 1988; Keatinge et al. 1988; Beck et al. 1991; Karaca et al. 1991). Harris (1995) compared seven years' data from a two-course rotation trial with wheat following wheat, medic, chickpea, lentil, vetch, melon, and fallow grown in a Mediterranean-type climate. The highest wheat (Cham 1) yield (2.26 t ha^{-1}) was obtained from a wheat-fallow rotation, and the lowest yield (1.00 t ha^{-1}) from wheat after wheat. The yield increases of wheat following various crops in the rotation compared with that of continuous wheat were 39%, 46%, 82%, 84%, 119% and 126%, respectively.

Legumes grown in a crop sequence with cereals have a positive effect on the system water-use efficiency (WUE). Because of their usually shorter growing period, some water may be left in the soil profile for the subsequent cereal crop, increasing the latter's productivity (Karaca et al. 1991; Harris 1995). Compared with the cereal-fallow system, cereal-legume rotations produce yields every year, thus increasing the system's overall WUE and its output in terms of quantity as well as nutritional quality (Pala et al. 1997).

In the Sahelian environment, Bationo and Vlek (1997) also demonstrated the benefits of a cereal-legume rotation for sustaining crop productivity. In southern Niger, millet-cowpea or millet-groundnut rotations doubled millet production over a four-year period (A. Bationo, personal communication) compared with continuous millet. Similarly, it was observed that millet-cowpea rotation had an effect equivalent to the addition of approximately 30 g N ha^{-1} yr^{-1} based on on-farm trials. It is worth mentioning that the beneficial effect of crop rotation cannot be attributed solely to increased N availability since most of the above-ground legume biomass is exported from fields for use as fodder. Likewise in southern Africa it is well-known that when grain crops (e.g. wheat) are grown in rotation with annual legumes, soil fertility is conserved and diseases can be prevented (Wiltshire and du Preez 1993).

Conclusions and Future Research Needs

Irrespective of the research results mentioned in this paper relating to improving water-use efficiency and hence production levels, stability, and sustainability, large amounts of rainwater are still lost and/or inefficiently utilized in farmers' fields. The possible mechanisms of losses and inefficiency are many, varied, and not always well-quantified. Further, at different locations, it is different subsets of those mechanisms that need to be understood and remedied—within the local human and socioeconomic context—if actual production per unit area is to reach the agricultural production potential in the dry areas of WANA and SSA. Biophysically, solutions to many of the problems will require the improvement of soil, water, and crop management at the farm level: first, to increase the capture and retention of incoming water; and second, to maximize the proportion of that water productively transpired by the crop. The choice of crops for the production systems, cultivar, the sowing date, plant density, fertilizer management, and control of diseases, insects, and weeds needs to best suit the local environmental conditions.

Given the low and erratic precipitation for crop production in the dry areas, research should be focused on improving water-use efficiency associated with increased production per unit area, and improved production stability. Adaptive research and a farmer-participatory approach, building on past experience, are the key issues for identification of acceptable techniques that match local needs and available resources, if potential yield levels obtained in on-station research are to be achieved in farmers' fields. Collaboration and exchange of information between agricultural scientists, and establishment of close linkages between scientists, extension workers, and farmers will allow a more rapid and sustainable solution to the food production problems and inefficient use of limited water resources. There is an urgent need for an integrated approach to simultaneously optimize soil water and nutrient use by crops in dry areas for greater efficiency and sustainability. For too long have these two aspects been researched independently. An integrated catchment management approach where soil water and nutrient balances are determined as per the land-use pattern should be investigated. This is a broader natural resource management perspective that can also supply information to off-site, downstream soil and water users.

In future, investigations on optimizing the use of water for a cropping system have to be focused not only at the level of a single field, but rather at the level of a watershed. Crop simulation modeling linked to GIS to capture spatial variability can facilitate the identification of best-bet options for farmers in a given biophysical environment. Linkage of biophysical to bioeconomic models should be a further step to match identified strategies with the socioeconomic conditions of resource-poor farmers in the semi-arid regions of WANA and SSA.

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Combating Nutrient Depletion Consortium: Goals, Objectives, and Activities

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Abstract

The Combating Nutrient Depletion Consortium (CNDC) is, like the OSWU Consortium, part of the Soil Water Nutrient Management Program. Its goal and objectives, as well as its methodology and activities are presented in this paper. Collaboration with OSWU will enable sharing of experiences and building knowledge interactively, and avoiding duplication wherever possible.

Resume

Tout comme OSWU, le consortium sur la lutte contre l'epuisement des elements nutritifs des sols (CNDC) fait partie du programme sur la gestion de l'eau et des elements nutritifs du sol. Ses buts et objectifs ainsi que ses activites et sa methodologie sont prisentes ici. Une collaboration entre le CNDC et OSWU semble judicieuse en matiere d'echange d'experiences et de developpement interactif des connaissances et afin d'eviter la duplication des efforts partout ou cela est possible.

Introduction

The knowledge gap between Africa and developed countries is widening due to the minimal advances made in that continent in information technology and decision-support systems. The success of the Combating Nutrient Depletion Consortium (CNDC) will depend on reducing this knowledge gap, by familiarizing researchers and other personnel with systems tools and methodologies so that the collaborating partners can themselves apply them in disseminating and extrapolating nutrient-management packages to farmers.

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The CNDC is one of the three consortia of the Soil Water Nutrient Management Program. It is a-sister consortium of the OSWU Consortium. CNDC will combat nutrient depletion through a holistic systems approach in the humid and subhumid tropics of sub-Saharan Africa and the African Highland Initiative (AHI)regions where reversing soil nutrient depletion and improving soil fertility are the major issues.

The purpose of this paper is to give an overview of CNDC's goals, objectives, and activities in order to facilitate collaboration with OSWU and to avoid duplication of efforts.

Goals and Objectives

The goal of CNDC is to *"reverse the soil nutrient depletion process and develop methodologies and a framework for effective transfer and extrapolation of nutrient-management technologies."*

In pursuit of this goal, the Consortium has the following objectives:

- To validate and use decision-support tools for combating nutrient depletion and development of sustainable production systems with regard to nutrient balance, crop productivity, and environmental and biological diversity.
- To enhance extrapolation and dissemination of results from the benchmark sites to farmers by training scientists from the region in the application of systems methodologies.

Methodology and Expected Outputs

The international convenors are the International Fertilizer Development Center (IFDC), Lome, Togo, and Tropical Soil Biology and Fertility (TSBF), Nairobi, Kenya. The Institute of Agricultural Research (IAR)/Ahmadu Bello University (ABU), Zaria, Nigeria, and the Kenya Agricultural Research Institute (KARI), Kenya, are the NARS co-convenors.

The core of the national partners of the CNDC is formed by the members of the West African Fertilizer Management and Evaluation Network (WAFMEN) coordinated by IFDC and the African Network for Biological Management of Soil Fertility (AfNet) of TSBF. The research and development activities of CNDC will build on the complementary strengths of these two networks.

In addition, it will collaborate with the Ecoregional Program for the Humid and subhumid Tropics of sub-Saharan Africa (EPHTA). The joint actions with EPHTA will provide added value by (1) securing full collaboration on nutrient-depletion research; (2) avoiding duplication; (3) bringing together the necessary multidisciplinary expertise to address the objectives of the project; (4) profiting from the complementary research being conducted throughout EPHTA; and (5) rationalization of institutional structures by working within the EPHTA set up.

The activities will be linked with four benchmark areas: the Northern Guinean Savanna, the Southern Guinean Savanna, Coastal Derived Savanna, and the degraded zone of humid forests.

The comparative advantage of the Consortium is its ability to bring together a critical mass (national and international experts) that can (1) validate the existing tools and methodologies that enhance extrapolation of nutrient-management strategies for soil fertility improvement; and (2) develop and implement innovative policy initiatives. Active farmer participation, on-farm validation of technologies, and confidence-building by training researchers and extension workers from NARS will improve the success of the Consortium's projects.

The expected outputs include, among other things:

- Validated decision-support tools for combating nutrient depletion;
- Identification of integrated nutrient management practices on site-, season- and crop-specific bases; and
- Increased institutional and human capacity for disseminating and extrapolating packages to farmers.

Activities in 1997 and 1998

In 1997, a CNDC Workplan Meeting was held (20-31 Oct). It was attended by representatives of four collaborating institutes: (1) the Department of Soil Science of the Ahmadu Bello University, Zaria, Nigeria (V.O. Chude and I. Amapu); (2) INRAB in Cotonou, Benin (M. Adomou, EPHTA coordinator for Benin, and J. Aihou Kouessi, Agronomy Division); (3) IITA, Ibadan, Nigeria (J. Diels, member of Balanced Nutrient Management System), and (4) IFDC-Africa, Lome, Togo (P. Dejean and U. Singh). The results of this meeting were:

- A CND proposal for 'Application of Decision-Support Systems for Nutrient Replenishment and Integrated Nutrient Management;"
- Consensus for collecting complete biophysical and socioeconomic data from ongoing and proposed research-station trials for ex-ante analyses using the simulation-modeling approach;
- The group also prioritized pertinent application of systems simulation for CND with respect to agroecological and socioeconomic sustainability.

The Project on Application of Decision-support Systems for Nutrient Replenishment and Integrated Nutrient Management (1998-2000) is being implemented by IFDC as part of CNDC activity. It is being carried out in collaboration with IITA, Ahmadu Bello University, Zaria, Nigeria, and the Institut National des Recherches Agricoles du Benin (INRAB). Work on the project is making good progress in the Northern Guinean Savanna (ABU) and the Coastal Derived Savanna (INRAB) zones. The expected project outputs include: (1) appropriate decision-support systems identified for CNDC application; (2) Ex-ante evaluation of nutrient balances and yield in key cereal food crops, annual cash crops, and perennial food crops; (3) validation and quantification of nutrient dynamics in these crops at two key benchmark areas of the EPHTA, the Northern Guinean Savanna and the Coastal Derived Savanna; and (4) training of personnel in advanced application of information technology and systems methodologies for technology transfer.

The collation of existing soil, climate, and crop data from the Northern Guinean Savanna (Zaria, Nigeria), the Coastal Derived Savanna (Benin) and selected sites in Togo began in November 1997 by IAR (Zaria), INRAB (Benin), and IFDC (Togo) to establish a natural resource base.

Historical experimental data from an experiment "Dynamics of Soil Nitrogen in Cereal-based Cropping System in Nigeria" conducted within the EPHTA region has been used to validate the CERES-maize model by IFDC.

A training program on computer simulation for crop growth responses to management was held in 1998 (Feb 9-14, 1998). The purpose of the workshop was to acquaint NARS partners with the use of modeling and simulation in experimentation and technology transfer.

A proposal on "A User-Oriented Approach to Application of Systems Simulation for Soil Fertility Improvement and Technology Transfer in Sub-Saharan Africa" (1999-2003) was submitted to the Ecoregional fund. The goal of the proposed project is development and diffusion of sustainable production systems for two sub-Saharan ecoregions, to assure food security, to trigger rural and economic development, and to arrest environmental degradation. Proposed collaborating institutions on this project are IFDC-Africa (Lome), TSBF (Nairobi), IITA (Ibadan), IAR/ABU (Zaria, Nigeria), INRAB (Cotonou, Benin), CIAT (Cali, Colombia), CRIG (Accra, Ghana), and ICASA, Wageningen Agricultural University, and the University of Hawaii.

Conclusion

The success of the Combating Nutrient Depletion Consortium (CNDC) will depend on reducing the knowledge gap between farmers and researchers and promote efficient use of inputs to combat nutrient depletion to attain sustainable production systems. CNDC, as one of the three consortia of the Soil Water Nutrient Management Program, is by virtue of its geographical location, the most appropriate body to have direct links with the OSWU Consortium.

Part C. Impact and Information Tools

Use of Decision-Support Tools in and Impact of Optimizing Soil Water Use Research in Burkina Faso

B Ouattara, S Youl, and J B Sare[1]

Abstract

A literature review has been carried out to evaluate the impact of research related to the optimization of soil water use in agriculture in Burkina Faso, as well as to assess the current knowledge, use and future perspectives of database management and decision-support tools. It appears that the impact of rainwater management technologies on the livelihood of producers and on the environment is largely dependent upon the prevailing agroecological conditions. For instance, soil and water conservation technologies that make use of indigenous know-how in the more arid areas result mostly in socioenvironmental rather than economic benefits for the producers. On the other hand, the use of soil tillage for more efficient rainfall water use, which is largely dependent upon the purchasing power of farmers, is more frequent in the cotton belt of the country where this practice generates substantial financial benefits. The existing management tools for this type of technical information for a more efficient decision support are very diverse and have been developed only recently. Since the 1980s, there has been a real tendency for a more specific use of such tools by national research institutions as well as some NGOs and international organizations. Climate simulation models have been the most used tools for making predictions related to agricultural production. The need to create access to such tools in other areas as well is pressing, and is most often linked to the development of geographical information systems.

Resume

Une revue de litterature a ete realisee pour faire le point sur l'impact des recherches dans le domaine de l'utilisation optimale de l'eau en agriculture au Burkina Faso ainsi que sur l'etat des connaissances, l'utilisation et les

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perspectives en matiere de gestion de bases de donnees et d'outils d'aide a la decision. Il apparait que l'impact des technologies de gestion de l'eau pluviale tant sur le niveau de vie des producteurs que sur l'environnement est largement dependant des conditions agro-ecologiques. Ainsi, les techniques de conservation des eaux et des sols qui valorisent le savoir-faire local dans les zones plus arides procurent aux producteurs des benefices beaucoup plus socio-environnementaux qu'economiques. Par contre l'utilisation du travail du sol pour une meilleure economie de l'eau pluviale, tres tributaire du pouvoir d'achat des paysans, est beaucoup plus accentuee dans la zone cotonniere du pays ou elle genere des benefices substaritiels. Les outils de gestion de ces informations techniques pour une aide efficace a la decision sont tres diversifies et ne se sont developpes que tres recemment. Depuis les annees 1980, on observe un reel engouement pour l'utilisation de fagon plus specifique de ces outils par les Institutions nationales chargees de la recherche ainsi que certaines ONGs et structures internationales. Les modeles de simulation des phenomenes climatiques ont ete les plus usites pour faire des previsions dans le domaine de l'agriculture. Toutefois, la necessite de disposer de ces outils dans d'autres domaines se fait de plus en plus sentir et est le plus souvent lie au developpement des systemes d'information geographique.

Introduction

Much research has been carried out in the domain of optimizing soil water use (Ouattara, Hien et al. in these proceedings), but the impact of this research has been generally very low. Information tools may help in increasing this impact.

Information tools for decision support [databases, models, and geographical information systems (GIS)] have been a recent development in terms of users but also in their diversity and nature. In the case of databases, one can distinguish the classical bibliographical databases (with documentaries), the specialized databases in research (agronomy, livestock, health), and databases containing other types of data made available for use by governmental and nongovernmental organizations (NGOs), and national and international organizations. The needs of users of information tools vary considerably, with each user having a specific purpose. Users in Burkina Faso are, for instance, the university (students and teachers), researchers of the National Center of Scientific and Technological Research (CNRST), national services (National Meteorology, Geographical Institute, Institute of Statistics and Demography, etc.), NGOs [e.g. Food Early Warning System (FEWS)], and other institutions (e.g. World Health Organization (WHO)-ONCHO, Antenne Sahelienne of the Wageningen Agricultural University).

This paper describes in detail the impact pf past research on optimizing soil water use and the use of information tools in Burkina Faso.

Impact of Research on Optimizing Soil Water Use

Various soil and water conservation (SWC) techniques have been developed in Burkina Faso (Ouattara, Hien et al. in these proceedings). Some of these have contributed to improvement of traditional know-how (stone bunds, land dams, Zai) in the semi-arid northern and central zones of the country. However, this has not been the case with water-saving techniques (plowing, earthing-up, tied ridges, etc.), because they require high investments which farmers cannot afford. This means that the impact of these technologies on the standard of living of the producers and on the environment will depend significantly on the means of the farmer or the availability of credit.

Impacts of Stone Bunds and Zai

Stone bunds and Zai have been implemented in a very large number of villages, but no data is at hand on the actual number or the area covered by these SWC techniques. An insight into the phenomenon can be had from the work of the Land Resource Management on the Central Plateau Project (PATECORE) in 240 villages to improve 10,000 ha (Hinchcliffe et al. 1995). In six villages, an average of 21% of the cultivated area was protected by stone bunds, 8% by earth bunds, 12% by grass strips, and 39% by two or more of these measures (de Graaff 1996). Kunze et al. *(1998)* report that women (of 86 households) less often receive plots with conservation works.

Reij (cited by de Graaff 1996) observed *400 fields* over a five-year *period and* reported that with stone rows there was a yield increase *of 100 kg* ha^{-1} (35%) *in dry years* (about 405 mm rainfall) and 360 kg ha^{-1} (65%) in wet years (about *640* mm) compared with fields without stone rows. For Zai, yield increases ranging from 300 kg ha^{-1} (35%) to 1100 kg ha^{-1} (220%) were reported (Kabore et al. 1994; Anon, cited by Maatman et al. 1998). The yield surplus obtained in these zones is entirely intended for household consumption and provides the farmers a certain food security by minimizing the drought risk. HinchcHffe et al. (1995) report that a deficit of 645 kg ha^{-1} was turned into a 150 kg ha^{-1} surplus by using these technologies. Data of Kunze et al. (1998) suggest that family plots with conservation works result in higher financial benefits.

An aspect of the environmental impact of stone bunds is reduced soil erosion (de Graaff 1996). Also, realizing their impact on water-holding capacity, many villages now have management committees to take control of conservation efforts in the village (Batterbury 1994). De Graaff (1996) reported that 13% of 100 farmers believed that stone bunds increase soil moisture, white 47% mentioned maintenance of productivity, and 23% pointed out reduced soil losses as the main functions of these bunds. Zai and stone bunds were used for restoration of degraded lands for agricultural or pastoral uses. Thus, in the central and northern parts of the country, farmers are showing greater interest in "forestry Zai". This technique consists of sowing seeds of weeds and small shrubs together with application of manure in the sowing holes of the Zai. Such a technique has beneficial effects on the environment because it raises agroforestry parks with a large number of species on previously bare soils (Hien 1995).

The Zai and stone bund practices-together or alone-provide farmers very significant socioenvironmental benefits. Since they do not require high financial investments, they are accessible to a large part of the rural population, with an estimate of more than 500 m ha^{-1} of stone bunds in the northern and central plateau areas (Kabore et al. 1994). Many case studies (Kabore et al. 1994; Bertelsen and Ouedraogo 1994; Bazongo 1998; Sedogo 1998) have reported a total cost/benefit ratio of about 4 for millet and between 2 and 3 for sorghum when stone bunds and Zai techniques were applied (benefit is the monetary value of the surplus yield in the local market). This implies that one needs an average of two to four years before the investment is recovered (Bazongo 1998). Labor costs represent about 50% of the total investment. These techniques require so much labor that they are being executed as community work. Future research needs to quantify better these socioenvironmental benefits and evaluate the hidden costs resulting from the different ways of support from NGOs and development projects to the rural population.

The enduring concern of research to improve these traditional techniques has brought together research and development institutes to join forces. This was seen in the enhanced collaboration among different partners in executing some important development projects such as the Special Project for Soil and Water Conservation (SWC/AGF) and the National Programme for Land Management (NPLM). At the scale of the Sahel, the Environmental and Agricultural Research Institute (INERA) ensures the coordination of the Natural Resource Management and Farming Systems (NRM/FS) Pole which is a subregional initiative involving the country members of the Inter-Countries Committee to Combat Drought in Sahel (CILSS). INERA, because of its large experience in the area of SWC techniques, has been assigned leadership in this domain within this Pole.

Impacts of Water-Saving Techniques

Different water-saving techniques under animal traction or mechanized cropping were widely diffused in the cotton areas of the country. They have contributed to improvements in cotton and maize production, which provided substantial revenues to farmers. The development of the cotton industry is thus a great advantage to facilitate their adoption.

Application of these techniques requires high financial investment (materials, agricultural inputs), which limits their adoption, especially in the food-producing zones. However, it appears that farmers using these techniques in high-risk, water-deficit areas have managed to secure their production and ensure a sustainable self-sufficiency in cereal production.

At the institutional level, INERA has worked on this effort for four years (1989-1992) with the International Research Network on Drought Resistance (R^3S). The results obtained have aroused the possibility of creating within INERA a kind of subregional laboratory to capitalize on the obtained results.

Databases, Models, and GIS

Databases and GIS

The existing databases in Burkina Faso relate to:

Weather. Available at the Meteorological Service (wind, sunshine, rainfall, temperature, etc.) derived from the numerous synoptical stations all over the country;

Soil type. Available at the National Soils Bureau (BUNASOLS);

Maps and photographs. Available at the Geographical Institute of Burkina Faso (IGB);

Research. Available at INERA and includes various domains (production systems, natural resource management, documentary systems);

Socioeconomic information. Available at the Directorate of Agropastoral Statistics; and

Population. Available at the Institute of Statistics and Demography.

Some databases have free access; others—the more specific ones—are less so and often coupled to models and decision-support software. This is the case with WHO-ONCHG where the epidemiological database has been developed to feed simulation models to follow an epidemic and to help in taking a decision whether to intervene or not in a specific zone. Another example is the case of BUNASOLS which is exploiting its database on soils as a commercial activity.

GIS is a set of tools to create, modify, manage, analyze, and represent spatial data representing a unit that can be georeferenced. GIS was rapidly taken up and applied by IGB, and is now also being used by development projects and consultancy firms. In research, Atlas-GIS was the first software, but now ArcInfo, ArcView, MapInfo, and Alliance are also being used. The cartographic and geographical databases are being used to produce thematic, administrative, and touristic maps.

Models and Decision-Support Systems

In Burkina Faso, various types of models are being used by different specialized institutions such as WHO, the International Centre for Research-Development on Livestock in Sub-humid Zones (CIRDES), INERA, planning services (Planning Department, Institute of Statistics and Demograhy, etc.), and also by NGOs. In research, biophysical models (simple or complex) and socioeconomic models are being extensively used, especially water-balance models. However, it needs to be noted that use of models is limited due to certain constraints (e.g. lack of awareness of models, and their updating and acquisition). Among the best-known are the models for: (1) crop water balance (BIP, Probe, Sanji), (2) rainfed crop growth (CP-BKF3 Cropsyst, Cropgrow), (3) nitrogen fertilization of maize (STD3FAM), (4) fertilizer response (N, P, K i.e., response curves for different crops), and (5) crop nutrient balance. Socioeconomic models include those to follow the functioning of households (NUTSHELL) and others used by INERA and the university.

The use of decision-support systems is limited and specific in each case. These go together with the models and databases being used. In the case of WHO-ONCHO, it is a system to follow the evolution of an epidemiological situation. When a certain threshold is reached, there is an alert and a decision has to be taken regarding intervention. This is also the principle being used by FEWS based at Ouagadougou. This NGO uses satellite data and indicators to estimate crop yields and to judge whether there is famine risk or not. Other groups use remote-sensing techniques for monitoring crop development, land-use changes, etc. (Reenberg and Rasmussen 1990; Adriansen and Rasmussen 1993; Matheson and Ringrose 1994; Groten and Ilboudo 1996).

Bioeconomic models, used as a decision-support system, are applied to analyze different scenarios including use of SWC techniques and policies (Deybe et al. 1994; Boussard et al. 1996; Deybe and Robilliard 1996; Ouedraogo and Bertelsen 1997; Maatman et al. 1998; Barbier 1998) and effects of extension (Ouedraogo and Illy 1999).

Crop water balance models allow, through the study of climatic and agronomic parameters, estimation of crop yields on the basis of calculated indices (van Noordwijk et al. 1994; Oumarou et al. 1997). It is thus possible to establish forecasts of the cereal balance and to take decisions in case of large estimated deficits.

The model CP-BKF3 simulates crop yield under different scenarios (of water and nitrogen use, soil water conservation techniques, etc.) for a field with or without plowing (Bazi et al. 1995; Verberne et al. 1995).

The model for following agricultural exploitation, NUTSHELL (Vlaming and Wijk 1997) allows establishment of the nutrient balance (N, *?,* K) for the entire exploitation, and estimates the losses of nutrients and, therefore, the risks of degradation. One can also address the problem of how the exploitation can restore these nutrients. This model also calculates the partial budget of the exploitation and allows indication of the most profitable activities for the farmer.

These different models are fed by collected data put in a database. As mentioned earlier, often the database is linked to the model that it feeds.

Evaluation of Use of Models and Future Needs

In terms of use intensity, models are in full bloom in various areas (research, planning, and development). This development is sustained by a qualitative evolution of human resources (computer scientists, statisticians) and a decline in equipment costs (computers, etc.), and further helped by better communications and easier access to media.

The potential domains and users remain the areas of research (academic, agricultural), development organizations, planners, and decision-makers. Urban centers (Ouagadougou and Bobo-Dioulasso) remain the predominant places for use of these information tools. It is therefore needed to plan their development in parallel with the development of activities in these cities. The project in the framework of the Desert Margins Program, however, is developing a multiscale decision-support system coupled to a GIS, which will link researchers, development organizations and other stakeholders in a village and commune (i.e., a 'district') in the north of the country (van Duivenbooden et al. 1998). Of importance will be the inclusion of old and new technologies that optimize soil water, use. Development of such a tool for watersheds is another challenge.

Conclusions

There is currently wide interest in the use of models and decision-support systems. This is demonstrated by the diversity of users as well as areas of application of these tools. However, it has to be noted that various problems (idea and/or adaptation, financing, implementation, etc.) have slowed down the evolution of these models and databases. On the other hand, an increasingly rapid evolution can be expected due to favorable factors (e.g. development of Internet, decline in the cost of equipment, specialized training courses for'educated young technicians and scientists). Using these information tools in the research for optimizing soil water use could help to increase impact in the mid to long term on increasing the understanding of the principles of soil, water, and plant relationships, extrapolating the outputs from site-specific field trials to wider areas, for prioritizing research and improved decision-making, and carrying out constraint analyses for alternative production systems.

The impact of past soil water use optimizing research entailed environmental and socioeconomic benefits. Impact of technologies that demand more financial investments has been low due to the absence of credit. Future research should help in better identifying the zones of application of these technologies.

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Impact of Optimizing Soil Water Use Research, and the Need for New Information Tools and Methodologies in Egypt

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Abstract

Integrated research activities in the domain of optimizing soil water use are badly needed in the area of rainfed agriculture in Egypt. Use of decision-support systems (DSS), models, geographical information systems (GIS), and databases is of utmost importance to plan and implement any developmental activity. Assessing the impact of past research is essential to formulate future plans and activities relating to optimizing soil water use.

Resume

Des activites de recherche integrees doivent urgement etre entreprises dans le domaine de l'optimisation de l'eau du sol en agriculture pluviale en Egypte. L'utilisation de systemes d'aide a la decision, de modeles de simulation et de bases de donnees est imperative pour la planification et la mise en oeuvre de toute activite de developpement. L'evaluation de l'impact des activites de recherche passees est essentielle pour decider des besoins futurs et des activites a mettre en oeuvre dans le domaine de l'optimisation de l'eau du sol.

Introduction

The main constraint of agriculture in Egypt is the limited water resources. Rainfed agriculture occupies about 2-3% of agricultural land. Although this may not be significant in relation to the total agricultural land, it is important to local communities and economies. Better management of resources would contribute to conservation of natural resources and better sustain the livelihood of these local communities. The latter are important objectives of Egypt's Environmental Action Plan (EEAA 1992).

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Soil and water management for maximum or optimum agricultural production (crop and livestock) taking into account conservation of environmental resources must be the basis for optimizing soil water use in any ecosystem.

The purpose of this paper is (1) to assess the impact of past research on optimized utilization of rainwater and use of other water resources to supplement rain under rainfed conditions; (2) to evaluate its effects on sustainability of the natural resource base; and (3) to summarize the use of information tools and technologies for better decision-making and prioritizing agricultural research and development.

Impact of Soil Water-Use Efficiency Research and the OSWU Consortium

Agriculture in Egypt is mainly irrigated agriculture; rainfed farming is done on only 2-3% of the agricultural land, and especially in the North-Western Coastal Zone. Because of this and some other factors (global, sociological, and political), there have been only a few scattered research activities with respect to rainfed agriculture. A major problem is that there *is* almost no continuity of such research and not enough basic infrastructure (e.g. weather stations) to support research in the region. Much of the important technical data needed is not available either because of the improper design of the research or the very narrow objectives. Moreover, there was almost no research plan for the region or much governmental interest as the area was not on the priority list of agricultural production until recently. Only in the last few years have some institutions started placing more emphasis on optimizing soil water use in rainfed agriculture (e.g. the ICARDA Nile Valley and Red Sea Regional Program, Matrouh Resource Management Project, Desert Research Center).

Past Research

As mentioned before, appropriate research for rainfed areas in Egyptian agriculture has been neglected (the available results are reviewed by Moustafa and El-Mowelhi in these proceedings). Consequently, there has been almost no impact of such research.

The net per capita farm income from crops and livestock in the rainfed areas of Egypt in 1992 was below the poverty line (around LE 590) for the small (50% of the population) and medium farmers. Even after including nonfarm income, small farmers would still be below the poverty line. Incidence of drought is common in the region and aggravates the poverty problem. In such drought years, the total income even of medium farmers may drop below the poverty line (WB 1993).

In such a situation, food security is doubtful and not guaranteed except through government support and subsidies.

All agricultural activities (crop production and livestock) in the rainfed regions of the country (northwest and northeast) are mainly dependent upon rainfall. Cultivation depends on various forms of water harvesting. In the absence of scientific soil and water conservation measures, water losses and soil erosion occur. On the other hand, the passage from traditional pastoralism to a more sedentary agriculture without adequate technical support has contributed to natural-resource degradation (overgrazing and soil erosion). The ecosystem in the region is now fragile.

There is no effective mechanism to tackle problems at the producer level, to identify priorities for adaptive research programs, and to facilitate regular updating of ongoing research and extension programs. As a result, the performance of research in meeting the needs of the region has been poor. In the past, there was almost no capacity building of NARS in this domain of research.

Future Expectations of OSWU Activities

Activities of the OSWU Consortium must be interdisciplinary and integrated in order to optimize soil water use. Carrying out basic and demand-driven research will result in many changes with respect to rainfed agriculture in Egypt. These should have impact on the following aspects.

Food Security

The research activities of OSWU must focus on producing a positive impact on overall agricultural productivity in order to increase the living standards of the beneficiaries-who are mainly poor farmers-and raise their income above the poverty level. Perhaps equally important, emphasis on water harvesting and off-farm activities will help to stabilize incomes, and thus minimize the effects of bad years. Food security must be the ultimate target.

Resources

Conservation of natural resources and their efficient use are the main objectives to be considered. The results of demand-driven research and their application will have a beneficial environmental impact by reversing the deterioration of fragile ecosystems and by reducing desertification. This will be accomplished through construction of an environmental infrastructure, watershed management in selected wadis, improved rangeland management, and agroforestry. Some of the water harvesting technologies used to increase productivity, such as dikes and contour ridging, have the added benefit of reducing soil erosion. Promoting the use of improved forage species, encouraging reduction of livestock numbers, and promoting better rangeland management would reduce overgrazing of rangelands.

In the last few years, the Matrouh Resource Management Project (MRMP)-funded by the World Bank-has successfully been building up a unique setup (human and infrastructure) and participatory, community-based operational models for integrated resource development and conservation in the fragile semidesert environment of the northwestern coastal area of the country. In the northeast, the recently established long-term crop-rotation trials-through ICARDA collaboration-will hopefully produce sustainable soil and crop management innovations to be adopted by farmers so that natural resources can be conserved and used most efficiently.

Soil and water management for maximum or optimum agricultural production (crop and livestock) taking into account conservation of environmental resources must be the basis for optimizing soil water use in any ecosystem.

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Science

An effective infrastructure base, e.g. laboratories, equipment, and other needed facilities, has to be established as well as the necessary database and information systems. The planned establishment of a "Matrouh Resource Management Center" as part of the MRMP may be an important step toward coordinated and integrated research for rainfed agriculture in Egypt. The OSWU Consortium should be involved in such a center.

There will be a good base for scientific research and extension in the region. This will help in establishing evaluation and monitoring programs for research activities. This will also create an effective mechanism to solve problems that occur at the producer level, to identify priorities for adaptive research programs, and to face disasters as well as unexpected conditions. The established databases as well as other information systems and infrastructure facilities are the core of development of science in the region.

Capacity-Building of NARS

The activities of OSWU must result in capacity-building of NARS according to the situation in the areas specified and identified. Under resource management programs in collaboration with ICARDA in the northwestern and northeastern rainfed regions, several researchers and extension staff have already been trained in this area. Effective extension could be a part within this context.

Use of Information Tools and Methodologies

Information tools and methodologies are now of great importance for data filing, analysis, and dissemination. They are also essential for planning. They help in prediction, simulation, and data analysis to reach certain conclusions to be presented to policy-makers for taking decisions.

There is great interest in Egypt in this area. The existing DSS, models, GIS, and databases are based on the needs of the relevant organizations. The software and programs used are based on the available data and analyses needed.

Actual Use of DSS, Models, GIS, and Databases

The Central Laboratory for Agricultural Expert Systems (CLAES) of the Agricultural Research Center (ARC) is working on formulating computer programs on cultivation and management of different crops, as well as prediction of their yields based on the inputs used.

Regarding irrigated agriculture, the IBSNAT-DSSAT models CERES-WHEAT and CERES-MAIZE have been used for wheat and maize, and the PEANGRO model for faba bean, to predict grain and biomass yields, crop season length, and evapotranspiration (Eid et al. 1995a,b). Other models have been used for the rainfed area of Egypt (North-Western Coastal Zone) either to estimate the crop yields of barley (van de Ven 1987) or to predict the effect of grazing on the growth of subshrubs and the water balance (van Duivenbooden 1985).

There is also cooperation between the Soil Water and Environment Research Institute (SWERI), ARC, and some national and international institutes and organizations in using some models for climate-change prediction and its impact on the production of certain crops. GIS is now used on a relatively large scale, especially in the area of soil survey, management, and reclamation. It is used by the Soil Water and Environment Research Institute, Matrouh Resource Management Project, Desert Research Institute, and many other institutions. Activities in establishing databases are one of the major concerns.

Evaluation of Use of Information Technology and Identification of Future Needs

Use of these facilities and technologies has been limited. Intensive training of staff is required to reap the maximum benefits of such facilities and technologies. Programmers and software and hardware engineers are badly needed.

Conclusion

The OSWU Consortium's unique approach of basing its proposed research on a firm knowledge basis — what is known and not known, and what are the real yield-limiting problems that need to be solved in water-deficient production systems —is considered an excellent way to achieve sustainable and efficient use of soil water. Collaboration with the planned "Matrouh Resource Management Center", the use of modern information tools, and capitalizing on results obtained elsewhere could provide a solid basis to optimize soil water use in a sustainable way and to achieve impact. This will result in increasing agricultural production, alleviating poverty, and conserving natural resources.

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Impact of Optimizing Soil Water Use Research in Iran

E Pazira[1]

Abstact

A major challenge to the development of agriculture in Iran is the shortage of water, because more than 90% of the total area of the country receives an insufficient amount of rainfall. Issues related to soil erosion, salinity, and sodicity are the other major problems in many parts of the country. In view of the ever-increasing population and the higher demand for food supply, the much-needed increase in crop production can be met by improving the productivity of available crop lands. This in turn implies the urgent need for proper management and utilization of the soil and water resources of the country without wasting them. To achieve proper soil and water engineering, techniques such as moisture conservation, water resources management, erosion control, drainage, flood control, and irrigation have to be improved. In this paper, the present status of soil and water resources of Iran with respect to resource potentiality and the relevant limitations are discussed. Further, the impact of optimizing soil and water use on the success of development programs is outlined, and it is concluded that an international forum like the Optimizing Soil Water Use (OSWU) Consortium can have a positive effect on solving the regional and domestic problems of the member countries.

Resume

Une des contraintes pour le developpement de l'agriculture en Iran est le manque d'eau du au fait que 90% de la superficie totale du pays regoit une pluviometrie insuffisante. Les problemes lies a l'erosion, a la salinite et a la sodicite des sols constituent la seconde contrainte dans la plupart des regions du pays.

Avec l'accroissement de la population et par consequent la demande de plus en plus elevee en ressources alimentaires, l'augmentation de la

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production agricole pourrait etre realisee par l'amelioration de la productivite des terres cultivies. Ceci pose la necessite d'une meilleure gestion et d'une meilleure utilisation des sols et des ressources en eau du pays. Pour atteindre une bonne gestion de l'eau et des sols, il est impiratif d'ameliorer les techniques de conservation de l'humidite, de la gestion des ressources hydriques, du controle de l'erosion et du drainage, des inondations et dans le meme temps, ameliorer les systemes d'irrigation.

Ce chapitre, fait l'etat des lieux des sols et des ressources en eau en Iran et discute les limitations de ces ressources. De plus, l'impact de l'optimisation de l'utilisation des sols et des eaux sur le succes des programmes de developpement est souligne. Il a ete ainsi conclu qu'un forum international comme le Consortium sur l'Optimisation de l'Utilisation de l'Eau de Sol (OSWU) peut avoir un effet positif dans la resolution des problemes rigionaux et domestiques des pays membres.

Introduction

The Islamic Republic of Iran is located between 25°N and 40°N latitudes and 44°E 64°E longitudes, and covers an area of about 165 million ha. A great part of the country is covered by mountains surrounding the rocky, sandy, and saline deserts of the central plateau, which naturally forms a closed basin containing various kinds of accumulations.

The two major mountain ranges in Iran are the Elborz and Zagrus ranges which form a great V-shaped physiographical area. The other three main physiographical areas are: the area within the V-shaped unit beginning as a high plateau and consisting of secondary ranges with the slope gradually ending in the deserts; the region of Khuzistan, which is a continuation of the Mesopotamian plains and is a low-lying plain; and finally the Caspian Sea coastal area which represents a separate climatic condition since it is situated below the sea level. With the exception of the Caspian Sea area, the climatic conditions in other parts of the country change from semi-arid to arid, depending on the location and altitude. Moreover, the distribution of rainfall is not uniform throughout the year and precipitation mostly occurs during the winter season with an annual average of about 240-250 mm.

Iran is an arid country where more than 90% of the total area receives an insufficient amount of precipitation (Pazira and Sadeghzadeh in these proceedings). Aridity together with high temperature, high evaporation rate (in some places more than 2000 mm year^{-1}) which exceeds the precipitation, is dominant in most parts of the country and is nearly the same in all plateaus. Therefore, dryland farming, except in certain parts and during the wetter years, is not economically feasible under the current farmers' soil and crop management practices.

Irrigation water is the main factor limiting the expansion and development of agriculture in the country, a problem to which the government is giving much attention in its effort to lay a foundation for a secure economy.

In conformity with the national economic, social, and cultural development plan, the agricultural sector has been viewed as a fundamental contributor to a safe economy. Currently, agriculture furnishes 25%. of Iran's GNP, provides 27% of the employment, and meets 85% of the food demand, as well as a large capacity for export of several agricultural and horticultural commodities. Given the fluctuating nature of productivity in the rainfed farming system, optimizing the import and storage of grain stocks will receive greater attention in the future.

Efficient water use and proper water management can greatly improve the agricultural situation of the country, because water is not always available in areas where good soils can be found. Also, considering the rather poor quality of irrigation water and improper use of water in agriculture, salinity problems have caused a gradual but noticeable reduction of soil productivity in many areas. In spite of the high resource potentiality, there are several natural problems related to agricultural development: (1) limited amount of irrigation water; (2) water quality problems; (3) soil salinity and sodicity problems in vast parts of the country; (4) unique climate with extremely hot summers; and (5) disease and pest problems.

In the light of these problems, the impact of past research relating to optimizing soil water use is discussed in this paper.

Impact of Soil Water-Use Efficiency Research

The establishment of some agricultural research institutes in Iran dates back to more than 50 years. The main body responsible for agricultural research in Iran is the Agricultural Research, Education, and Extension Organization (AREEO), comprising a well-distributed network of 11 national research institutes, 30 provincial research centers, and more than 100 research stations representing all the agroecological zones in the country.

The issue of soil and water use optimization in Iran is mainly dealt with by three research institutes: Iranian Agricultural Engineering Research Institute (IAERI), Soil and Water Research Institute (SWRI), and Dryland Agricultural Research Institute (DARI).

As a result of the research activities carried out by these institutes, several important problems pertaining to soil and water use such as lining of canals, application of pressurized irrigation, land-levelling, tillage practices, crop rotation, and use of supplemental irrigation have so far been dealt with.

Considering the type (snow or rainfall), amount, and distribution of precipitation and other climatic factors in the dryland areas and their effects on the growth of cereals, pulses, oilseeds, and foliage crops, it has been observed that the production rates for such crops are directly proportional to the amount of precipitation, which demonstrates the high degree of dependency of yield on precipitation. This indicates the urgent need for application of supplemental irrigation in years of low or limited rainfall. This has been practised where either surface or groundwater resources are available and easily accessible during spring and summer. Currently, farmers in the medium-to low-rainfall zones use supplemental irrigation for cereals during the growing season, but not in advance of the production season.

From the results of investigations, it is now clear that supplemental irrigation has a significant effect on timely germination and crop establishment in autumn as well as at the flowering and complete growth stages of the crop, which can double the yield in dryland regions.

The diverse research and development needs of farmers in the dryland regions of Iran are mainly met by DARI. This institute has 12 research station centers in different agroecological regions of the country, and ever since its establishment in 1992, has concentrated on research activities concerning cereals (wheat, barley), food legumes, and oilseeds, completing a total of 85 research projects till October 1996. This includes 53 projects on cereals, 23 on pulses, 3 on oilseeds, and 6 on foliage crops. Improved wheat, barley, and chickpea varieties have been released in different regions for general cultivation by farmers in Iran.

Projects on soil and crop management have demonstrated that proper techniques in most of the dryland rainfed cropping systems (dominated by cereal/fallow rotations), such as timely tillage, dry sowing in early autumn with optimum seed rate of improved varieties with adequate fertilization and weed-control can increase crop yield by up to 100% depending on the season and location However, improved soil and crop management practices have not been adopted by dryland farmers at satisfactory levels yet (FRMP 1995). Only 20% of the farmers use first tillage in time in fallow years, and only 8% of the farmers apply three tillage needed at the same period. This improper application of tillage causes loss of rainwater either as runoff or evaporation during the fallow period which leaves an insufficient moisture in the soil profile that the crop cannot sufficiently benefit from. About 85% of the farmers use local crop varieties which are susceptible to yellow rust. Use of the improved varieties that have been released under technology-transfer activities should be emphasized much more. Drill is used by only 8% and 16% of the farmers for barley and wheat, respectively. Most of the farmers broadcast the seed and cover with moldboard which reduces the crop yield remarkably because of improper stand establishment as a result of nonuniform seed distribution between 0 cm and 25 cm in the plow layer. The importance of fertilizer is known to farmers, but fertilizers are not applied in sufficient amounts because of nonavailability in time. Fertilizer is one of the most important management practices affecting crop yield substantially. Only 25% of the farmers are aware of proper weed control practices.

These problems can be seen very remarkably when comparing production fields of research stations, where all soil and crop management practices are applied in time and properly, with the farmers' fields. The positive effect in research station fields is mainly based on efficient and effective rainwater capture and use by crops under improved soil and crop management practices (Harris et al. 1991).

Conclusions

Problems affecting Iranian agriculture are being tackled not only at the institute and organization levels but also at the farmer's level. The government is giving special attention to several aspects of agriculture: use of improved and selected seeds and plants, control of pests, veterinary science and animal husbandry, use of chemical fertilizer, farm mechanization, appropriate farm practices, extension of modern agricultural methods, conservation of soil, water, forest, pasture, and other natural resources, farmer cooperation and the cooperative system, expansion of agroindustries, plans for producing more cereals, oilseeds, and foliage crops, and establishing large-scale irrigation projects. Its strategy is not only to use more lands but also to get a higher yield per unit area mostly under irrigated conditions. But attention should also be given to rainfed production systems which cover more than 60% of the cultivated area.

Data on impact of past research should be collected, and use of simulation models could help in better identifying alternative management practices that increase agricultural outputs and maintain the sustainability of the system.

In rainfed areas, the OSWU Consortium could facilitate integrating the soil and crop management practices for improved water-use efficiency through better moisture conservation through timely and proper tillage, along with better crop management including improved varieties, optimum sowing date, method and seed rate, optimum fertilization, and weed control. Close linkage with extension and farmers who should participate in on-farm research and technology transfer activities—in problem identification as well as application of improved technologies—will allow use of conserved water more efficiently. This will eventually lead to a higher adoption of innovations, and to an impact on farmers' welfare and, thus, the overall economics of the country.

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Impact of Research on Soil Water Use in Jordan

A Al-Nabi Fardous and A Al-Shrouf[1]

Abstract

The management of Jordan's limited resources, which necessitates a long-term effort in order to be properly addressed, requires the development of a national agricultural research strategy which would help the national agricultural research system prioritize its research and technology-transfer programs in such a way as to best utilize the agricultural research resources of the country. The limited availability of water, as well as the deterioration of the quality of the water available fdr agriculture are major constraints impeding the intensification of agriculture in Jordan. The prospects are for a decrease in water availability for agriculture in the future. Therefore, ways must be found to improve water-use efficiency and maintain the quality of this precious resource These include the use of more water-use efficient crops, reduction of losses in transmission and distribution, and employment of farm management methods to include all the factors which will result in optimum water-use efficiency.

Resume

La gestion des ressources limitees de la Jordanie necessite une approche a long terme pour etre effective et requiert le developpement d'une strategie nationale pour la recherche agronomique qui aiderait le systeme de recherche national a prioritiser ses programmes de recherche et de transfert de technologie de maniere a mieux utiliser les ressources de la recherche agronomique du pays. La disponibilite limitie ainsi que la deterioration de la qualite des eaux utilisables par l'agriculture sont les principals contraintes qui limitent l'intensification de l'agriculture en Jordanie. Les perspectives font entrevoir une baisse de la disponibilite en eau pour le futur. Il est donc imperatif de trouver des moyens pour ameliorer l'efficience et la qualite de Veau. Ceci comprend l'utilisation de cultures

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plus efficiente dans leur utilisation de l'eau, la reduction des pertes dans la transmission et distribution, et l'utilisation de techniques de gestion a la ferme qui incluent tous les facteurs qui peuvent engendrer une efficience optimale de l'utilisation de l'eau.

Introduction

Jordan is a country with limited rainfed agricultural land, scarce water resources, and scanty and erratic rainfall. The total land area is about 89,460 km^2, which receives an annual average of 8.4 billion m^3 of rainfall. Jordan has been suffering from severe water shortages since the 1960s. The country's demand for water has grown more rapidly than the development of new water supplies. The annual deficit of water supply may increase to nearly 1.2 billion m^3 by the year 2015. Supply increments and severe demand reductions will not be able to limit the deficit to its present level. Therefore, it is imperative to implement a water policy that employs cost-efficient means to narrow the gap between water supply and demand.

Jordan is dominated by an arid climate. About 90% of the country receives less than 200 mm of annual rainfall. Only 5% of the rainwater goes to recharge the groundwater. The dominance of arid conditions and uneven rainfall distribution are the main factors affecting the availability of water, thus limiting the development of agricultural production in irrigated and rainfed areas.

Cultivated rainfed areas cover about 0.5 million ha, and are primarily used for producing field crops (wheat, barley, and summer vegetables).

Food imports have risen dramatically from JD 132 million in 1980 to JD 481 million in 1994, or almost three times the 1980 import values, while food exports have risen from JD 52 million to JD 158.9 million during the same period. Food imports were almost 19% of total imports into the country. The level of self-sufficiency ranges from 15% for wheat to over 100% for most vegetables. The production of vegetables far exceeds domestic consumption and constitutes a major volume of agricultural exports and foreign exchange earnings in the agricultural sector. Tomatoes constitute by far the major vegetable produced. Agriculture contributed 6.3% to the gross domestic product during the period 1980-92.

Agricultural research and extension efforts in Jordan started in 1953. The goal of these activities has been to improve the productivity of the farming systems in both rainfed and irrigated agricultural lands. Some of these efforts have succeeded and the results were transferred to farmers. Tillage practices, introduction of new varieties, fertilizer rates and applications, the introduction of irrigation systems, protected farming systems, and Integrated Pest Management (IPM) have been some of the practices adopted fully or partially by farmers. Many research findings and recommendations were, however, never adopted.

The purpose of this paper is to highlight the impact of past research on Optimizing Soil Water Use (OSWU) and future expectations on the basis of the identified problems relating to research and technology-transfer activities and use of information tools for generalization of research findings and to assist decision-makers in prioritization of research activities.

Impact of Soil Water-Use Efficiency Research

Past Research

The limited availability of water as well as the deteriorating quality of the water available for agriculture are major constraints impeding the intensification of agriculture in Jordan. The prospects are for less water available for agriculture in the future. Therefore, ways must be found to improve water-use efficiency and maintain the quality of water. These include the use of more water-use efficient crops, reduction of losses in transmission and distribution, and employment of farm management methods that will result in optimum water-use efficiency.

Poor farm production practices and poor range management methods are major constraints to agricultural development. These include excessive and improper use of water, fertilizer, pesticides, and other inputs, high cost of inputs, and unsuitable or low-quality seeds and seedlings. All of these factors must be addressed if costs are to be reduced.

Impact on Farmers' Income

The Balama Project [a collaboration between the Ministry of Agriculture and the Arab Center for the Study of Arid Zones and Drylands (ACSAD)] completed a water-harvesting project in Balama over a three-year period (1985-1988). Using simple techniques, the volume of runoff was increased around olive, almond, and pistachio trees, thus increasing the soil moisture content in the root zone. Better growth of these trees was recorded at the experimental site as compared with trees without these techniques. The project also included techniques such as contour terraces and ridges for pasture and range improvement. The impact on income has, however, not yet been investigated.

Impact on Resources and Environment

The Jordan Highland Development Project implemented the results of research on soil and water conservation techniques on steep lands suffering from erosion. It constructed rock dams, contour stone bunds, trapezoidal bunds, and earth contour bunds to use the runoff water to increase the soil moisture around trees such as olive, almond and pistachio. The total area that was thus completed is about 6,000 ha.

The Zarqa River Basin Project also has employed soil and water conservation techniques to prevent soil erosion, with the main objective of reducing the sediment load in the floodwater feeding the King Talal Reservoir and to improve the productivity of the soil. About 3,000 ha have been served by this project (FAO 1995).

The Muwaggar Project is part of an overall research project aimed at combating desertification in Jordan. One of its objectives is to develop means to effectively utilize surface water for various agricultural activities (Taimeh et al. in these proceedings). The impact zone of the project represents 13% of the total area.of Jordan.

The Saklah Project, addressing also soil erosion, water-use efficiency, water harvesting techniques, has covered about 30 ha sown to barley, fruit trees, and range crops.

In addition, the following practices have been used in several soil and moisture conservation projects.

- Contour cultivation: Runoff is reduced by trapping water in the furrows, thus increasing infiltration into the soil;
- Ripping: This practice is mainly used in areas to be sown with olive or other fruit trees.
- Terracing: Different types of terraces are constructed according to the soil type and conditions. They are designed to control runoff in high-rainfall and to conserve water in low-rainfall areas. The different types of terraces which have been constructed in dryland farming areas are (1) earth banks, (2) grandoni terraces,'(3) bench terraces, and (4) contour stone terraces (Taimeh et al., in these proceedings).

Impact on Science

Extensive soil and crop management research in Jordan has generated a high amount of experience and knowledge on tillage practices, crop rotation, fertilizer application, and many other agricultural practices. But there still is no effective and practical mechanism to be recommended on a large scale concerning effective rainfall and quantification of data for water harvesting techniques.

Capacity-Building of NARES

The National Center for Agricultural Research and Technology Transfer depends on government funding which is very limited. In order to develop the sustainable research capacity in Jordan, the budget allocated for the Center should be increased. This seems unlikely to happen in the near future. So NARES in Jordan is at the crossroads: either it must raise resources from nongovernmental organizations or minimize research activities to the level allowed by the government budget.

Future Expectations

The future environment in which research is likely to operate is characterized by (1) an increase in population (5.3 million by the year 2000 and over 7 million by 2010); (2) lower water availability because of the lowering of the groundwater table and reduced quality;, and (3) less available land due to degradation and desertification. As a consequence, all possible steps should be taken to increase the efficiency of rainfed and irrigated agriculture to maximize self-sufficiency so as to minimize expensive food imports.

Continued research in the domain of optimizing soil water use is expected to have an impact on farmers through an increase in the productivity of the land through adoption of different soil moisture conservation techniques such as tillage, crop rotations and their management, supplementary irrigation, water harvesting, etc. OSWU is expected to make a positive impact on poverty reduction and food security by increasing productivity which will lead to an increase in the farmers' income and bring poor farmers above the poverty level.

Another potential impact would be reduction of erosion and conservation of soil water thereby reducing the deterioration of the ecosystem and desertification.

The potential impact of OSWU research on science is expected to be (1) improved knowledge of optimum tillage, crop rotation, fertilizer application, and techniques that may increase the effective rainfall, (2) improved knowledge of crop water requirement and irrigation scheduling; (3) establishing an effective high-technology infrastructure and information system; and (4) new information tools and methodologies to increase water-use efficiency.

The potential impact on capacity-building of the NARES comprises trained scientists in modern information techniques and modeling, and an improved strategy for agricultural research.

Finally, impact is further stimulated through development projects. The ongoing project 'Improvement of Agriculture productivity in the arid and semi-arid zones of Jordan' aims to define criteria for the planning and development of Jordan's arid lands based on the results of trials, surveys, and predictive data. Positive impact is sought to be achieved through research and development activities on (I) watershed management (e.g. less erosion); (2) efficiency of *supplementary irrigation; (3)* production of current and alternative cropping and *livestock systems; (4) knowledge* level of farmers; and (5) research (i.e., establishing a national center for the development of arid zones).

The potential impact of the Project on Water Harvesting Prediction and Optimization Model, *is* expected to be on farmers' income, resource use, and science through a better watershed management on the basis of an integrated prediction optimization model for water harvesting, storage, and utilization of water to reduce soil erosion and increase crop production.

Use of Information Tools and Methodologies

During the last two decades, a great diversity of modeling approaches have been developed and made available. Some models dealing with watershed management have been adopted and verified under Jordanian conditions. The results indicate that such models can be used successfully in watershed management.

Two major activities are being conducted in the steppe region. Modeling techniques aim at optimum land utilization through either on-farm water harvesting or catchment-water harvesting. A holistic developmental approach is employed in both projects.

Research should further focus on the operational use of these models (e.g. use by development projects and policy-makers). Research is needed with respect to parameter estimation for different crops and soils. Calibration and validation of crop simulation models should be carried out under various field conditions. The introduction of simultaneous heat and water flow models under rainfed conditions in Jordan is highly needed.

Some models deal with watershed management had been adopted and verified under.Jordan conditions. The results indicated that these models can be used successfully in watershed management.

Although linear models were developed to determine water-use efficiency of different crops, future models should deal with the whole system through the following techniques: (1) crop type: through sowing tolerant crops to droughts; (2) agricultural practices (tillage, crop residue, soil type, and fertilizer application methods, and rates); (3) use of supplementary irrigation; (4) crop rotation; and (5) water harvesting techniques.

Two major activities are being conducted in steppe region. Modeling techniques aim at optimum land utilization using either on-farm water harvesting or catchment water harvesting. on-farm water storage or catchements storage. Holistic developmental approach is employed in both projects.

Modeling concerning water-use efficiency needs further efforts on adapting and creating models like GIS or DSS because their use is currently only limited to some research projects.

Conclusion

Irrespective of the achievements in research on OSWU, only partial adoption of soil and crop management practices has been achieved so far. More effort should be directed to transfer of the existing results to farmers' fields. At the same time, capacity-building of NARES should be emphasized to increase the knowledge base of the researchers to implement multi- and interdisciplinary research, which is very important in the area of optimization of water use in agriculture. In addition, there is a need to start selecting geo-referenced data sets that can be manipulated on GIS and for modeling purposes for the generalization of site-specific research results to wider areas. There is need to consolidate the few existing models and build comprehensive databases. There is also a need to formulate policies regarding the use of information tools and methodologies in Jordan. The present situation is characterized by uncoordinated efforts as there are few linkages among organisations involved in data management.

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Soil Water Use Research Impact and Use of Decision-Support Systems in Dryland Agriculture of Morocco

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Abstract

The Aridoculture Center has been working on soil water use since its creation in the early eighties.In its 16 years, this institution has generated knowledge and developed methods and technologies relevant to the constraints of fragile dryland farming systems of Morocco. Most of the technologies were taken to the farmers, within a farming system participatory approach, either as a single technology or as a package of technologies. All the technologies tested in farmers' fields showed a positive impact on production in all regions. Some of them are discussed in this paper and quantitative indicators of the impact are given. However, impact assessment and evaluation of most of these technologies is still to be done. Development of sustainable agricultural systems requires access to better information. Elaboration of databases and decision-support systems has been one of the research priorities of the center. Therefore, many surveys have been done and data related to climate, farming systems, crop production, and socioeconomics have been compiled. Moreover, some models have been validated and adapted to Moroccan conditions. However, this is only the beginning toward development of more reliable and better integrated databases.

Resume

Le Centre d'Aridoculture a mene des recherches sur l'utilisation de l'eau du sol depuis sa creation au dibut des annees 80. Apres 16 ans cette institution a genere des connaissances et a developpe des technologies adaptees aux contraintes des systemes de culture qui sont tres fragiles au Maroc. La plupart de ces technologies ont ete testees chez les agriculteurs

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N. van Duivenbooden, M. Pala, C. Studer and C.L. Bielders (eds.). 1999. Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia, and North and Sub-Saharan Africa. Proceedings of the 1998 (Niger) and 1999 (Jordan) workshops of the Optimizing Soil Water Use (OSWU) Consortium. Aleppo, Syria: ICARDA; and Patancheru, India: ICRISAT. pp 367-374.

dans le cadre d'une approche participative, comme simple technologie ou comme des paquets de technologies combinees. Toutes les technologies testees dans les champs des agriculteurs ont montre un impact positif sur la tendance de la production dans toutes les regions. Quelques-unes sont discuties dans cet article avec des indicateurs quantitatifs. Cependant, l'etude d'impact et revaluation de la plupart de ces technologies reste toujours necessaire. he developpement d'un systeme de production viable necessite l'acces a l'information. L'elaboration de base de donnees et des outils d'aide a la decision a toujours ete une priorite de recherche pour le centre. Par consequent, plusieurs enquetes ont ete menees et les donnees relatives au climat, systemes de production, production des cultures et socio-economiques ont ete collectees. En plus de cela, des modeles ont ete valides et adaptes aux conditions marocaines. Cependant, ce travail ne peut etre qu'un debut pour la constitution de bases de donnees fiables et plus integrees.

Introduction

The arid and semi-arid regions of Morocco are characterized by low annual rainfall (200-450 mm) and high fluctuations of precipitation. In these regions, drought can occur at any time during the growing season. However, two periods of drought are very likely (ElMourid and Watts 1993): drought that occurs usually during spring and affects seed-set and development, and early drought that occurs less frequently during the emergence and seedling stages. Late in the growing season, lack of water is usually associated with heat stress so that yield is reduced because of the erratic conditions. Crop yields are also highly variable from one year to another with coefficients of variation reaching 47%. The predominance of shallow soils aggravates the situation in these regions. These type of soils have low water storage capacity and cannot conserve water to be used during the later crop stages (Boutfirass, El Gharous, Elmourid et al. in these proceedings). Given these environmental characteristics, the crop and livestock productions are very low and highly irregular, and years of marginal crop production are quite common. Dry-farming techniques of growing cereal crops such as barley, wheat, and maize have been developed and practised for centuries. Cereals constitute the main crop and are grown in rotation with fallow, and food and forage legumes. When used in the rotation, fallow plots are most of the time grazed up to springtime. Barley dominates in areas receiving less than 300 mm (Gibbon 1981).

In response to these challenges, the Institut National de la Recherche Agronomique (INRA) established a dryland agriculture research center (i.e., Centre Aridoculture, Settat) in 1982. The Aridoculture Center has addressed research problems from a systems perspective. The most important thrusts that were developed are related to: (1) conservation of natural resources (soil, water, genetic resources), improvement of their management and optimization of their uses; and (2) development of agronomic, biophysical, and socioeconomic databases, use of modeling, and decision-support systems.

The research strategy in the arid and semi-arid areas of Morocco has been oriented toward (1) characterization of the environment and its variability in order to target research thrusts and orient farm management toward better use of the available water; (2) development of water and soil conservation techniques that decrease runoff, evaporation, and erosion and increase soil water availability to plants; and (3) implementation of techniques that allow the use of plant-available water more efficiently.

During its 16 years, this institute has generated knowledge, and developed methods and technologies relevant to the constraints of fragile dryland farming systems and natural resources of Morocco. Studies were conducted on crop rotations, tillage, water harvesting, sowing date and plant population, and weed control (Boutfirass, El Gharous, Elmourid et al. in these proceedings). However, more work remains to be done on natural resources management especially in terms of optimization of soil water use. The OSWU Consortium, in the context of its objectives and priorities, can help tremendously in fulfilling the national research policy.

The objectives of this paper are to present the impact of past research in the domain of soil water-use optimization, and to indicate the possibilities for use of information tools in future research activities.

Impact of Research Achievements

Most of the research findings have been taken to the farmers' fields either as single technologies or as a package of technologies. Different ways of technology transfer have been adopted depending on the degree of farmers' involvement in the verification trials. All the technologies tried with the farmers showed a positive impact in all the regions of Morocco. For instance, in the Tadla region, increases of up to 100% in on-farm wheat grain yield have been obtained for many years by using a package of improved variety, drill, early weed control, and nitrogen application. Forage production too has been boosted from almost nothing to more than 2 t ha^{-1} by using new varieties (El Mejahed 1998). In the Doukkala region, on-farm maize and chickpea grain yields have more than doubled just by the introduction of new drought-adapted varieties (Anonymous 1997). Shrubs and forage crops in alley cropping have allowed farmers to benefit from marginal lands which they used to leave as continuous fallow for grazing. The protein feeding value of these lands increased by 250% on average (Anonymous 1997), with associated consequences for livestock improvement. No data are, however, available on the number of farmers applying this technology.

The use of a drill with the right seeding rate instead of broadcasting the seeds saves up to 100 kg ha^{-1} of seed and improves stand establishment. Chemical control of weeds saves around 5 US$ ha^{-1} compared to hand weeding by labor. Moreover, hand weeding causes crop damage.

The no-till drill has been tried recently on a large scale at the farm level. Preliminary results show an average yield increase of 50% relative to the conventional sowing method. These results were obtained in three different farms within the Chaouia region (Anonymous 1998a).

The use of fertilizers has also improved as illustrated by the increase of more than 200% in the amount of fertilizer sold in Morocco from 1980 to 1998. Since the Aridoculture Center started soil test calibration in farmers' fields, many farmers are basing their fertilizer applications on soil analysis. In 1993, 2400 soil samples were analyzed at the fertility lab in the Aridoculture Center. In 1998, we tested 7000 soil samples for an average of 500 farmers.

Double-purpose barley has been successfully introduced to farmers in four main regions of the arid zones. Farmers' adoption of this technology has been estimated at more than 60%. This technology was also combined with an application of 20-40 units of nitrogen, depending on the rainfall. This allows farmers to secure at least feed for their animals in dry years, and increase their income in more favorable years. With this technology they can well manage the drought risk.

Studies showed that water can be transferred from one season to another if appropriate rotations and soil management practices are used (Boutfirass, El Gharous, Elmourid et al. in these proceedings). Wheat, following black fallow can benefit from the residual water stored during the preceding year. With chemical fallow, where weeds are controlled only by herbicides and where evaporation is reduced because of the absence of soil cultivation, it has been shown (Kacemi et al. 1994) that up to 75 mm of water can be stored and that wheat yields and water-use efficiency are substantially improved, especially during dry years. However, no impact has been measured yet on the application of this technology.

For drier conditions where livestock is the main source of income for farmers, biomass production is more important. Therefore, forage crops, shrubs, and cacti were studied and developed. However, no data are yet available on the use of these practices by farmers.

Many other soil water-use related technologies have been developed. However, more work is still to be done in terms of technology transfer to the farmer, and impact assessment of these technologies and the ones that are already being used by farmers.

Use of Information Tools and Methodologies

In Morocco, as in most developing countries, agriculture is the most extensive and important user of land, water, and biological resources. As such it impinges on other resource-users and sectors. The use of natural resources in agricultural production must therefore be weighed against nonagricultural uses.

To resolve competing interests for the use of land and water resources, decision-makers need information about the economic and environmental costs of different natural resources to different user groups. Formal procedures that can accommodate appropriate measures of the consequences of different options for natural-resource use are needed by NARS for determining priorities and making decisions about allocation of resources needed for research at different levels of systems aggregation (crop, farming system, and for regional and national land-use planning).

Trials as the principal means of evaluation of technical change may be replaced to some extent with simulation models. By providing quantitative information on the technical and economic impacts of different courses of action, systems methods provide valuable support to the decision-making process. This form of support is particularly important for determining the direction of dryland region development where production is variable from year to year, depending on the climate.

Models allow integrated evaluation of research and other policy instruments. Well-validated and calibrated models substitute for costly, long-term experiments, as a more agile and flexible evaluation tool. Building these models, however, requires a substantial investment in data collection and in understanding the mechanisms underlying the agroecosystem and production system.

The development of sustainable agricultural systems requires access to better information than most often is the case. The generation of information as a goal in itself will increase in importance, and will require the strengthening of data gathering, database elaboration, and analysis capacity in research institutions.

Databases Available at the Aridoculture Center

Elaboration of databases has been one of the research priorities of the Center since its creation in 1982. Therefore, many surveys have been done in the arid and semi-arid regions to gather information needed to build up a research program that targets the real problems of farmers. The first database elaborated is related to farm typology. This database contains all information about different categories of farms based on socioeconomic and biophysical parameters (e.g. land tenure, sources of income, farm plot acreage, livestock, crops, and cropping systems, etc.) in the surveyed regions.

The second database contains climatic data, i.e., rainfall and temperature data for more than 70 years in the arid and semi-arid regions of the country. For recent years, more information was collected on climate such as solar radiation, wind speed, and evaporation.

Recently, different laboratories of the Center decided to create research results databases. The first one was elaborated in the Agronomy laboratory and contains all the available information about agronomy trials including measures and observations since 1984. The other laboratories are working on the same topic. However, this database should be worked out more to be easily accessible. A common unit that can gather all the available information, process it, and help in its use should be created at the Center.

Sustainability-oriented research will have a specific implication for the process of research development. This will be based on environmental characterization and information availability, and on more interdisciplinary collaboration at the national and international levels. This new perspective will require a minimum database setup. At the national level this minimum database should integrate the following data sets: (1) climatic data, (2) topographic data, (3) soil data, (4) crop and production data, (5) hydrological data, and (6) socioeconomic data.

Use of Models

GIS and Rainfall-Runoff Model

In Morocco, winter rainfed areas with less than 200 mm of rainfall are suitable for runoff farming. The use of rainwater in runoff agriculture could be an efficient land and water management approach, which could contribute to a slow recovery of pastoral vegetation, crop production, and forestry. Under the water husbandry project, a study has been conducted to define potential sites for runoff production and identify potential water harvesting systems in selected agricultural areas (Anonymous 1998b). This study used the GIS coupled with the rain-runoff model.

SIMTAG, CERES-Barley, and MULTISIM Simulation Models

SIMTAG is a growth simulation model that has been validated for the semi-arid regions of Morocco (ElMourid 1988). It simulates bread wheat growth, development, and yield components. It also estimates the evolution of soil moisture and water use by the crop.

CERES-barley does almost the same job for barley. This model has also been used and validated for the Moroccan semi-arid conditions (Hanchane et al. 1999).

MULTISIM is a yield distribution simulation model. It is based on surveys of experienced farmers. Means, variances, and covariance are inputs of MULTISIM which generates a series of yields in a normal distribution. This normality is obtained using the Box-Muller approximation (ElMourid et al. 1996). The comparison of SIMTAG-estimated and MULTISIM-estimated yields for a given region reveals yield gaps that can be filled just by adequate technology transfer (Boughlala et al. 1994).

Spatial Weather Generator (SWG)

This model is used to generate a long series of climatic data that are relevant to agricultural production. It was developed at ICARDA (Goebel 1990) and validated for Moroccan conditions (Elouali et al. 1999). It contains three parts that consist of (1) parametric estimation of statistical coefficients using original climatic data; (2) stochastic reproduction of synthetic sequences of climatic data using the estimated coefficients; and (3) spatial interpolation of the coefficients. Therefore, synthetic data related to rainfall, minimum and maximum temperature, and solar radiation can be generated for whatever location or studied region.

SIMTAG, MULTISIM, and SWG were used and combined in an agroecological characterization of the arid and semi-arid regions of the central-western part of Morocco and Saiss region (Balaghi and ElMourid 1999). This work showed the high value of using models in identifying options for development, targeting technology transfer, identifying recommendation domains, and helping in decision-making. It has to be extended to the other regions.

Conclusion

In the Moroccan dryland areas, crop and livestock integration is the main characteristic of rainfed agriculture. Its improvement is challenging. Research has developed suitable farming practices and techniques that have contributed to an increase in WUE and yield, and which have been adopted to a certain extent by farmers. However, to increase their impact in the drier areas, emphasis should be on greater increase of total biomass production.

The research impact on farmers' practices has been achieved because a technology-transfer approach based on farmers' participation was applied. There is, however, a need for further quantification of the impact of research in the domain of optimizing soil water use.

With the increase in information needs and restrictions in terms of means allocation, attention should focus on more sustainable agricultural systems through a better integration of disciplines. Sustainability-oriented research will have specific implications for the process of research and development. This shift will be based on environmental characterization and information availability, and on more interdisciplinary collaboration at national and international levels, and on the use of information tools. This requires a further development of databases, and capacity building for data evaluation and utilization within the NARS.

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impact of Soil Water Use Optimization Research and Need for New Information Tools and Methodologies in Niger

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Abstract

Soil water research and application of technologies have been carried out in two separate ways in Niger. Few of the results obtained by national and international organizations have found application in farmers' fields. At the same time, agricultural development projects, in need of proven technologies, have adapted and used several water conservation techniques without sufficient expertise to measure the real impact. This background calls for development of information tools and new methodologies capable of gathering field data and using them in models and GIS for a broad transfer of knowledge.

Resume

Les recherches sur l'eau du sol et les technologies appliquees ont ete menees separement au Niger. Tres peu de resultats obtenu par les institutions nationales et internationales, en matiere de gestion de l'eau du sol, ont pu trouver des applications directes en milieu paysan. Au mime moment, les projets de diveloppement agricoles, du fait de leur besoin urgent en technologies testies, ont adapte et utilise plusieurs technologies de conservation de l'eau sans une expertise suffisante pour mesurer les impacts reel. Cet historique plaide en faveur du developpement d'outils d'information et de nouvelles technologies capables de rassembler les donnees existantes de terrain et de les utiliser dans des modeles et SIG pour un large transfert de connaissance.

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Introduction

Two broad types of crop production systems exist in Niger, i.e., rainfed and irrigated. Irrigation is practised in two ways. The first is year-round-crop production With a relatively good water supply from the Niger river, water stored in dams, and from groundwater. The main crops are rice, onions, wheat, sorghum, and cotton. The latter two crops are also grown in the rainy season with supplemental irrigation. The second irrigated production system is seasonal, and based on traditional irrigation methods using temporary water sources (such as lakes, ponds, and shallow groundwater) to produce vegetables and fruits.

About 95% of the total cereal production originates from rainfed crops, millet and sorghum (Sidikou 1998), with two major constraints limiting crop productivity: low soil fertility and water availability. Water availability to these and other major rainfed crops (cowpea and groundnut) is a function of both climatic (i.e., temperature, solar radiation, wind, humidity) and soil factors (texture and other physical properties). Research conducted in Niger by national and international institutions has focused on technology development, and on process and methodology development to improve water-use efficiency by crops, as reviewed by Moustapha et al. in these proceedings.

The purpose of this paper is to establish the impact of this past research, and indicate the extent to which information tools and methodologies are available for scaling up these results to larger rainfed areas.

Impact of Soil Water-Use Efficiency Research and of OSWU

Impact on Farmers

In irrigated agriculture, water-use efficiency has likely increased through management techniques based on a proper sowing calendar, water distribution systems, and water-lifting devices.

In rainfed agriculture, successful techniques based on runoff water management and groundwork to store more moisture in the soil have been applied in farmers' fields in several regions of the country. For example, water harvesting techniques have been used and adapted to landscape positions ranging from the plateau to the valley. On the plateau, alternating strips of bare and plowed cropland are used for flat laterite soils. Zai and half-moon plots are also used to manage both soil moisture and nutrients from applied manure. Highly degraded soils on the plateau are being used for tree and grass production. On slopes too steep for crop production, trenches are dug to collect runoff water and grow trees. On gentle slopes, stone-protected earth bunds are constructed along contour lines and crops are sown between the bunds. In the valley, stream protection with stone lines and groundwater recharge using permeable dams are commonly used to reduce erosion and grow crops with surface and underground stored moisture. Application of these techniques has been possible because development projects have provided training and support to build structures. As no formal impact studies have been carried out, although some information has recently been stored in WOCAT (Liniger et al. 1998), quantification of the impact of past research is not possible at this moment in time.

Impact on Science

Many research findings on water use by crops may not yet be applicable in farmers' fields, but they represent an advance in scientific knowledge. Some such examples relate to: (1) lack of soil water conservation between seasons; (2) effects of crop-residue mulch and surface-tillage mulch on surface evaporation; and (3) identification of optimal sowing dates. The need for joint research on crop water and nutrient availability (two constraints to crop production in the Sahel) has been underscored. Another impact of this research is model development integrating several disciplines, and projection of results to other conditions.

The review of past research by Moustapha et al. in these proceedings, facilitated by the OSWU Consortium, will be instrumental in the prioritization of future research in this domain.

Capacity-Building of NARS

The number of NARS scientists working on soil water management has increased from 2 in the early 1970s to about 15 now. At the same time, the number of institutions carrying out research on this topic has increased too: ICRISAT, IIMI, ORSTOM, University of Niamey, and some European universities and institutes (University of Wageningen, Institute of Hydrology) are working on the subject. Until a few years ago, there was little collaboration between these institutions, and consequently, the impact on capacity-building of NARS was limited. At present, the situation has improved much, with joint planning (Bielders et al. 1999) and training workshops (e.g., in the use of WOCAT; co-financed by OSWU) being held.

Future Expectations

Research on optimizing water-use efficiency is likely to improve resource use. For instance, less water can be applied in the case of supplemental irrigation, and the efficiency of fertilizer use can be increased. It will also help reduce the risk of crop failure caused by variability in rainfall distribution during the growing season.

The activities of the OSWU Consortium will improve collaboration not only between local research and development tea.ms, but also between countries sharing similar soil water management problems.

Use of Information Tools

Models and decision-support systems (DSS) have been used in Niger since the end of the 1980s for research purposes in specific fields such as crop growth, water balance at the plot and field levels, in agrometeorology for cropping-season evaluation or to suggest alternative cropping patterns. Most crop-growth models such as DSSAT, CropSys, and water balance models (SWATCH, ENWATBAL) have been used for specific research topics or for calibration in semi-arid environments. DHC has been used at AGRHYMET for evaluating rainfall during a season. Some details have been described by Moustapha et al. in these proceedings. The APSIM model has been reviewed at ICRISAT to look at the availability of data to fulfill the required input data. The millet component of this model has been developed recently and has not been tested by ICRISAT for West African conditions.

Databases exist for climatic data, population, and land use, but there are shortcomings due to incomplete and often unknown databases. It has recently been decided to use WOCAT to a larger extent to monitor use of soil and water conservation technologies in the country. This tool is extremely useful in measuring impact, and can be used by research and development projects and NGOs. A working group in this respect has been formed to avoid duplication of efforts and increase exchange of information (Bielders et al. 1999).

Spatial information tools such as GIS, capable of integrating various databases and models with spatial information, are available only to a few institutions (ICRISAT, ORSTOM, AGRHYMET, and the University of Niamey). INRAN is currently establishing its GIS unit with the help of ICRISAT and PGRN (a long-term natural resources management project, World Bank-funded).

The models listed in Table 1 have been used for various purposes. GIS has been used not only for analyses and mapping of long-term data (rainfall, soils, etc.), but also to map resources in specific regions (e.g. ILRI program in Banizoumbou).

Identification of Future Needs

Research on optimizing soil water use in the semi-arid regions of West Africa requires the integration of several disciplines to overcome various constraints with regard to soil water availability to plants. The major factors in this research are weather and soil parameters, crops, and population. This makes it necessary to develop models and DSS to guide land-users and policy-makers. Models are useful to scientists and institutions which have enough expertise and computing facilities to gather and analyze data to solve specific soil water problems. DSS are simple ways to arrive at complex decisions, with a varying degree of input data requirements. The bioecomomic models being developed (van Duivenbooden et al. 1998), which address planning of land use with improved technologies, should be refined with soil and water conservation techniques. Future activities of INRAN within the framework of OSWU should address both models and DSS fields.

Conclusions

A lot of scattered data exist in the field of water use from various research and development projects carried out in Niger during the past 15-30 years. This data has been used to a certain extent, but it should be used more under real cropping conditions and made available to farmers and other stakeholders through practical guides (as done for other technologies; Ly et al. 1998). OSWU future activities in

Table. 1. Models and databases available in Niger.

TOOI	Name of software	Use	Institution
Model	DHC	Seasonal water balance	AGRHYMET
	ENWATBAL	Soil water balance	INRAN
	CROPWAT	Soil water management	INRAN
	SWATCH	Soil water balance	ICRISAT
	CROPSYS	Crop growth	ICRISAT
	DSSAT	Crop growth	INRAN, ICRISAT
	APSIM	Crop growth	ICRISAT
	GAMS, etc.	Analysis of agricultural production	INRAN, ICRISAT, ILRI
GIS	ArcView/Info	Land evaluation Climatic data mapping Population and resources mapping	ICRISAT, INRAN, ILRI AGRHYMET, ICRISAT ICRISAT, Ministere du Plan, University of Niamey
	Atlas GIS	Land evaluation	ICRISAT, INRAN
Database	Various	Climatic data (rainfall, temperature PET, solar radiation, etc.)	Meteo Nat., AGRHYMET, ACMAD
	WOCAT	Soil and water conservation techniques	INRAN, ICRISAT, NGOs
	SOTER	Soil types	ICRISAT, University of Hohenheim
	Various	Groundwater, stream flow, etc.	Direction des Ressources en Eau
	Various	Population, cropped area, livestock, etc.	Ministere du Plan

Niger should make this goal possible either through new technologies developed locally or through adapted knowledge from similar environments. Spatial aspects can be easily included through GIS. WOCAT seems a very useful tool in further quantifying the impact of past results in the domain of optimizing soil water use in rainfed agriculture. Finally, bioeconomic modeling should further help in identifying the best options for farmers in this drought-prone country.

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Impact of Optimizing Soil Water Use Research, and the Need for Using New Information Tools and Methodologies in South Africa

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Abstract

Research in the domain of optimizing soil water use has been carried out since the 1970s with a fair adoption rate among farmers of the results. Case studies in the summer-rainfall areas indicate yield increases of 5-46% for maize and wheat upon implementing reduced-tillage and residue-mulching technologies. A wide spectrum of models, CIS, and databases are currently in use. Empirical rate-of-return studies have been done on various horticultural, field crop, and livestock enterprises, while the environmental impact of some research programs has been qualitatively evaluated. Impact studies have also been conducted on the economic efficiency of water use for irrigation. However, there is an urgent need for formal impact-assessment studies on the numerous research efforts regarding the optimization of water use in drylands. An integrated research approach should be pursued to simultaneously optimize soil water and nutrient use by crops in dry areas for greater efficiency and sustainability.

Resume

La recherche dans le domaine de l'optimisation de l'utilisation de l'eau du sol a demarre dans les annees soixante-dix, et les resultats obtenus ont connu un taux d'adoption non negligeable de la part des producteurs. Des etudes de cas dans les zones a pluie estivales ont montre que des augmentations de rendement de l'ordre de 5 a 46% peuvent Stre obtenus pour le ble et le mais suite a l'utilisation de la pratique du travail du sol minimum et du paillage avec les residus de culture. Une large gamme de

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modeles, de SIS et de bases de donnees sont actuellement utilises. Des itudes empiriques sur le taux de rentabilite ont ete effectutees sur diverses entreprises horticoles, agricoles et d'elevage. De meme, l'impact environnemental de certains programmes de recherche a ete evalue qualitativement. Des etudes d'impact ont egalement ete conduites sur l'efficience economique de l'utilisation de I'eau pour l'irrigation. Toutefois, il existe un besoin urgent pour des etudes d'impact formelles relatives aux tres nombreux efforts de recherche dans le domaine de l'optimisation de l'utilisation de Veau en zone seche. Une approche integree de recherche doit etre poursuivie afin d'optimiser simultanement l'utilisation de l'eau et des elements nutritifs par les cultures dans les zones seches pour une meilleure efficience et une agriculture plus durable.

Introduction

Research in the domain of optimizing soil water use (OSWU) has been carried out in South Africa since the 1970s with various results (see Beukes, Bennie et al. in these proceedings). Under the auspices of the Group for Development Impact Analysis of the Agricultural Research Council of South Africa (ARC-DIA), rate-of-return (ROR) studies on agricultural research and development at the national level put the estimate at 44% (Khatri et al. 1996). Empirical ROR studies have also been conducted on various horticultural, field crop, and livestock enterprises (Thirtle et al. 1998). These initiatives were expanded to also include a number of technology-specific case studies (Table 1).

The University of the Orange Free State (UOFS) has conducted several studies on measuring impact in terms of the economic efficiency of water use for irrigation (Oosthuizen 1991; Oosthuizen et al. 1996). These studies have mostly been funded by the Water Research Commission of South Africa. However, no formal impact-assessment studies have so far been conducted on the numerous research efforts regarding the optimization of water use in the semi-arid crop production areas of South Africa, as reported in the national review by Beukes, Bennie et al. in these proceedings. One of the future challenges of the ARC-DIA is to extend the conceptual and empirical initiatives made so far to include natural resource-use aspects.

Table 1. Empirical rate of return (ROR) studies on ARC- research programs.

Program	ROR (%)	Reference
Russian wheat aphid integrated control program	22-28	Marasas (1999)[1]
Proteaceae research and development	8-12	Wessels et al. (1998)[1]
Lachenalia research and development	7-12	Marasas et al. (1998)'
Cover crop management	44	Thirtle et al. (1998)

1. These studies were technically and financially supported by SACCAR and the ARC.

The purpose of this paper is to highlight the impact of past research in the OSWU domain and to identify the need for further research based on the levels of impact. Further, we review the informaticm tools and technologies available, and their use in generalization of research findings for wider areas, and characterization of the biophysical and socioeconomic environment for prioritization of research and development.

Impact of Soil Water-Use Efficiency Research

Past Research

Farmers

Research on efficient soil water use in the semi-arid crop production areas of South Africa has been aimed at optimizing the components of the soil water balance in the two distinct management periods used by farmers. The first is the period of rain storage lasting from the harvest of the previous crop till sowing of the next, while the second period is from sowing till harvest. Results are presented by Beukes, Bennie et al. in these proceedings of extensive on-station and on-farm research to quantify water losses through evaporation, runoff, and deep drainage, and on measures to minimize these losses by methods such as mulching, soil surface modification, and sowing patterns. Increased soil water storage through fallowing, improved infiltration, and water harvesting have also received attention.

Cultivation practices. Reduced tillage with residue mulching, aiming to reduce evaporation and runoff losses and to increase infiltration, has been extensively practised by farmers in the 1970s and 1980s for dryland cereal production. Table 2 contains some case studies of the impacts of these practices on, *inter alia,* yields in the central summer-rainfall area of South Africa. In summary, it can be said that wheat yields increased by 20-33% depending on the cropping system, while maize yields increased by 5-46% depending on the soil type, rainfall, and tillage system. However, residue-borne diseases of maize and wheat have led to a decline in this practice in recent years.

Following many years of demonstration trials on vast areas of sandy soils, most farmers have adopted the practice of using tine implements in a controlled traffic system (i.e., using the same plant and traffic lines, respectively) to conserve soil water, combat wind erosion, and alleviate subsoil compaction. Other well-established management practices to optimize rainfall and available soil water are to use area-specific sowing dates, cultivars, row widths, and sowing densities. Hensley (unpublished data) has shown that in-field water harvesting with small basins under erratic rainfall on heavy clay soils is a promising practice for small-scale farmers.

Pre-plant soil water storage. One of the oldest, and somewhat controversial, technologies for increasing plant-available water is lengthening of the fallow period. The majority of soils cultivated for cereal crop production in the semi-arid regions of South Africa have sandy topsoils underlain with semi-impermeable layers that

Table 2. Case studies of impacts of past OSWU research at farm level.

Rainfall (mm)	Clay content in soil (%)	OSWU and other practices	Crop	Impacts
350	6-10	Crop residue mulch	Maize	16% yield increase Runoff reduced Wind erosion reduced
<400	6	Minimum tillage	Maize	20-33% yield increase
		Crop residue mulch	Wheat	Reduced risk and economic stability
		Controlled traffic		Wind erosion reduced
		Fallow		
		Crop rotation		
500	23	No-till	Maize	27% yield increase (2.75-3.5 t ha^{-1})
		Crop residue mulch		No surface sealing Reduced erosion
550	15-20	Minimum tillage	Maize	46% yield increase
		Crop residue mulch		Water conservation Erosion protection Margin above costs: 81%
700	45 (Vertic)	Minimum tillage	Maize (Irrig.)	Yield: 11.5 t ha^{-1} (breakeven: 6-7 t ha^{-1})
		Crop residue mulch		Infiltration improved
900-1100	30-60	Minimum tillage	Maize	5% yield increase
		Crop residue mulch		Less water stress in dry periods

restrict drainage losses. Fallowing can consequently be very successful in these areas. It is therefore a standard practice because of higher and stabler yields. Secondary benefits, not directly related to more efficient soil water use, are increases in available soil nutrients (e.g. nitrogen mineralization) and organic matter content from crop residues. The average yield increase through fallowing is about 30% per unit cropped area. This yield increase must be seen in perspective with the smaller area that can be planted annually with fallowing systems. The major contribution, however, is the reduction in risk of drought damage to crops, something that is very difficult to quantify (A.T.P. Bennie, personal communication).

Resources and Environment

More efficient use of water for irrigation purposes by using correct irrigation scheduling methods can lead to major water savings. Correct irrigation scheduling will minimize the danger of salinization, creation of shallow water tables, waterlogging, leaching of nutrients, and pollution of underground water. Under dryland crop production conditions, the practices of minimum tillage and residue mulching are conducive to maintaining and even improving the soil structure due to an increase in soil organic matter. A comprehensive study by Du Toit et al. (1994) showed that depletion of organic matter in major South African soils has reached a serious state, indicating thus a nonadoption of the proposed technologies.

The environmental impact of specific research programs has been qualitatively evaluated in a number of cases (Niederwieser et al. 1997; Wessels et al. 1998), but quantitative measurements have been precluded by the nonavailability of systematically collected time series data. The negative environmental impact of soil erosion and off-site sediment deposition has also been reported (Aihoon and Kirsten 1994).

Science

Several research projects have been completed with the objective of improving our scientific knowledge of the processes controlling the optimization of soil water use under conditions of high atmospheric demand, as reviewed by Beukes, Bennie et al. in these proceedings. These processes include evaporation from the soil surface; infiltration-runoff relationships; losses from deep percolation and properties affecting the upper limit of plant-available water (PAW) in the soil profile; separating the plant and soil evaporation components of evapotranspiration for different cropping practices; quantification of the impact of water stress on plant growth; soil compaction and its effect on root growth and water supply to plants; and properties controlling the depletion of plant-available water from soils as well as the lower limit of PAW.

The quantitative research, where it was combined with cropping or tillage practices, impacted directly on the more accurate expression and/or comparison of soil water-use efficiency parameters. In several cases, this resulted in the adoption of practices by farmers that led to major improvement in yields and reduction in drought risks. Other end products of the research projects with scientific objectives were improvement of existing models and development of models that generate data that are valuable as decision-support information. Unfortunately, maybe because of the complex nature thereof, impact-analysis studies on this type of research have not yet been conducted. A useful contribution to science has been the formulation and validation of the "profile available water capacity" (PAWC) concept by Hensley and De Jager (1982). The concept is now widely applied in irrigation scheduling procedures in South Africa.

A characteristic of semi-arid areas is that the rainfall is not only low but also erratic, thus limiting the value of short-term field experiments. The use of crop models together with long-term climate data provides the solution. An intrinsic weakness of these models, however, is their inability to simulate root growth over a range of soils in a reliable way. A scientific contribution has been the formulation of the principle that stress curves should be crop-ecotope specific, and not generic. Supportive experimental evidence has been obtained by Botha and Hensley (1998).

Capacity-Building of NARS

The National Department of Agriculture has the responsibility for national research policy and is in the process of developing a national agricultural research system (NARS). The Agricultural Research Council (ARC) with its network of specialist and commodity-based institutes has the national mandate for research, technology development and transfer, and is the principal agricultural research institution in South Africa. Extension services are the prime responsibility of the nine provincial departments. Adaptive and on-farm (farming systems) research is performed in joint ventures between the ARC, the provinces, and universities. The Water Research Commission (WRC), a statutory body under the Department of Water Affairs, has played a major role in developing research capacity at various institutions. Efficiently controlled funding and execution of a large number of research projects over a period of more than 20 years, focusing on optimizing water use, have produced a wealth of valuable information and experienced research workers. Soil, agronomy, and other scientists from the mentioned institutions have generated a wealth of experience, knowledge, and self-development in soil water research and related fields over the past two to three decades. The reviews of Beukes, Bennie et al. in these proceedings and Morse (1996) provide comprehensive overviews in this regard. The number of scientists working in the OSWU domain have increased from about five some 30 years ago to more than 50 at present (A.T.R Bennie, personal communication). The soil water discipline is a popular field of research at various universities (e.g. Bloemfontein, Pretoria, Stellenbosch). Training and infrastructure capacities are maintained accordingly.

Future Expectations

Farmers

As the South African population increases, the demand for food production will expand, putting farmers under increasing pressure to maintain food security. Farmers, like all other water-users, have the responsibility to adopt water-saving and conservation methods in their efforts to produce food. They will need to change toward more efficient use of water by switching to, *inter alia,* more water-efficient and higher-value crops, leaving the lower-value and less efficient crops to be grown in those countries blessed with higher rainfall (Ossin 1999), In these efforts, farmers should make ample use of the existing scientific knowledge and indigenous practices to save and conserve water.

Resources

By. the year 2020 the country will reach its limit in the availability of natural water resources (Ossin 1999). With its mean annual rainfall of 511 mm and only one major perennial river, South Africa is not well-endowed with this resource. Water scarcity will accelerate the present efforts by the government and various industries to reclaim waste water, effluent, and mine water, the latter being a major source of water if it can be reclaimed in an economically viable manner. New legislation on water is reflecting the reality of South Africa's serious predicament and has been successful in increasing public and industrial awareness of the importance of water and the need to start saving this scarce resource.

Science

An integrated approach is tirgently needed to optimize the use of both soil water and nutrients by crops in dry areas for improved efficiency and sustainability. These two aspects have been researched independently for too long. Furthermore, an integrated catchment management approach in which soil water and nutrient balances are determined per land-use pattern within a catchment has never been investigated in South Africa. This is a broader natural resource management perspective that can also supply information to off-site, downstream soil and water users.

With regard to modeling, there is a need for (1) a resource-based model or procedure that can be used to calculate the minimum farm size to produce a required income from crop production, with given soil-climate-crop resource combinations; (2) a model to enable daily rainfall data to be converted into intensity data; such a model is considered essential to obtain reliable long-term runoff values; and for (3) testing the employment of ENSO-based climate predictions in modeling approaches to assist in long-term assessments of the value of different production techniques.

Capacity-Building of NARS

Years of international isolation of South Africa have prevented the establishment of professional linkages with international research centers. Capacity-building was restricted to a few institutions at the national level, sometimes functioning in isolation in this respect and thereby duplicating efforts. However, opportunities for increased collaboration, both on a regional and international scale, are now a reality, and should be strengthened. The advantages for South Africa of recently joining the CGIAR System must now be fully utilized. We should strive to actively participate *inter alia* in the System-wide Soil, Water and Nutrient Management Program (SWNMP), which is aimed at a coordinated, global, multiscale research approach that will be able to draw on the comparative advantages offered by international agricultural research centers, NARS, and advanced research organizations. It will now be possible for our soil water researchers to accelerate their scientific efforts through sharing of experiences and common methods, databases, and models across regions. They should assemble core groups of resource management experts to improve research efficiency through collaboration and capacity-building. The custodian of the

NARS, the National Department of Agriculture, should strengthen institutional capacity to implement policies and programs.

Use of Information Tools and Technologies

Introduction

Locally and internationally developed crop growth and soil water balance computer models are currently being tested and used in South Africa by several institutions. Institutions with GIS facilities have developed their own information systems that function in a GIS environment. Several of these systems are currently in use to provide decision support in e.g. agriculture, forestry, hydrology, and the environment. Likewise many institutions have developed their own databases on natural resources. Some of the largest databases reside with, inter alia, the Department of Water Affairs and Forestry, and the ARC-Institute for Soil, Climate, and Water (ARC-ISCW). To date, lack of national coordination has caused duplication, incompatibility of computer software, and databases being incomplete or inaccessible. A consortium consisting of ARC-ISCW, the University of Pretoria, and the Council for Scientific and Industrial Research has obtained government funding to develop an integrated spatial resource information system for South Africa, known as SA-ISIS 2000. The key objective will be to make data and information (both spatial and nonspatial) on the environment available and accessible to a wide stakeholder group through models, decision-support systems, and the Internet.

Existing DSS, Models, GIS Information Systems and Databases

A list of GIS information systems and databases is given in Table 3, while Beukes, Bennie et al. in these proceedings give a list of models.

Actual Use of DSS, Models, GIS Information Systems and Databases

Long-term results are necessary for reliable production-technique recommendations and production-risk quantification under semi-arid conditions. These are obtainable using tested crop models and long-term climate data. Attempts to improve the reliability of the PUTU and DSSAT wheat and maize models by comparing measured and simulated yields on a range of ecotopes have also been made by Beukes, Bennie et al. in these preceedings. Production forecasts and yield estimates, using GIS information systems linked with crop models, have a major impact on the free market system in South Africa. The functioning of the so-called 'futures market', where tonnage of crops are sold ahead of harvesting and then resold like shares, depends on the first yield estimates of the season. Under the semi-arid conditions of crop production, stored soil water is an important input parameter for crop models. Its efficient management with an appropriate model, like SWAMP, can be a valuable decision support to farmers.

Table 3. Information systems and databases available in South Africa.

Name	Application	Institution
GIS Information systems		
CCWR[1]	Rainfall, temperature, pan evaporation, and altitude	Dept. of Agric Eng., Univ of Natal, Pietermaritzburg
FSDA-IT[1]	Crop estimates and natural resource decision support	Free State Dept. Agric, Bloemfontein
ICIS[1]	Integrated catchment management	Dept. of Agric. Eng., Univ of Natal, Pietermaritzburg
ISCW-GIS[1]	Spatial information on soils, climate, land types, land cover, terrain, etc.	ARC-ISCW, Pretoria
Various	Natural resource, crops, livestock, demo-graphic, developmental, and drought-risk information	Nine provincial depts. of agric.
Databases		
Various	Analyses data, climate, land cover, land types, soil profiles, maps, and topography	ARC-ISCW, Pretoria
Various	Water quality, stream flow, etc.	Dept Water Affairs and Forestry, Pretoria
Various	Rainfall, temperature, pan evaporation, altitude, etc.	Dept. of Agric. Eng., University of Natal, Pietermaritzburg
Various	Land cover, grazing capacity, veld types, erosion, etc	National Dept Agric, Pretoria

1. CCWR = Computing Centre for Water Research; FSDA-IT = Free State Department of Agriculture-Information Technology; ICIS = Integrated Catchment Information System; and ISCW-GIS = Institute for Soil, Climate and Water -Geographic Information System.

Evaluation of Use of Information Tools and Identification of Future Needs

Due to the uncoordinated, fragmentary, and isolated use of models, DSS, GIS information systems, and databases in South Africa, these information technology tools have been underutilized and underestimated in agricultural production. It is therefore foreseen that the use of models and information systems will increase in the near future. A strong need exists to make use of the artificial neural network concept to generate information for quick decision-making, or where quantitative data are lacking. It is envisaged that the SA-ISIS 2000 project will provide an integrated spatial information system for, inter alia, agricultural management and decision support in South Africa within two to three years. The comparative advantages offered by this system to make natural resource data available to a wide interest group through, for example, the Internet will then be available for consortia within SWNMP. The contribution of the latter Program to ecoregional programs will be boosted. Scientific progress will be accelerated through sharing of data, information, methods, and experiences across regions. Research and indigenous knowledge required to globally improve natural resource management and soil water-use efficiency will be more accessible to users and decision-makers.

Conclusions

Agriculturally-related environmental impact, including soil water-use efficiency, has not yet been empirically studied through quantitative measures in South Africa. There is an urgent need to extend the conceptual and empirical initiatives conducted to date, to also include the environmental aspects related to agriculture. Impact assessments should be conducted on the wealth of research (Beukes, Bennie, et al. in these proceedings; Morse 1996) regarding the optimization water use in the semi-arid crop production areas of South Africa. The feedback to researchers, planners, policy-makers, and donors may improve the management and decision-making processes regarding priority-setting, implementation, and management of research activities with respect to soil water research. However, unless impact assessment is institutionalized and the mechanisms are in place to monitor and collect the relevant data as part of the implementation of research programs, *ad hoc* impact assessments would be very costly.

Secondly, locally and internationally developed crop growth and soil water balance computer models are currently being used in South Africa by several institutions. Several institutions have GIS information systems to provide decision support in various fields. Many institutions have built up their own databases on natural resource data. To date, lack of national coordination has caused duplication, incompatibility of computer software and databases being incomplete or inaccessible. A consortium consisting of the ARC-ISCW, the University of Pretoria, and the Council for Scientific and Industrial Research has obtained government funding to develop an integrated spatial resource information system for South Africa (SA-ISIS 2000). The key objective will be to make data and information (both spatial and nonspatial) on the environment available and accessible to a wide stakeholder group through models, decision-support systems, and the Internet. Consortia within the SWNM Program Will be able to draw on this comparative advantage in terms of data, methods, and experience offered by the system.

Thirdly, a strong need exists to make use of the artificial neural network concept, like the Bayesian Belief Network program, to generate information for quick decision-making, or where quantitative data are lacking. With regard to modeling *per se* there is a need for: (1) a resource-based model, (2) a model to convert daily rainfall data to intensity data, and (3) a model to employ ENSO-based climate predictions in modeling approaches. No such model, which focuses specifically on dry areas and the crops grown there, is currently available. It would, however, greatly facilitate the attaining of the overall long-term goal of the OSWU Consortium for WANA and SSA.

Finally, there is an urgent need for an integrated approach to simultaneously optimize soil water and nutrient use by crops in dry areas'for greater efficiency and sustainability. These two aspects have been researched independently for too long. Furthermore, an integrated catchment management approach, where soil water and nutrient balances are determined per land-use pattern in a catchment, has never been implemented in South Africa. This broader natural resource management perspective can also supply information to off-site, downstream soil and water users.

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Impact of Optimizing Soil Water Use Research, and the Need for Using New Information Tools and Methodologies in Syria

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Abstract

Farming in dry areas is associated with high risk both in terms of year-to-year fluctuations in yield, and long-term decline in productivity due to degradation of the resource base. Research results clearly indicate that there is a great potential for increasing food and feed production to meet the demand in Syria while conserving water resources and improving soil productive capacity through improved soil and crop management practices in the rainfed regions of the country. However, experimental results obtained either from experimental stations or farmers' fields have yet to be transferred to farmers in wider areas. The Syrian government has placed a special emphasis on this aspect in the last decade. Most of the research findings have been tested through improved variety trials for evaluation and release, through participatory on-farm trials or through demonstrations in farmers' fields by extension agents. As a result of these efforts, yield increases of 1-2 t ha^{-1} have been observed in the last decade following adoption of certain soil and crop management practices under rainfed conditions. These practices include more timely cultivation, earlier sowing, increased planter use compared to broadcast method, improved fertilizer use in the drier areas, P in particular on barley, and pest control practices related to diseases, insects and weeds. Major yield increases have been observed by introducing supplemental irrigation for winter crops, wheat in particular.

A GIS unit was established in 1993 within the framework of a development planning project to assist in the preparation of an agro-ecological assessment of agricultural potential and the quantitative analysis of some of the most pressing problems in Syria, i.e., soil

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degradation and water resource deficiency. Soil databases have been stored in digital format, processed, and analyzed and outputs given to decision _makers to be used for prioritization of agricultural research and development projects.

Resume

L'agriculture en zones seches est associee a des risques de production eleves, aussi bien en terme de variabilite inter-annuelle des rendements que de baisse de productivite suite a la degradation des ressources. Les resultats de la recherche ont demontre le potentiel pour ameliorer la production d'aliments pour repondre a la demande tout en preservant les ressources en eau et la capacite de production des sols au moyen de pratiques ameliorees de gestion des sols et des cultures dans les zones pluviales du pays. Cependant, les resultats experimentaux obtenus soit a partir d'essais en station, soit de maniere localisee dans les champs paysans doivent a ce jour encote etre transferes a plus grande echelle. C'est dans ce domaine que le gouvernement a porte toute son attention au cours de la derniere decade. La plupart des resultats de la recherche ont ete testes au moyen d'essais varietaux pour leur evaluation , d'essais participatifs en milieu paysan, et de demonstrations par les services de vulgarisation dans les champs des paysans. A la suite de ces efforts, des augmentations de rendements de 1 a 2 t ha-1 ont ete observees sous culture pluviales au cours de la derniere decennie suite a l'adoption de certaines pratiques de gestion ameliorees. Ces pratiques comprennent des pratiques culturales opportunes, le semis pricoce, l'utilisation de semoir plutot que le semis a la volee, l'amelioration de l'utilisation des engrais en zone seche et en particulier le P sur l'orge, et les pratiques phytosanitaires contre les insectes, les maladies et les adventices. Des augmentations de rendement importantes ont ete constatees suite a l'introduction de l'irrigation d'appoint dans les cultures d'hiver, et dans le ble en particulier. Une unite de SIC a ete mise en place en 1993 dans le contexte d'un projet de planification du developpement afin d'assister dans la preparation d'une evaluation agro-ecologique du potentiel agricole et l'analyse quantitative de certains des problemes les plus importants en Syrie, a savoir la degradation des sols et le deficit des ressources hydriques. Ainsi, des bases de donnees sur les sols ont ete digitalisees, transformees, et analysees, et les resultats ont ete communiques aux decideurs pour etre utilises dans la prioritisation des projets de recherche et de developpement agricole.

Introduction

Farming in dry areas is associated with high risk both in terms of year-to-year fluctuations in yield and long-term decline in productivity due to degradation of the resource base. The dry areas are characterized by fragile ecosystems where soil erosion, overgrazing, and depletion of water and nutrient reserves can threaten long-term productivity.

The climate, soils, land-use pattern, production systems and socioeconomic aspects of Syria have been dealt with in detail by Jumaa et al. in these proceedings. Dryland farming is characteristic of northern Syria, and pastoralism is practised in the steppe. There are opportunities in Syria for increasing crop and livestock production through the use of improved crop genotypes integrated with improved soil and crop management practices, which can lead to more efficient use of natural resources (soil and water) and externally derived inputs (fuel, fertilizer, and pesticides). On the other hand, improper management practices may lead to severe environmental degradation, unless proper attention is given to resource conservation. Sustaining increases in agricultural production while simultaneously conserving the resource base through optimized soil water use is a vital objective of our studies.

Agriculture and rural development have been given the highest priority by the Syrian government. The most important underlying aims are: Achieving self-sufficiency in strategic basic food commodities; making optimum use of land and water resources and conserving these resources where they are threatened; increasing the productivity and output of crop and livestock production; and, above all, applying the principles of liberalization and competition to the rural scene. Implicit in both the national economic and agricultural development policies is the concern of the government for the welfare and advancement of the rural people and for alleviation of poverty. This has become more important in recent years as the incidence of drought in agricultural production areas has become more frequent, while the high population growth has continued.

Although irrigated agriculture accounts for up to 60% of crop production, rainfed cereals, dryland horticulture, and range and village sheep production are the cornerstones of the Syrian farming system and the principal anchors of the pattern of rural life. Therefore, improving the utilization of rainwater through drought-tolerant field crops combined with improved management practices has received much attention in the principal research programs carried out in collaboration with ICARDA. In addition, there has been great emphasis placed on optimizing supplemental irrigation water availability from surface as well as underground sources for winter crops in the rainfed areas of the country. Major components and results of research in relation to optimizing soil water use have also been dealt with by Jumaa et al. in these proceedings. It can be summarized here that proper crop rotation using high-yielding, drought- and disease-resistant varieties grown on a well-prepared seedbed, with optimum sowing time and plant geometry, adequate fertilization, and protection from diseases and pests can substantially improve the productivity of water available either from rainfall or from other sources.

The aim of this paper is to present the impact of past research in the domain of optimizing soil water use, to identify further research needs, and to present the use of information tools and technologies to characterize the biophysical and socioeconomic environment for prioritization of research and improvement in decision-making.

Impact of Water-Use Efficiency Research

Impact on Farmers

Research results clearly indicate that there is a great potential in Syria for increasing food and feed production to meet the growing demand, while simultaneously conserving water resources and improving the soil productive capacity through amended soil and crop management practices in the rainfed regions of the country (see Jumaa et al. in these proceedings). However, results obtained either from experimental stations or farmers' fields are yet to be transferred to farmers in wider areas. The Syrian government has placed special emphasis on achieving impact from research and translating results into production increases and sustainable natural resource management.

Most of the research findings have been tested in farmers' fields in one way or another. Verification trials for improved varieties for evaluation and release (GP 1995; 1996), on-farm trials conducted in farmers' fields with the farmers' involvement (Jones and Wahbi 1992; Pala et al. 1996a), and demonstrations in farmers' fields by extension agents in collaboration with farmers and researchers (Extension Directorate 1989) are examples of such efforts. As a result, yield increases of cereal crops of 1-2 t ha^{-1} have been observed in the last decade under rainfed conditions, facilitated by the adoption of certain soil and crop management practices. The practices accountable for this production increase include more timely cultivation, earlier sowing, increased use of planters in preference to broadcasting, improved fertilizer use in the drier areas (particularly of P in barley), and adoption of pest, disease, and weed control. However, the most important factor for yield increase has been the introduction of supplemental irrigation for winter crops, in particular wheat (Oweis 1997).

With respect to the impact of research on production increases and overall resource-use efficiency in Syria, there has not been much work carried out directly by the national program. However, since Syria's agricultural policy pays special attention to wheat production, with the twin objectives of improving the living standard of producers and achieving self-sufficiency, the government has concentrated its planning on improving the productivity of the existing wheat land, therefore tailoring research to fulfil that need. Toward that goal, extension and credit institutions have been, organized, and farmers encouraged to mechanize production. The government has initiated various infrastructure projects to provide irrigation facilities, and wells are being dug by the government and the private sector.

Through a cooperative program between the Ministry of Agriculture and ICARDA, new varieties of lentil (Idleb 1) and chickpea (Ghab 3) were widely adopted by farmers because of their high yields and disease resistance. Wheat varieties grown since 1994 are Cham *4,* Bohoth 1, Bohoth *4,* and Bohoth 5 under irrigation, Cham 5 and Cham 6 under rainfed cropping, and Cham 1, Cham 3, and Bohoth 6 under rainfed/irrigated conditions. Cham 1 and Cham 3 cover about 63% of the total durum wheat area, and about 56% of the wheat producers grow these two varieties. Local durum wheat varieties are grown by only 27% of the farmers, showing a very high rate of adoption of the improved varieties (Mazid et al. 1998). However, few farmers have adopted the new improved barley cultivars irrespective of their productivity and increased water-use efficiency, due to the high costs and, often, nonavailability of seeds and lack of information about them.

Several research results have demonstrated that appropriate fertilizer use improves water-use efficiency (Cooper et al. 1987; Cooper 1991). According to a diagnostic farm survey on barley production in 1982, average barley yields were around 0.5 t ha^{-1}, and only about 10% of the farmers were using fertilizer on barley in Zone 2 and Zone 3. After several years of on-farm research on barley responses to fertilizer, conducted in collaboration with ICARDA (Jones and Wahbi 1992), a positive impact could be observed on farmers' adoption of fertilizer use on barley. According to the latest survey, 87% of the farmers in Zone 2 but only 47% in the drier Zone 3 were using fertilizer on barley, which demonstrates the differences in behavior of farmers from different agroecological zones (Mazid 1994). As a result of these studies, the government has adjusted its fertilizer allocation policy in order to improve the total agricultural output.

On the basis of the strong emphasis given to technology transfer to farmers, the Socioeconomic Department of the Directorate of Scientific Agricultural Research, the Ministry of Agriculture and Agrarian Reform, conducted a multiyear study on the adoption and impact of improved wheat production technology in collaboration with ICARDA. The farm survey was conducted over three seasons and included nine provinces representing about 91% of the national wheat area (Mazid et al. 1998). The results of this survey were presented on the basis of a production function fitting best the components of production practices applied by farmers. This production function uses multiple regression analysis, linking the productivity of each hectare with multiple variables such as rainfall, high-yielding variety, number of irrigations, quantity of applied nitrogen fertilizer, previous crop, and application of herbicides. The model could explain about 53% of the changes in durum wheat yield in Syria (Mazid et al. 1998).

Multiple regression analysis based on the survey results indicated that improved varieties increased yield by 847 kg ha^{-1} compared to local varieties; growing durum wheat after legumes or a summer crop increased yield by about 659 kg ha^{-1} compared with continuous wheat; and that the application of herbicides increased average yield by 302 kg ha^{-1} in the same field. Each 1 mm of rainfall increased durum wheat yield by 1.91 kg, and the use of 1 kg of net nitrogen increased yield by about 6.5 kg. This increase slows down with higher application of N fertilizer until an optimal limit *is* reached, after which production decreases (Mazid et al. 1998).

Using supplemental irrigation, the expected yield increase is 1,049 kg ha^{-1}, and about 1,755 kg ha^{-1} under, full irrigation. When the number of irrigations surpasses the recommendations, the expected yield is 1430 kg ha^{-1}. This clearly demonstrates that application of full irrigation or more-than-recommended irrigation water reduces the water-use efficiency of wheat remarkably. If this message can be conveyed to farmers, the impact of research on supplemental irrigation would be substantial: it would allow allocating the same amount of water to larger areas, and substantially increasing the total production of winter crops, particularly of wheat which is the strategically most important staple crop for the country (Oweis 1997).

Agricultural technology affected all groups of farmers, small, medium, and large holders. This is a more positive result than has been experienced in other countries, where technology generally favors large holders, and small farmers often do not benefit at all. The preliminary estimate was an increase of 1,661,000 tons of durum wheat. National income would increase by about 17.4 billion Syrian Lira annually (407 million US$). About 23% of this increase is due to the impact of irrigation, 34% to the use of improved varieties, 24% to fertilizer, and 19% to land and crop management. About 32% of the impact came from fully irrigated areas, 31% from supplemental irrigation areas, and 37% from rainfed areas. In spite of this remarkable increase, there is still a gap in productivity between potential and actual yield. This requires further effort, either in agricultural research or extension (Mazid et al. 1998).

Impact on Science

Research directed at increasing production through optimized use of soil water either from rainfall or other surface or underground water sources, or by using rainwater harvesting technologies has been described by Jumaa et al. in these proceedings. Many research results have been transferred to farmers and adopted to various degrees, depending on their socioeconomic conditions. However, one major impact of all this research was to improve the scientific knowledge of the researchers involved in the studies. It helped in (1) creating a better understanding of the physical, chemical, biological, and environmental principles that underlie and control the productivity and sustainability of cropping systems, particularly with respect to soil characteristics, and water and nutrient dynamics; and (2) developing strategies for efficient management of soil, water, and nutrients in production systems.

The review of past research by Jumaa et al. in these proceedings, as initiated by the OSWU Consortium, was a tool to define the existing problems and to prioritize future research with respect to soil water use and its optimization.

Capacity-Building of NARS

Human resource capacity-building through training activities is the main focus of many research programs. Only increased understanding of the principles of the soil-water-plant relationships underlying improved soil and crop management practices can help to solve the problems related to production systems and facilitate identification of improved production and natural resource management.

The number of NARS scientists working in the domain of soil and water management has increased from 8 in the mid 1970s to about 120 now. Several regional and international institutions such as ACSAD and ICARDA work very closely with the NARS in this area, to train the local researchers in soil water and crop improvement and management research, and conduct collaborative research in the OSWU domain.

Future Expectations

Given the high population growth of about 3.3% in Syria, the food and feed demand has to be met in the future in an environment of even more limited resources, particularly of water. Although a bigger part of agricultural production comes from irrigated agriculture, rainfed areas still cover 80% of the total cultivated land. Therefore, optimizaticn of rainwater use holds great potential for increasing the agricultural production. In addition, wherever water is available in rainfed areas, the technology of supplemental irrigation rather than full irrigation for winter crops has to be transferred to farmers in order to get maximum efficiency of use of scarce water resources.

More emphasis will have to be given to transfer of improved soil and crop management practices to farmers, including improved crop varieties in optimum crop rotations, to achieve sustainable and economic production. Further, more research is needed on water harvesting in the dry areas, and residue management for water conservation and improving soil fertility in order to obtain maximum benefits in terms of optimization of soil water use.

Use of Information Tools and Methodologies

The Syrian Ministry of Agriculture's mandate includes the promotion of agriculture through sustainable use of natural resources, most notably land and water. Such an objective cannot be achieved without reliable information on soil and water resources. This is possible after assessing the availability of reliable information and finalizing the structure of a database, and present it in a standard format for potential users.

Existing DSS and Models

Decision-support systems are not yet in use in Syria. Although agricultural land is mostly owned by the private sector, the Government controls agricultural cropping and prices. Law 14 of 1975 prescribes how agricultural land should be used, and provides for penalties for noncompliance. Accordingly, production plans and targets for different crops are set on an annual basis by the Supreme Council on Agriculture, and implemented by the Ministry of Agriculture and Agrarian Reform (MAAR). Production licenses are issued by local authorities to individual farmers and cooperatives. On the basis of these, farmers and cooperatives can apply for preferential loans and subsidized inputs. Some of the crops are in the process of deregulation, but the Government retains the statutory right to regulate other crops in the irrigated areas in the interests of sound rotational practice for improved use of water and externally derived inputs. In contrast, livestock, fruit, and vegetable production are free from regulations.

Besides its control of cropping, the Government sets the procurement prices of major crops and of the inputs. Procurement prices, which had been maintained below their free or international market levels in the past have been adjusted in the last few years to exceed in some cases world market prices. Meanwhile, prices of agricultural inputs, which have been subsidized to date, are gradually being adjusted to reflect market levels.

Crop simulation models such as CropSyst and SIMTAG are mostly used at ICARDA, and their outputs have been given elsewhere (Stapper and Harris 1989; Stapper 1993; Stockle et al. 1994; Pala et al. 1996b; Pala 1998).

Existing GIS and its Actual Use

A Geographic Information System (GIS) uses geographically referenced data as well as nonspatial data, and includes operations which support spatial analysis. A GIS is a unique system to capture, input, store, retrieve, manipulate, analyze, and present geographic data to produce interpretable information. The use of GIS aims at answering real-life questions. The components of GIS are hardware, software, data, and people.

The MAAR needs to utilize a GIS system because of the need for tools and personnel able to strongly enhance the ministry's planning and management capabilities; necessity of technological advancement to quantitatively approach important subjects like land evaluation, land-use planning, natural resource management, and environmental assessment and planning; necessity of producing high-quality outputs in due time; and need for sustainable planning and management of land. Thus, a GIS unit was established in the Soils Directorate in 1993 within the "preparatory assistance to agroecological assessment of the agricultural potential for development planning" project. Quantitative analysis of resources is required for some of the most pressing problems of soil degradation in Syria, such as rapid deforestation, water overexploitation and degradation, rapid urbanization, and demographic expansion.

Sustainable planning and management requires a quantitative analysis of the most serious problems in Syria, i.e., soil degradation (erosion, salinity, desertification, waterlogging, etc.) and water-resource deficiency. Therefore, the main aim of establishing the GIS unit was to develop a soil database in digital format in order to process, and analyze the information and support the decision-makers.

The outputs obtained from this project have been:

- Soil units map at a scale of 1/500,000
- Climatic map (127 climatic stations)
- Soil suitability map for wheat in Syria

- Climate suitability map for wheat (length of growing period)
- Soil and climate suitability map for wheat at a scale of 1/500,000
- Irrigation methods map (drip-sprinkler-flow) according to soil classification data.

The Soil Directorate has carried out other projects using GIS facilities, such as the development of a soil database (SOTER) aimed at producing thematic maps, soil degradation maps, and calculating water erosion.

Other projects conducted include:

- Monitoring and Combating Desertification in the Syrian Steppe, or "The Bishri Mountain Project", in cooperation between ACSAD, GORS, and the German company for technical cooperation, GTZ, in which GIS was utilized to determine the affected sandy areas and the changes that have been taking place in the steppe over many years.
- Mathematical modeling to define water harvesting, maximum water accumulation, and location through a DEM 3-dimension system; flow direction and maximum accumulation of water were calculated by flow accumulation in crossing with a rainfall data map.

Evaluation of GIS Use and Future Needs

The GIS unit in the Soil Directorate is carrying out specific jobs according to the ministry's needs. This work is being conducted at a good level of performance with regard to the available equipment and existing database.

The future needs run parallel with the Soil Directorate's objective to achieve an optimal database system, i.e., to reduce the scale of data from 1:500,000 to 1:25,000. Establishing such a soil information system needs more training opportunities that deal with metadata and rational database management systems. Furthermore, software needs to be updated with the latest versions, accompanied with compatible hardware that can operate these systems. If these needs can be satisfied, its expected that the Soil Directorate-GIS section will fully achieve its mandate.

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Impact of Water Use Efficiency Research and OSWU, and Use of Information Tools and Methodologies in Turkey

M Avci[1]

Abstract

In the last 50 years, improved crop husbandry practices and crop varieties have increased wheat yields three-fold, from 0.8 t ha^{-1} to 2.4 t ha^{-1}. In this success, the techniques developed for water conservation and efficient water use have played a major role. Activities for optimum use of soil water have dominated the research programs of the NARES and contributed much to their scientific development and capacity-building. The OSWU Consortium has facilitated a review of past developments in this domain, and an elucidation of future research needs. Besides conventional methods, the use of new intelligent tools and satellite-based information systems has been increasing. However, these activities seem to be uncoordinated and disparate. Therefore, they need reorganization and transformation into large-scale coordinated projects.

Resume

Au cours des 50 dernieres annees, l'utilisation de varietes ammeliorees et de pratiques ammeliorees de gestion des cultures a permis de tripler les rendements en ble, passant ainsi de 0.8 a 2.4 t ha^{-1}. Ce succes est du dans une large mesure au developpement de technologies permettant la consevation et une utilisation plus efficiente de l'eau. Les activites liees a la gestion optimale de l'eau du sol ont domine les programmes de recherche des SNRA et ont largement contribue au developpement de leurs capacites humaines et scientifiques. he consortium OSWU a permis d'evaluer critiquement les acquis dans ce domaine et d'identifier les besoins futurs en matiere de recherche. En plus des, outils conventionnels, l'utilisation de nouveaux outils intelligents et de systemes d'information bases sur les

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informations satellitaires est en progression constante. Cependant, ces activites continuent a etre menees sans grande coordination et au cas par cas. Une reorganisation et une transformation de ces activites en projet de grande envergure semble donc necessaire.

Introduction

Water conservation and efficient use are the primary principles of agriculture in Turkey's dryland areas. Because farmers know the importance of rainfall, which is the primary and only source of water, they call it "rahmet" meaning abundance. Recognizing soil water as a vital factor in agriculture, the government has supported water conservation and efficient use ever since the establishment of the republic. So, almost all of the research thus far has been directed toward production technologies to increase water conservation, particularly in fallow areas, and efficient water use by wheat crops (Avci, in these proceedings).

In addition, there have been intensive research programs* aimed at producing new, high- yielding varieties of crops over the past three or four decades. Special attention has been given to breeding for resistance to diseases and insect pests, and a good deal of success has been achieved. However, although improved high-yielding varieties are available, yields of crops at the farmers' level have remained unsatisfactory. This is largely due to poor management of soils and crops. It is well-understood that improved crop varieties cannot realize their yield potential unless good soil and crop husbandry practices accompany them, and vise versa. In the harsh environments of the dryland areas, the main factor limiting crop yields is availability of water. Variability in water supply due to seasonal differences in rainfall leads to proportionate variability in crop yields. On the other hand, research indicates that good management along with improved crop varieties can considerably increase the efficiency of use of available water from rainfall, leading to high crop yields (Avci, in these proceedings). In other words, more production can be achieved from each mm of rainfall if the crop is well-established and adequately fertilized, the weeds are eradicated, and good crop rotations employed.

This paper highlights the impact of past research in the field of optimizing soil water use, and makes an inventory of information tools and methodologies to scale up these technologies.

Impact of Water-Use Efficiency Research

In general, improved varieties and efficient crop husbandry practices have increased wheat yield three-fold in the last 50 years, from 0.8 t ha^{-1} to 2.4 t ha^{-1} (Fig. 1). This increase was largely due to improvements in the rainfed wheat production system, as more than 90% of the wheat acreage is in the dryland areas.

Research results indicate that good and timely tillage practices during fallow led to higher water conservation and higher yield and better weed control in the subsequent crop (Avci, in these proceedings). Use of agricultural machinery allowed farmers to

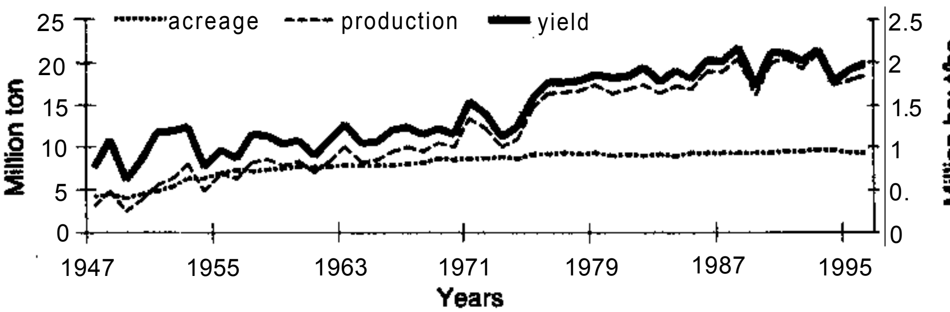

Figure 1. Trends of cropped land, production, and yield of wheat from 1947 to 1996 in Turkey.

till the land and sow the crop in time. This resulted in higher yield of wheat through increased rainwater-use efficiency (Kalayci et al. 1989).

After extensive research in dryland agriculture, a package of practices was developed and transferred to the farmers. The majority of the farmers have adopted this package in the dryland region. Uzunlu (1992) indicated that the adoption level of the recommended wheat technology for the wheat-fallow system by Central Anatolian farmers was about 59%. The underlying reasons for nonadoption of new technologies were the complexity of the technologies, lack of information, and the cost of or nonavailability of inputs at the required time.

Since 1980, research has been directed to eliminate fallow to further increase water-use efficiency. Research activities on long-term crop rotations and short-term management techniques were planned and conducted with rural development and extension projects. Fallow replacement with legume or oilseed crops remarkably increased the WUE in Central Anatolia. Except continuous wheat, most of the cropping sequences were economically worthwhile. Fallow-replacement projects were successfully conducted, and annual cropping was largely adopted by farmers, although incentives that were given to farmers to produce legumes instead of fallowing the fields were suspended after two years of application. At present, farmers grow chickpea, lentil, and sunflower in rotation with wheat or barley. These farming practices proved to be economic and profitable in most cases because the farmer earns money every year instead of once in two years. This provides extra benefits to farmers against the high inflation rate by gaining cash money one year in advance, and farmers are able to make some savings also by avoiding tillage expenditures in the fallow year. Economic returns from some edible legumes or oilseed-wheat rotations were estimated to be at least 119% compared with the fallow-wheat rotation (Uzunlu and Ozcan 1987). The latest statistics show that the replaced fallow areas by those crops is about 5 million ha. Today, only 4 million ha is allocated to fallow.

Production of edible legumes on fallow increases food security for the rural and urban population and allows a more balanced diet. It also ensures that the poorest segments of society have an adequate income or entitlement to meet the basic nutritional requirements. The decrease in grain yield of wheat by 3% to a little more than 10% under annual cropping as compared with wheat yield after fallow does not pose any threat to food security related to wheat production at the farmer's as well as the national level. On the other hand, Turkey has become one of the prominent exporters of food legumes in the world.

Science and Capacity-Building of NARES

Extensive crop management research on agriculture in Turkey's dryland conditions has generated a lot of experience and led to improved infrastructure, especially for soil, water, and nutrient management research. Many research institutions have their origins in the "Seed Improvement Station" which was a former institution under the Central Research Institute for Field Crops (CRIFC), such as institutes today dealing with soil and fertilizer, plant protection, agricultural machinery test and research, and seed certification.

Turkish research institutions were well-equipped by some national research and extension projects such as the Agricultural Extension and Adaptive Research Project (TYUAP), Fallow Replacement Project (NAD), and to some extent the Agricultural Research Project (TAP). The majority of the research institutions have their own laboratory equipment to carry out basic soil and plant analyses that help in increasing the outputs of research in the domain of optimizing soil water use. ICARDA-supported projects have also played an important role, and have made a great contribution to the development of production technologies.

OSWU Activities and Future Expectations

The first significant activity of the OSWU Consortium was to review past research aiming at efficient soil water use. This activity, supported financially by the OSWU Consortium, was a very important opportunity for researchers to review and draw conclusions from past research. It enabled us to identify and understand the research background in this subject, and learn about the successes and failures of the process of transfer of technology to farmers. In the light of the review, the research subjects that have high priority for each country were determined. Future planning for optimizing soil water use would be based on this review.

In the future, OSWU will make positive impacts on poverty alleviation and food security. In dry areas, food and feed production is totally dependent on the amount of precipitation-induced soil water. Nutrient- and water-use efficiencies are closely related. Farmers must adopt practices for trapping water in the soil, for conserving it for later use, and for efficient crop use/Efficient infiltration, conservation, and use of water will result in higher food and feed production, which will per se lead to food and feed security for man and animal.

Higher crop production may be accomplished partly by lessening surface runoff, increasing infiltration, partly by reducing evaporation from the soil and partly by efficient use of water by suitable crops and cropping patterns. In some cases, in spite of an increase in water accumulation in the soil and consequently the yields, the water-use efficiency might not have increased. This indicates that increase in water-use efficiency is much related to genotypic differences in crop species. Thus, crop management research should be closely coordinated with variety-improvement programs. The Department of Agronomy of CRIFC, in contrast with other soil and water institutions, works in close collaboration with the varietal development (crop improvement) programs in the same institute and other similar institutes.

Increase in the WUE of any crop variety cannot be maintained unless the amount of accumulated water is sustained for a long period. This can be achieved through improved soil physical conditions such as improved infiltration, and/or reduced runoff and soil loss. Turkey's land characteristics and soil properties give scope for soil and water losses because most of the dryland areas have steep slopes and are vulnerable to accelerated erosion. Furthermore, addition of crop residue to agricultural soils is not widely practised. This aggravates the threat of erosion. All these factors lead to yield decline regardless of the rotational system.

Our expectation from the OSWU Consortium is that it should support research in Turkey, aimed at (1) improving soil physical properties in order to catch and store rainwater; (2) reducing runoff and soil loss; and (3) to identify a new system to leave crop residue or cover crops on the surface which will add organic matter to the soil and protect it, particularly in sloped areas.

Use of Information Tools and Methodologies

In Turkey, the State Statistics Institute is one of the main institutes dealing with all kinds of data. The Ministry of Agriculture and Rural Affairs (MARA) has its own agency for this task. The Project and Statistics General Directorate of MARA has an agency in each county; it has the responsibility of implementing projects and collecting crop information regularly, and submitting it to the general directorate.

Modern information tools and methods are being used by many institutions in Turkey. However, the difficulties experienced in accessing information on research activities from various sources, and in using information tools and models indicate that the attempts to make use of modern information technologies have been rather erratic, small-scale, and uncoordinated.

The TUBITAK-MAM (Marmara Research Center of Turkish Scientific and Technical Research Institute) and Cukurova University are the most experienced information technology users. For about five years, work has been intensified to create databases in some areas. The disparate activities on decision-support systems (DSS), models, and GIS being conducted in Turkey indicate that they are relatively new, although some intensive experience is being accumulated in some local institutes.

Existing DSS, Models, GIS, and Databases

Information Technology activities have so far been concentrated on the use of GIS technologies. Remote-sensing methodologies form the base of these activities. During 1984-86, a pilot project was conducted to determine the wheat acreage in Turkey. It used satellite images provided by Landsat (TM and MSS). It was very successful in determining the areas of wheat in large fields of state farms. The estimate of wheat areas in state farms was as precise as 95% of the real acreage. However, the resolution of the Landsat images (30 x 30 m) was too low to detect small fields, and thus the methodology was not applicable nationwide. TUBITAK-MAM-BTAE, the group of Space Technologies (UTG), has been conducting the following projects.

GIS Base for Yesilirmak Basin Development Project

The objective of this project is to provide natural, economic, and social parameters of five provinces located in the basin in computer software for planners and decision-makers. A three- dimensional digital model of the basin has been prepared integrating land use, vegetation, soil and climate information, and roads and administrative boundaries of the urban areas. The 'agroecological zones of crop production' were determined as a sample of the use of prepared layers of GIS.

Monitoring Watershed Management Activities in Eastern Anatolia Through Satellite Images

The results and impact of the activities of the inhabitant-participatory watershed rehabilitation and management project, financed by the World Bank and conducted by MARA and the Forestry Ministry, have been monitored using satellite images. The project was successful in determining the actual economic situation of the project area. It is planned to apply this methodology to other watersheds.

Erosion Mapping by Using Satellite images

The objective of the project was to determine and map the extent of soil erosion in the Dalaman stream basin. The project has been successful. A map was produced along with the soil conservation measures recommended for the area such as terracing, contour tillage, and strip cropping (MAM 1996).

Miscellaneous Projects and Activities

The Department of Soil of the Cukurova University has completed the land-use and soil maps of the Southeastern Anatolian Project (GAP) by using satellite images and ground data. The ODTU and BILKENT universities have laboratories for processing the image data, and have performed some work, although not related to wide areas. The Ankara University agricultural faculty has carried out a wheat modeling project in collaboration with CRIFC and Trace Regional Research Institute to test the available models and identify ways to construct a new wheat model for Turkish conditions. A few years ago, ICARDA also initiated training as well as application of a cropping systems simulation model (CropSyst) for wheat in the Central Anatolian Plateau in collaboration with CRIFC and the Soil and Fertilizer Research Institute (SFRI). The results were promising since crop growth, cumulative evapotranspiration, and grain yield of an improved wheat variety (Gerek 79) under different rates of N application could be simulated with 90% agreement with the actual data.

As a part of the Insitu Conservation of Genetic Diversity Project, a GIS and remote-sensing center has been established at MARA. This project provided technical assistance to the personnel of three ministries, MARA, Ministry of Environment, and Ministry of Forestry. The support was provided by ESRI Inc. of Redlands, California, and ISLEM GIS of Ankara, Turkey. The project mainly focused on preparing a database design, performing data automation, and documenting the automation procedure.

In the framework of the project, 1:30,000 scale soil maps for the Ceylanpinar pilot area and 1:25,000 scale maps for the Kazdaic pilot area were automated, referenced to UTM (Universal Transverse Mercator) coordinates, and linked to attribute data. These base maps and thematic maps provided the means for the linkage of the plant species-related fieldwork data. Huge amounts of data of the Kazdaic pilot area could not be automated fully because of some difficulties originating from the linkage of field data. Two other important data sources for the project, i.e. the National Plan and the Turkish Climate Atlas were digitized, and a valuable Turkish Database was created. The layers were political boundaries, settlements, drainage network, transportation, and digital terrain automated on the 1:250,000 scale topographic map which can be perfectly used for identification of target zones for specific technologies, including optimizing soil water use.

The Soil and Fertilizer Research Institute in Ankara has been trying to make a digital soil map by transferring the previous soil map and its attributes into software.

Future Needs

The most important and urgent need for DSS, models, and GIS works in Turkey seems to be centralization and coordination of all activities and infrastructure, and directing it to broader problems. This will strengthen the efforts for establishing information systems and provide a good deal of economy. In the present situation, each institution has been trying to set up a GIS laboratory, implement small projects, and train its personnel. The solution is to create a task force to deal with problems in forming databases needed at the national level. Small projects do not cover problems as a whole, and effort, time, and funds are not used effectively and are wasted to some extent.

Nationwide, multidisciplinary as well as interdisciplinary and collaborative projects are necessary to be effective in implementation, in identifying tangible solutions to problems, and to process all accumulated information into efficient decision-support systems.

In terms of effective use of soil water, an early-warning system should be established to inform farmers about possible drought spells and their severity. In order to do this, georeferenced soil databases for agricultural lands and continuous meteorological data flow and crop models are required.

Conclusions

The following conclusions can be drawn regarding the impact of research on water-use efficiency in Turkey.

- Turkey has made great progress in dryland cereal production, mainly due to improved technology for efficient water conservation and use.
- The activities of various projects to improve wheat yields through optimizing soil water use resulted in good capacity-building of NARES.
- The OSWU Consortium, by facilitating a comprehensive review of research for optimizing water use, has made a great contribution to prioritizing the future needs for research and extension.
- Decision-support systems, model use, and GIS applications and related infrastructure in Turkey require centralization and coordination to make them cost efficient and allow efficient use.

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Impact of Optimizing Soil Water Use Research and the Need for Using New Information Tools and Methodologies in Zimbabwe

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Abstract

Considerable research on optimizing soil water use in semi-arid environments has been documented. However, the impact of such research on the livelihoods of the poor rural communities and on research institutions has not been widely reported. This paper reports some of these impacts. The state of research information record-keeping in Zimbabwe is assessed to determine whether modern information tools and methodologies can be used to increase research efficiency. The role of the OSWU Consortium and its activities in spearheading research in optimizing soil water use is outlined.

Resume

Les activites et resultats de la recherche dans le domaine de l'optimisation de l'eau de sol dans les zones semi-arides ont ete documentes. Par contre, l'impact de cette recherche sur la vie des communautis rurales et les institutions de recherche n'a pas ete suffisamment documente. Ce chapitre presente quelques exemples de ces impacts. Il present igalement l'analyse du niveau de sauvegarde des informations fournies par la recherche afin de determiner si les outils d'information modernes peuvent itre utilises pour accroitre l'efficacite de cette recherche. Le role du consortium OSWU et ses activites comme fer de lance dans la recherche de l'optimisation de l'utilisation de l'eau de sol est igalement presente.

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Introduction

The success of any technology or innovation can be measured against its success in substantially reducing poverty and improving the quality of life of its beneficiaries. In this case, the success of optimizing soil water use research can be assessed against its impacts on poor rural communities living in the semi-arid areas.

Research on optimizing soil water use in Zimbabwe has been going on for some time. Unfortunately, the information generated has not been compiled systematically, has many gaps and is not readily accessible to other researchers and end-users (Mzezewa et al. in these proceedings). For instance, information has not been collected in the format that can be manipulated in the Geographical Information Systems (GIS) or for modeling purposes.

This paper highlights the impact of past research on optimizing soil water use and explores use of information tools and methodologies to further investigate options for enhanced efficiency.

Impact of Soil Water Use Efficiency Research and of the OSWU Consortium

Past Research

The Overseas Development Administration (ODA)-funded program in southeastern Zimbabwe on community garden schemes using limited ground water resources (Lovell et al. 1996) is an excellent example of transfer of technical research findings from the research station to the real world. The project evaluated innovative ways of providing rural communities in the semi-arid areas more reliable and safer water supplies for domestic purposes and for garden-scale production of vegetables for home consumption and sale. Baseline surveys and routine monitoring showed that:

- The schemes are economically viable, with an average internal rate of return of 19% and annual total gross margins of US$ 2500 ha^{-1} per scheme.
- Price increases for plots within the garden schemes indicate the degree of welfare improvement that the program is bringing to its members. Many people originally uninterested in the scheme now wish to join, to the extent that at one site there is a willingness to forfeit 16% of a year's income from rainfed crops as participation fee.
- The schemes provide extensive marketing opportunities for the sale of dry-season vegetables to the surrounding communities and townships. The schemes also offer an opportunity for wealth creation and income diversification.
- The wells and gardens play an important role in improving the welfare of women and children in the community, by making more efficient use of time and labor allocated to horticultural practices, improving nutrition in the household, and providing an important source of disposable income for household items, education fees, etc.

Routine monitoring and feedback from local institutions have indicated that some specific environmental benefits of the schemes include:

- A reduction in pressure on the cultivation of marginal lands, particularly stream banks.
- Decreased soil erosion due to a reduction in the cutting of nearby trees and bushes used to build and repair garden fences.
- The promotion of "long-term" land management strategies, due to decreased risk and improved security of tenure the scheme supplies.
- The experience and confidence gained from implementing and managing the community garden can help in the implementation of further community-focused projects that promote sustainable environmental management practices.

The Romwe catchment study established a research facility in Natural Region IV (Lovell et al. 1998). The catchment is fully instrumented to measure all components of the water balance. Hydrological, social, and economic baseline information has been assembled with the participation of the local people, and a comprehensive database established. For example, in the 1995/96 season runoff was reported to be equivalent to 4.6% and 20.5% in the red and grey sub-catchments and 8.2% and 9.4% from the woodland subcatchment and the whole subcatchment, respectively. In the 1995/96 season, erosion rates of 6.2 t ha^{-1}, 0.4 t ha^{-1}, and 1.1 t ha^{-1} were recorded from the grey, red, and woodland subcatchments and the whole catchment respectively.

Past research in the domain of optimizing soil water use has also focused on tillage practices that aim at increasing soil water. The benefits of tied-ridging versus conventional tillage were assessed by Nyagumbo (1993). Farmers who adopted the tied-ridging technique realized higher returns than those who used conventional tillage. Mazhangara (1996) showed that the adoption of the tied-ridging technique improved net farm income by 22%.

Impact is also being obtained as improved knowledge of farmers on soil and water conservation principles and technologies through use of visual teaching aids (Chuma and Murwira 1999).

Institutional capacity-building was one of the benefits of research on optimizing soil water use in this country. The GTZ-funded conservation tillage program equipped the Institute of Agricultural Engineering (IAE) with automatic weather stations, soil water-measuring devices, computers, and vehicles to upgrade the knowledge base, data acquisition and evaluation, and to conduct and assess research effectively and efficiently.

OSWU Consortium Activities and Future Expectations

OSWU Consortium activities in Zimbabwe are at the inception stages. Only the national review document on past and present soilwater research (Mzezewa et al. in these proceedings) has been completed as an OSWU activity.

It is anticipated that funds will become available for more research and technology transfer in the domain of optimizing soil water use. Increased OSWU Consortium activities will have to focus on relevant technologies and innovations to combat rural poverty. It is expected that food security in the drought-prone areas will be further enhanced by participating in OSWU. It is also expected that scientists involved in such activities will boost their understanding of issues related to soilwater use research in semi-arid environments. Zimbabwe will see increased capacity-building in its national research systems and advice on appropriate management systems for enhanced water-use efficiency in dry-area agriculture. The research activities of OSWU will help scientists to develop guidelines for national and regional policies to promote efficient and acceptable water-use and management techniques within the development of dry-area agriculture.

Use of Information Tools and Methodologies

In Zimbabwe, substantial agricultural information has been obtained from on-station, on-farm, and greenhouse studies. The data has to be scaled up to extrapolate to the national level. Modeling is widely used for estimation, prediction, and scenario-building. GIS can be a powerful tool for integrating and synthesizing environmental data. An obvious key requirement is that the data must be georeferenced and have a defined spatial and temporal framework (Chenje et al. 1998). Building of such data sets locally is only just beginning. Similarly, extensive use of GIS techniques is not yet a feature of environmental monitoring or research in Zimbabwe. There are some organizations that are starting to take a lead in the use of information tools and methodologies. These include ICRISAT and CIMMYT in collaboration with DRSS, the Department of Meteorological Services, National Early-Warning Unit (NEWU), Institute of Agricultural Engineering (IAE), and the Institute of Environmental Studies.

Existing and Actual Use of DSS, Models, GIS, and Databases

Modeling Hydrological Change in the Romwe Catchment (NR IV)

The Institute of Hydrology (IH), UK, in collaboration with DRSS, adopted two modeling approaches to simulate ground water levels in the Romwe catchment over the period 1992-96. The ACRU and the CRD models were used in this study.

The ACRU model contains a soil water balance and was used to simulate drainage from daily rainfall and evaporative demand, and groundwater levels were predicted as a function of drainage aquifer storage and water table height. It is a physically based model for distributed catchment simulations on an irregular cell or subcatchment basis, developed at Natal University, South Africa. In this study, the soil water balance component of ACRU version 323 was used in lumped mode to calculate drainage (Lovell et al. 1998).

The soil water balance model was tested against measured values of runoff, soil water content, drainage, and soil evaporation for the 1994/95 season and runoff for the 1995/96 season. Measured and simulated values of the groundwater level over the period 1992-96 were also compared. It was established that the groundwater levels simulated by the ACRU model to mimic drainage followed the observed levels closely. Both the timing and magnitude of the groundwater rise and pattern of recession are well-described (Lovell et al. 1998).

The CRD model was also used to simulate groundwater levels from monthly rainfall in Romwe, but with a lower accuracy than the ACRU model due to monthly calculation on which the CRD model is based. However, the annual fluctuations track the observed fluctuations very well. As with the ACRU model, groundwater rise was also overestimated in the 1994/95 rainy season using this model, due to the adequate distribution of rainstorms in that year (Lovell et al. 1998).'

Modeling Rainfall Anomalies

A computerized operational normalized rainfall anomaly index called the rainfall availability index (RAI) was developed for the Mutoko district (NRIV; Unganayi and Calooy 1993). The RAI was derived from rescaled probability values computed from reduced rainfall variates using the cumulative Normal Frequency Distribution Function. The index is useful in detecting and monitoring rainfall anomalies, particularly drought, because it exactly emulates the variations (temporal and spatial) in rainfall amounts. Positive or negative values of the RAI imply above- or below-normal rainfall amounts, respectively. The information on RAI can help in mitigating the impacts of drought or wet spells, thereby reducing societal vulnerability. According to the authors, the index can further be derived based on crop water requirements and some rainfall anomalies will then be defined according to the crop. This makes the indices applicable to irrigation scheduling in dry areas.

Regression Models for Estimating Actual Evapotranspiration of Maize

The linear regression models, developed by Ngara (1993), estimated actual evapotranspiration of maize grown in the Zimbabwean central plateau. Evapotranspiration is particularly important in irrigation or supplementary irrigation scheduling. These models were adopted and the method of least squares was used to estimate the regression coefficients. Actual evapotranspiration was regarded as the dependent variable and the independent variables were (1) initial available soil moisture, (2) daily air temperature, and (3) daily rainfall. Three sets of linear regression models were then derived from these variables, for two soil layers (0-50 cm and 0-100 cm) at five growth interphases (i.e., emergence to 9th leaf, 9th leaf to tasseling, tasseling to flowering, flowering to milky ripeness, and milky ripeness to full ripeness). The coefficient of determination (R^2) values gave a measure of the goodness of fit of the models.

For the five stages, the R^2 values followed a normal distribution with peak values of between 0.90 and 0.95 during the tasseling-flowering interphase. This is the period when photosynthetic processes are most active and maize plants are most sensitive to water stress. Therefore, the models can be effectively used to estimate actual evapotranspiration during this moisture sensitive phase, so that appropriate (supplementary) irrigation can be applied. However, during the early and late phases, mild moisture *stress* has relatively less damaging effect on yields.

Water Requirement Satisfaction Index (WRSI)

In collaboration with NEWU, the Agrometeorological Section of the Advisory Services branch in the Department of Meteorological Services monitors crop growth (Tarakidzwa 1998). This is achieved through meteorological station observers who provide detailed information collected at four fields around the station and by running a water balance model for each decade. The model, originally developed by FAO, is based on a computer water balance specific to eight crops for calculating the Water Requirement Satisfaction Index (WRSI). This index (expressed as a percentage) indicates the extent to which the water requirements of a crop have been satisfied in a cumulative way to any stage of the growing season. Bernadi (1990) has modified the model to suit local conditions.

The WRSI is an empirical model and does not consider complex processes associated with crops and soils. The index is the output of the crop water balance method which uses meteorological observations recorded at a specific geographic point (station), while the crop performance factors (i.e., yield) are estimated over a wider geographic area (district, province, country). The district-level yields estimated by this method widely vary and are generally on the high side when compared with information obtained from field reports.

Agricultural Production Systems Simulator (APSIM)

The APSIM model was developed primarily to simulate the agricultural production systems in northern Australia. The model has the ability to simulate the response of a range of crops to climate, to a wide spectrum of soil water and nitrogen environments, alternative management options, and changes in the cropping sequence (Carberry et al. 1996).

In Zimbabwe, it is used by ICRISAT/DRSS to model the growth of sorghum and maize. Data collection for model calibration and validation at the Matopos Research Station, Chiredzi Research Station, and various on-farm sites is just beginning. Preliminary results available indicate that APSIM overpredicts sorghum yields at Matopos (Gono, personal communication) This poor performance of the model is attributed to lack of proper genetic coefficients for the sorghum varieties being tested. Lack of comprehensive data sets at the many trial sites is a problem that needs to be overcome. Future OSWU research could be used to develop the necessary data for using the model for wider areas in combination with GIS in order to map outputs for research prioritization and decision-making in development areas. The risk management in the Southern African Maize Systems Project (a CIMMYT-managed project, involving collaboration between CIMMYT, DARTS, and Bunda College in Malawi, DRSS, IAE, University of Zimbabwe, and APSRU) is using APSIM to model the growth of maize. Results of 1997/98 field work have been used to model maize (variety SG 501) growth at Makoholi (NR IV). Predicted yields were encouragingly close to the observed yields (Shamudzarira 1998). Similarly, simulation of water dynamics was quite promising as evidenced by a close similarity between the observed and simulated soil water contents at different depths during the season. This indicates scope for using this model in the near future for other crops.

Identification of Future Needs

In order to improve the performance of models like WRSI, there is a need to add more sites to increase coverage and resolution, and to examine the representativeness of the rainfall/synoptic stations in communal areas and districts. Yield assessments based on agrometeorological methods need to be extended to semi-arid areas.

In order to map the way forward, a spreadsheet for comparing simulated output to the observed data was developed and this, together with the experimental data input spreadsheet, will soon be distributed to all the focus groups who were collecting data for the Risk Management Program (RMP) in the 1998/99 season. Field trials to collect data for model calibration and validation are established both on-station and on-farm. On-station trials have been established at Domboshava, Henderson Research Station, Horticultural Research Centre, and Makoholi Research Station.

Available data on the existing models have been collected mainly from the higher-rainfall areas. There is a need to concentrate efforts in the semi-arid areas so that the models become more applicable to the dry-area production systems.

Conclusions

There is a need to start collecting georeferenced data sets that can be manipulated on GIS and for modeling purposes. It is necessary to consolidate on the few existing models and build comprehensive databases. There is also a need to formulate policies regarding the use of information tools and methodologies in the country. The present scenario is characterized by uncoordinated efforts where there are no linkages among the organizations involved in data management.

Impact-assessment studies are needed for the past research on optimizing soil water use (except the IH projects) to determine the importance of the developed technologies and to use them to improve the welfare of farmers through improved production while conserving the natural resources.

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Part D. Workshop Results

Preliminary Analysis of the Potential Impact of the OSWU Consortium on Improved Agricultural Production in Dryland Areas Using a Bayesian Belief Network Approach

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Abstract

In a working group during the 1998 workshop, Bayesian belief networks were used to assess the potential impact of OSWU activities over the next five years. Preliminary analysis using a simple belief network shows that, if OSWU takes a multidisciplinary approach, the impact on agricultural production could be significant in areas with a high demand for OSWU technologies and where there is significant scope for yield improvement. A more complex belief network was constructed and this will be finalized as an OSWU activity.

Resume

Dans le cadre d'un groupe de travail tenu au cours de l'atelier de 1998, l'impact potentiel des activites de OSWU au cours des 5 prochaines annees fut evalue au moyen des riseaux bayesiens de croyance. Une analyse preliminaire au moyen d'un reseau bayesien simplifie montre qu'en adoptant une approche multidisciplinaire OSWU pourrait avoir un impact significatif sur la production agricole dans les zones ou la demande pour des technologies d'optimisation de l'utilisation de l'eau du sol est grande et ou le potentiel d'accroissement des rendements est eleve Un reseau bayesien de croyance plus complexe a egalement eti concu et sera finalise dans le cadre des activites de OSWU.

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N. van Duivenbooden, M. Pala, C. Studer and C.L. Bielders (eds.). 1999. Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia, and North and Sub-Saharan Africa. Proceedings of the 1998 (Niger) and 1999 (Jordan) workshops of the Optimizing Soil Water Use (OSWU) Consortium. Aleppo, Syria: ICARDA; and Patancheru, India: ICRISAT. pp 425-436.

Introduction

The OSWU Consortium has the long-term goal of promoting sustainable and profitable agricultural production in dry areas based upon the optimal use of available water. It was decided during the 1998 workshop, that Bayesian belief networks should be used to provide an initial assessment of the potential of short-term impact of proposed OSWU activities on agricultural production in dryland areas. It was also recognized that belief networks could give a first assessment of the relative importance of some of the different OSWU activities that were being proposed and discussed during the workshop. Consequently, two belief networks were constructed during the workshop. This paper describes the methodology used and reports the preliminary findings.

Methodology

As Bayesian belief networks provide a method of representing relationships between variables even if the relationships involve uncertainty, unpredictability or imprecision, they are an ideal framework for the analysis of natural resource management systems. Links between variables can be established deterministically or probabilistically using field data or, if more appropriate, expert opinion. By adding decision variables (variables that can be controlled) and utility variables (those we want to optimize) to the relationships of a belief network, it is possible to form a decision network. This can be used to identify optimal decisions. The theory and methods of constructing belief and decision networks have been described by a number of authors (e.g. Spiegelhalter et al. 1993). Batchelor and Cain (1998) provide examples of interdisciplinary data analysis of water management systems using belief networks.

The following steps were used to develop two belief networks that represent the impact that activities of the OSWU consortium will have on agricultural production in dryland areas:

- Three workshop participants identified the main variables that influence the uptake of improved soil and water management practices and improvements in agricultural production in dryland areas.
- A cause and effect diagram was constructed (Fig 1).
- Discrete state and boundary conditions were defined for each variable.
- Data were inputted into the conditional probability tables for each variable. This was initially carried out on the basis of the expert opinions of three workshop participants. Subsequently, the tables were updated to take into account the opinions of all the workshop participants.
- Following comments and discussion during a workshop plenary session, a more complex cause and effect diagram was constructed.
- Some of the main input data for the more complex belief network were elicited However, time constraints precluded further development of this network during the workshop.

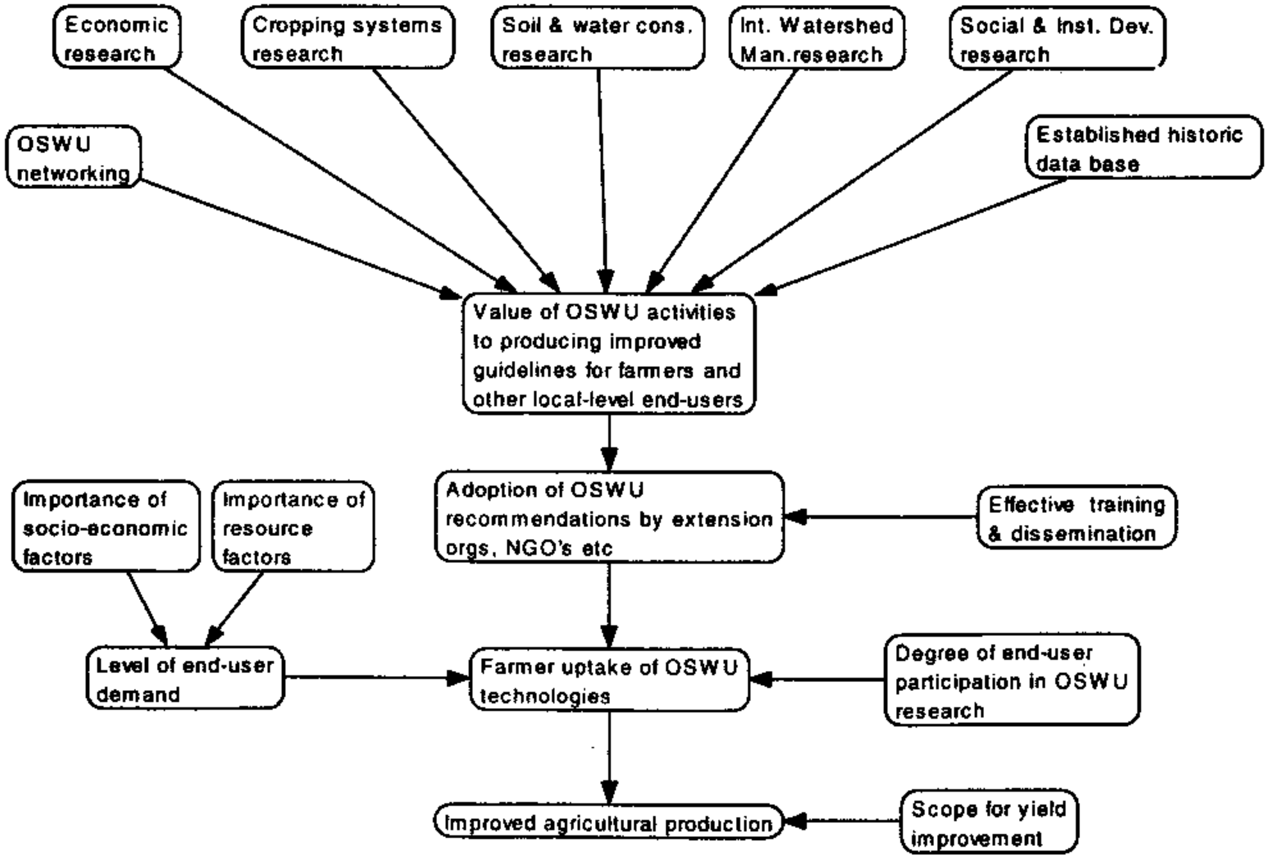

Figure 1. A Simple cause and effect diagram representing the relationships between OSWU activities and other variables that influence agricultural production in dryland areas.

- The less complex belief network was used to investigate a range of scenarios to know the perceived sensitivity of improved, agricultural production to the other variables in the belief network.

Input data were entered into the Bayesean belief network on the basis of the impact that OSWU activities would have on sustainable and improved production over a period of five years from May 1998 (given appropriate levels of funding). Another assumption was that the adoption of improved soil and water management practices would continue regardless of whether the OSWU consortium is funded, albeit at a lower level. Conditional probabilities for the farmer uptake and improved agricultural production variables were elicited on the basis of the number of farmers out of a sample of 100 that would experience high, medium or low uptake or improved production respectively.

Results and Discussion

In the first cause and effect diagram (Fig. 1), the main OSWU activities or variables were identified as being (not in order of importance): OSWU networking, economic research, cropping systems research, soil and water conservation research, integrated watershed management research, social and institutional development research, and establishment of a database. It was perceived that all these activities would to some extent contribute in the production of improved guidelines for farmers or other local-level end users. Assuming that the guidelines are appropriate and also assuming effective training and dissemination, it can be expected that these will be adopted by extension organizations, NGOs, and others. Uptake of guidelines will depend primarily on the level of end-user demand, on whether extension agencies and others are promoting OSWU technologies, and on whether the development of the guidelines has taken cognisance of the needs and aspirations of end users. Finally, it was felt that improved agricultural production would depend on uptake of OSWU technologies by end users and on the scope for yield improvement (which will vary regionally and seasonally).

Figure 2 presents the less complex belief network compiled on the basis that no OSWU consortium activities take place and that there is a low level of end-user demand and scope for yield improvement. The result of this scenario is that improved soil and water in dryland areas will result in high improvements in agricultural production on 1 farm out of a 100 during the next five years and moderate and low improvements in yield on 6 and 93 farms out of a 100, respectively.

Figure 3 presents the less complex belief network compiled on the basis that no OSWU consortium activities take place and that there is a moderate level of end-user demand and scope for yield improvement. Here, improved soil and water in dryland areas will result in high improvements in agricultural production on 29 farms out of a 100 during the next five years and moderate and low improvements in yield on 16 and 55 farms out of a 100, respectively.

Figure 4 shows the less complex belief network compiled on the basis that all the OSWU consortium activities take place.and that there is a moderate level of end-user

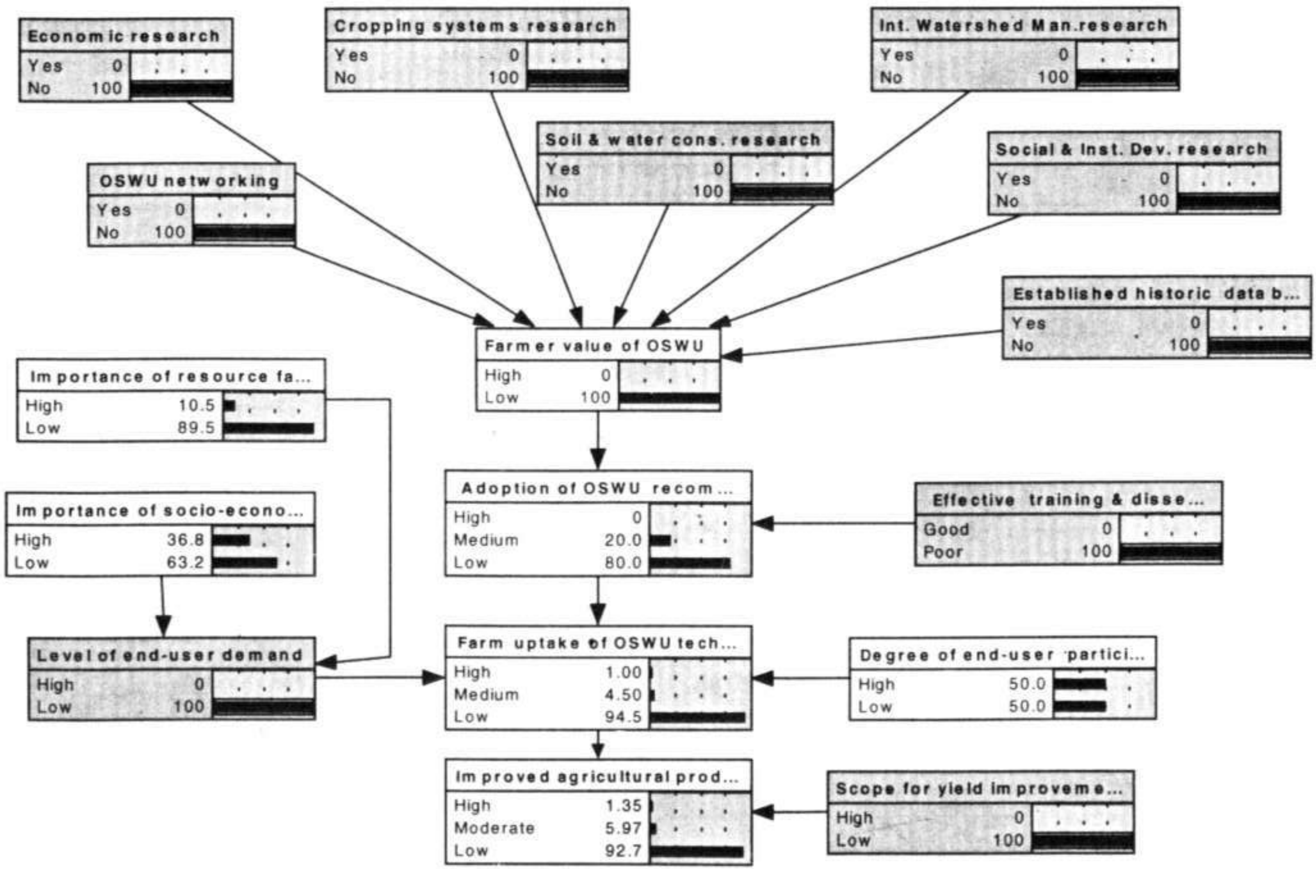

Figure 2. A compiled version of the less complex belief network, with no OSWU activities taking place and low levels of end-user demand and scope for yield improvement.

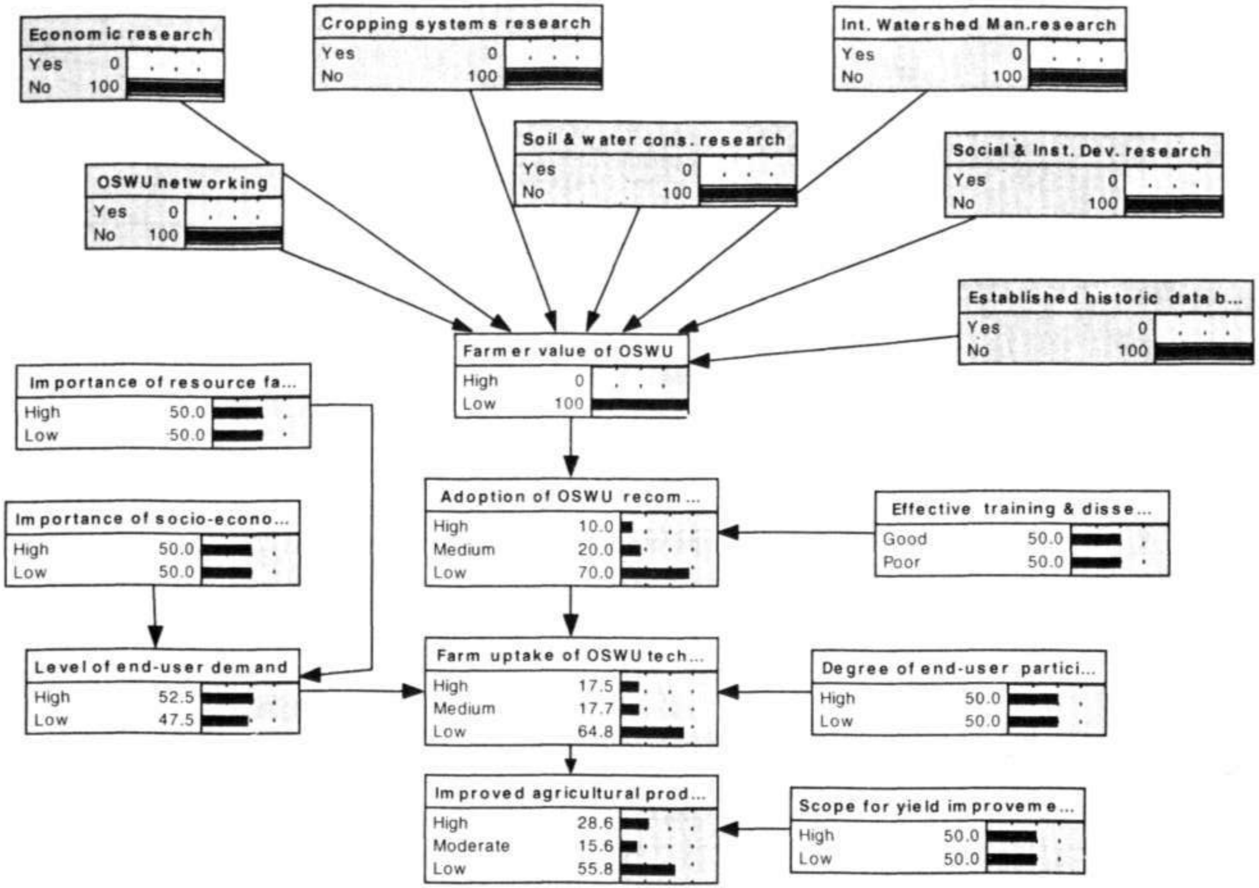

Figure 3. A compiled version of the less complex belief network with no OSWU activities taking place and a moderate level of end-user demand and scope for yield improvement.

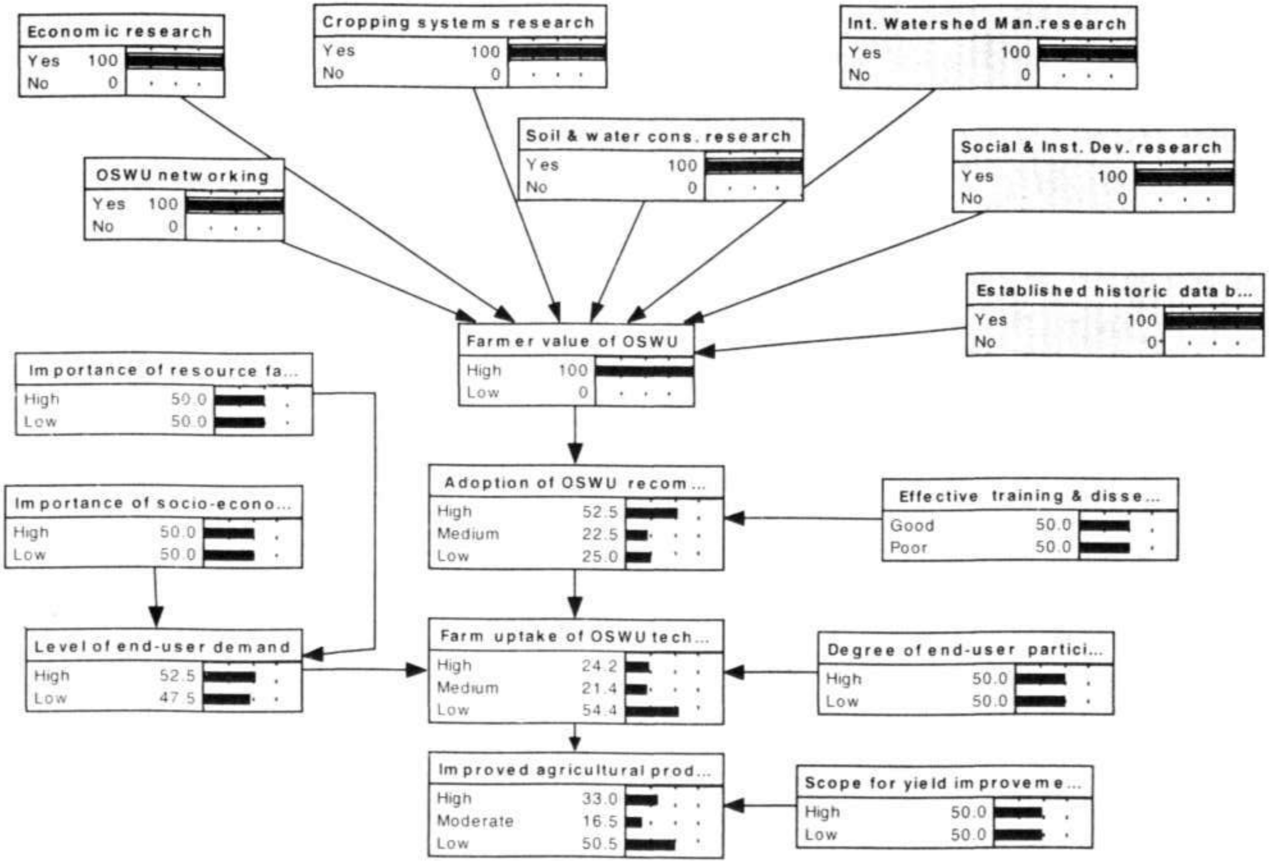

Figure 4. A compiled version of a less complex belief network with OSWU research activities taking place and moderate levels of end-user demand and scope for yield improvement.

demand and scope for yield improvement. The result of this scenario is that improved soil and water in dryland areas will result in high improvements in agricultural production on 33 farms out of a 100 during the next five years and moderate and low improvements in yield on 17 and 51 farms out of a 100 respectively across the WANA and SSA regions. In case research is being carried out on economics, cropping systems and watershed management, a further increase in the 'high' category is obtained at the expense of the lower (33 as against 51% (Fig. 4). A comparison of the scenarios (Figs. 2 and 3) suggests an estimated impact of OSWU is a high or moderate yield improvement on an additional five farms out of a 100 over a period of five years. This represents a 15% increase in improvement in the high category.

A comparison of all these three scenarios shows that, according to the expert opinions of the workshop participants, improvements in production are relatively more dependent on levels of end-user demand and scope for yield improvement than they are on proposed OSWU activities. Considering this, a high increase in crop production on five farms out of a 100 across the WANA and SSA regions would be a considerable achievement.

Figure 5 shows the relative importance of proposed OSWU activities from the perspective of farmers (and other local-level end users), policy makers, and researchers. This figure uses the mean values of data elicited from all workshop participants (Table 1). It can be seen that the workshop participants recognized the importance of the OSWU consortium being involved in a range of activities and that the advantages to be derived from these benefits will vary for different users.

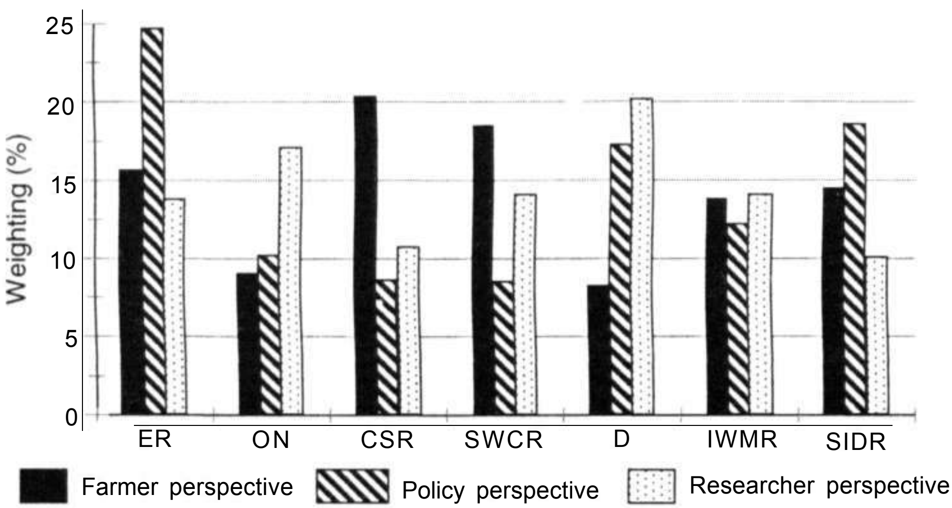

Figure 5. The relative importance of proposed OSWU activities from three different perspectives. ER = economic research; ON = OSWU networking; CSR = cropping systems research; SWCR = soil and water conservation research; D - database; IWMR - integrated watershed management research; and SIDR = social and institutional development research.

Table 1. The relative importance of the seven variables that influence the uptake of improved soil and water management and dryland production technologies, with respect to farmers, policy makers, and researchers, as estimated by the 1998 workshop participants.

Country	Economic research	OSWU networking	Cropping System	Soil conservation	Database	Integrated watershed management	Social and institutional development
Farmers' perspective							
Nigeria	20	2	8	15	5	10	40
Turkey	40	5	15	20	5	5	10
ICARDA	5	5	30	20	5	20	15
Mali	12	10	25	25	5	8	15
Zimbabwe	10	10	30	30	10	5	5
Morocco	20	10	20	20	10	10	10
Egypt	15	5	15	20	10	30	5
Syria	20	15	15	15	15	15	5
Jordan	10	20	20	20	5	20	5
S.Africa	15	4	22	21	10	8	20
Niger	5	5	40	20	10	10	10
Burkina Faso	5	15	25	5	0	30	20
Institute of Hydrology	20	15	5	10	20	10	20
ICRISAT	22	5	15	17	5	13	23
Totals	219	126	285	258	115	194	203
Mean	16	9	20	18	8	14	15
Policy perspective							
Nigeria	20	5	10	10	30	10	15
Turkey	60	1	5	3	1	0	30
ICARDA	20	10	10	10	20	15	15
Mali	22	14	8	6	20	10	20
Zimbabwe	30	10	10	15	5	5	25

Continueed

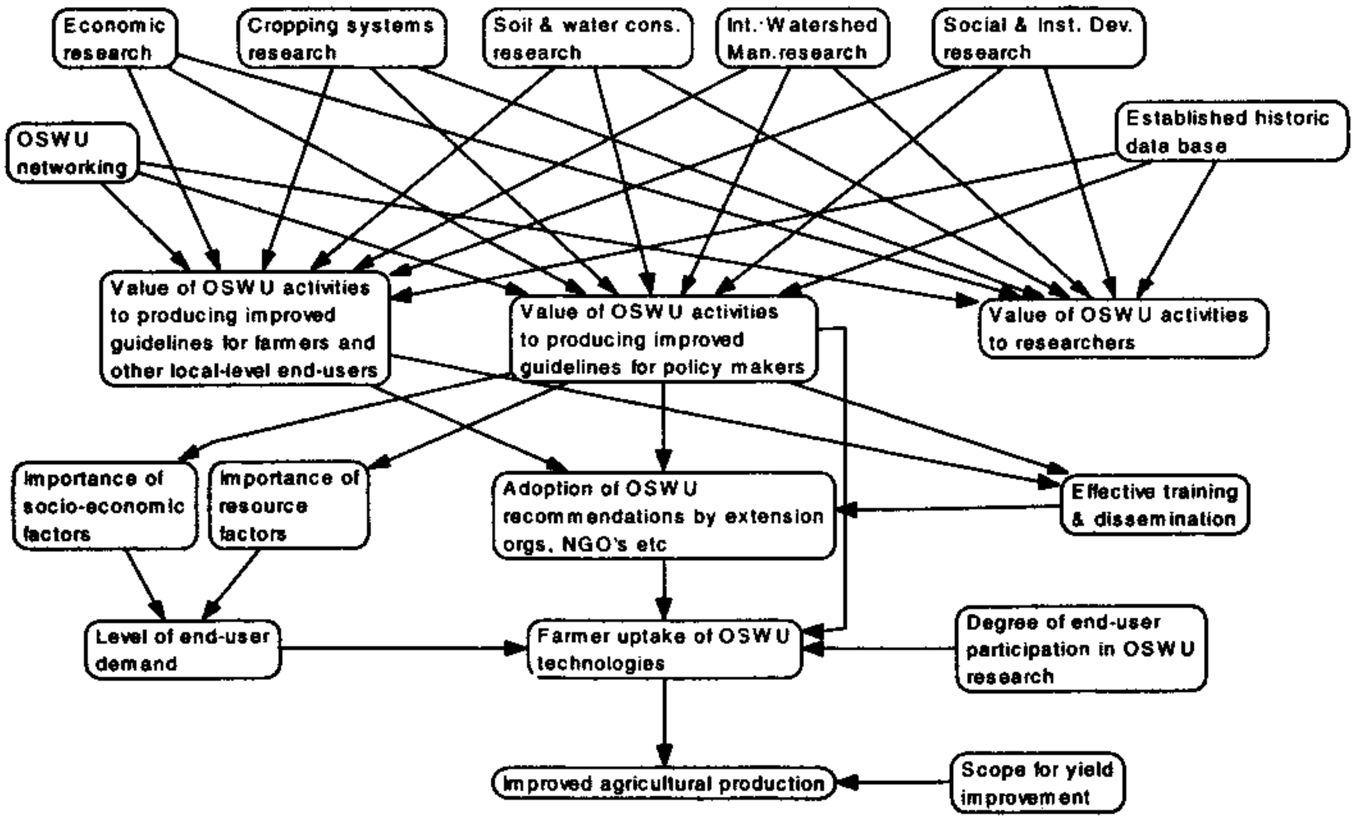

Figure 6. The complex cause and effect diagram representing the relationships between OSWU activities and other variables that influence agricultural production in dryland areas.

Figure 6 presents the more complex cause and effect diagram. The fundamental logic that forms the basis of this diagram is the same as for the less complex version. The extra variables that have been included relate to the benefits that can be derived from OSWU by policy makers and researchers. It was perceived that OSWU activities will provide information that can be used by policy makers when attempting to create enabling environments for improved uptake of OSWU technologies. It was also perceived that policy is an important instrument for manipulating demand for OSWU technologies.

It is proposed to elicit additional data from workshop participants to be used to develop a functional version of the more complex belief network. This version could be used by researchers when planning and implementing future activities and in discussions with donors to show the potential impact and consequences of OSWU activities on agricultural production in dryland areas.

Conclusions

The exercise of creating a belief network demonstrated that this technique can be used effectively as a framework for focused discussion and systematic analysis of a complex multivariate system. In this case, the multivariate system encompassed the potential uptake pathways and impact of improved soil water management practices in dryland areas. The use of belief networks was successful in extracting expert knowledge from workshop participants in a numerical form, thereby permitting statistical data analysis and interpretation/Preliminary results confirm that, to have a significant impact on agricultural production in dryland areas, the OSWU Consortium must take a multidisciplinary approach. They also showed that OSWU could have a significant impact across the WANA and SSA regions but that this will be greatest in areas with a high level of end-user demand and scope for yield improvement.

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Summary of the Workshops

N van Duivenbooden[1], C Studer[2], M Pala[2], and C L Bielders[1]

Abstract

During the 1998 workshop, national review papers revealed the enormous experience in this field of research in the member countries. Results could, however, be further elaborated and extrapolated by using information tools. The reviews were used to identify gaps in knowledge and prioritize new OSWU research. Although no formal impact assessment studies were carried out, some indications are presented in the 1999 workshop that past research in the domain of optimizing soil water use did have an impact on farmers' yield, welfare and income, as well as on the environment and the capacity building of NARS. WOCAT has been identified as a useful tool in the impact assessment of soil and water conservation technologies. The presentation on information tools clearly showed the importance of these technologies in OSWU *member countries, but also highlighted the absence of a common focus/strategy for using these models. The observations are being used to improve the focus and functioning of OSWU.*

Resume

Au cours de l'atelier de 1998, les revues nationales de la litterature scientifique ont revele la tres importante experience des pays membres dans ce domaine de recherche. Les resultats existants pourraient cependant etre developpes davantage et etre extrapoles grace a l'utilisation des outils de l'information. Les revues de litterature ont ete utilisees pour identifier les manquements dans les connaissances et pour prioritiser les nouvelles recherches a entreprendre dans le cadre d'OSWU. Bien qu'il n'y ait pas eu d'etudes d'impact formelles, pendant l'atelier de 1999 plusieurs indications ont ete presentees montrent que la recherche passee en matiere d'optimisation de l'utilisation de l'eau du sol a eu un impact sur les rendements, le revenu et le bien-etre des paysans, ainsi que sur l'environnement et sur le developpement des capacites des SNRA. Le

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N. van Duivenbooden, M Pala, C. Studer and C.L. Bielders (eds.). 1999. Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia, and North and sub-Saharan Africa. Proceedings of the 1998 (Niger) and 1999 (Jordan) workshops of the Optimizing Soil Water Use (OSWU) Consortium. Aleppo, Syria: ICARDA; and Patancheru, India: ICRISAT. pp 437-446.

programme WOCAT est retenu conime un outil utile pour l'etude d'impact des technologies de conservation des eaux et des sols. La presentation sur les outils de ['information a clairement montre l'importance de ces technologies dans le pays membres d'OSWU, mais egalement l'absence de concertation et d'une stratigie commune pour l'utilisation de ces modeles. Les diverses remarques sont utilisees pour ameliorer la convergence des efforts et le fonctionnment d'OSWU.

Introduction

The OSWU Consortium held its first workshop at Sadore, Niger, between 26 Apr and 1 May, 1998, and the second one in Amman, Jordan from 9-13 May, 1999. This paper focuses on the scientific content of the workshops while the next one dwells on the consequences and conclusions of these technical aspects on the organizational aspects of the consortium.

Workshop at Sadore

Participants and Program

The workshop was held at the ICRISAT Sahelian Centre at Sadore, Niger where OSWU Consortium participants came from WANA (Egypt, Iran, Jordan, Morocco, Syria, and Turkey) and sub-Saharan Africa (Burkina Faso, Mali, Niger, South Africa, and Zimbabwe; Appendix 2). The representative from Kenya was unable to attend the workshop in which each representative presented a national review, except the one from Burkina Faso who presented a paper on a related subject. External opinions were obtained through Dr. C. Batchelor (Institute of Hydrology, UK), Dr. Moussa (Project Keita, Niger), and Prof. VO. Chude (Combating Nutrient Depletion Consortium, Nigeria), while keynote presentations were made by Drs M. Pala and C.L. Bielders.

Prior to the workshop, a field trip was organized to an area near Tillaberi (80 km Northwest of Niamey), where various water harvesting techniques and erosion control measures were viewed.. Discussions were also held with farmers on their perception of these technologies.

Technical Discussions on Country Presentations

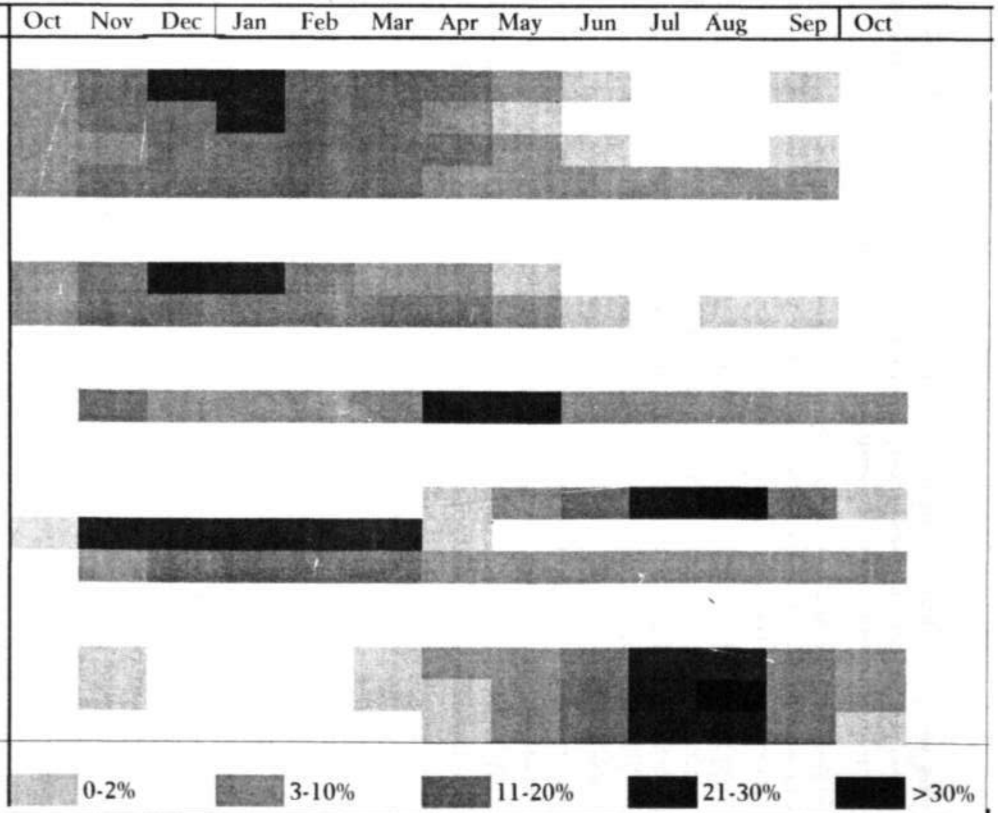
The various presentations brought into focus how 12 member countries differ in their biophysical and socioeconomic conditions. Table 1 presents the differences in rainfall distribution in the OSWU countries. It is beyond the scope of this chapter to discuss the differences in detail.

Some highlights of the discussions during the workshop are presented here:

- The issue that soil water storage is influenced by the water holding capacity of any given soil (varying from < 0.1 to > 100 mm depending on the rooting zone) and

Table 1. Rainfall distribution in the 12 member countries of the OSWU Consortium.

Region/country	Rainfall (mm)*
West Asia	
Iran	50-1600
Jordan	50-550
Syria	200-600
Turkey	200-500
North Africa	
Egypt	100-170
Morocco	200-450
East Africa	
Kenya	500-800
Southern Africa	
South Africa (winter)	200-3000
South Africa (summer)	400-900
Zimbabwe	
West Africa	
Burkina Faso	300-1200
Mali	150-3000
Niger	100-900



* = variation in space.

that we can do little about it (hydro-fixing chemicals excluded) was discussed. However, the role of roots in water capture has often been ignored. It was felt that the focus should be on root density and not root depth.

Minimizing evaporation in farmers' fields is imperative since water lost through evaporation is completely lost ('actual losses' versus 'paper losses'; the latter being recuperated in the water balance at the watershed level).

- Supplemental irrigation (i.e., the addition of small amounts of water to essentially rainfed crops when rainfall fails to provide sufficient moisture for normal plant growth) is an important technology in WANA, but seems to have few possibilities in SSA. Its success depends, in addition to plasticity of crop, on biophysical conditions.
- The terms water productivity and water-use efficiency can both be used, but in situations where water is recycled, the term productivity is more appropriate.
- OSWU should conduct 'in-situ' research rather than 'in-vitro' research (i.e. more development-oriented, applied, adaptive, and participatory research).
- Simulation models can serve as an important tool to identify knowledge gaps and research needs, develop technologies, and to map outputs of technologies in combination with GIS. However, this modeling should be done in a farmer participatory way (e.g.. inputs and outputs should be measurable by or in collaboration with farmers), it should not be too complicated. Moreover farmers' perceptions should be utilized wherever possible.
- Regarding socioeconomic issues, it was acknowledged that most research technologies are not being adopted by farmers. While the 'normal' thinking is to do research on 'why the farmers are not doing what we want them to do?', it was proposed to, on the contrary, 'research the reasons why technologies are adopted'. It was found that farmers do not adopt OSWU technologies because there are constraints, though this is not always the case. Farmer beliefs and perceptions are different from those of researchers.
- Permanent water points (e.g. drilled holes) could increase the (financial) output of farmers or in other words, add significant value to the agricultural system. Growing vegetables with a mulch of stones could be such an activity.
- The two problems associated with integrated water management are reconciliation of decision-making at local and regional levels, and the interaction between researchers and users of technologies. This reiterates the need for a multiscale and participatory research approach by the OSWU Consortium. It was felt roles should be assigned to different stakeholders (farmers, community, etc.) for watershed-level research,
- Results obtained at the field-level should be elaborated and extrapolated to larger areas (e.g. village- or watershed-level) with similar agroecological conditions.

In addition to research issues of the OSWU Consortium, the following methodological ones were identified which are cross-cutting issues among various projects and programs (e.g. ecoregional projects, such as the Desert Margins Program, and the Water Husbandry Program):

- Improvement of runoff modules or routines in crop simulation models. Since runoff largely depends on the intensity of rainfall, and intensity is measured only at a very few meteorological stations, alternative ways of estimating the parameter are required.
- Ways to integrate disciplines through a modeling approach based on Bayesian Belief Networks.

Importance and Role of OSWU

The goals and objectives of the OSWU Consortium were slightly changed. OSWU's uniqueness, its approach, functioning and characteristics were discussed, while at the same time emphasizing on its strong networking role. During the national reviews, it was felt that OSWU activities should focus on meeting the needs of the particular countries. The target groups to be focused and the identification and prioritization of activities in the OSWU Consortium proposal made up an important part of the discussions. The comparative advantages of OSWU member institutions were identified and summarized. In addition, linkages with other consortia, particularly within SWNMP, were examined. The outcome of all these discussions is reflected in the next paper.

Workshop in Amman

Participants and Program

Apart from NARS representatives of three SSA (Burkina Faso, South Africa, and Zimbabwe) and six WANA countries (Egypt, Iran, Jordan, Morocco, Syria, and Turkey), three delegates from the convening Centers, ICARDA and ICRISAT, participated in the workshop. NCARTT (Jordan) organized two field trips, introducing the participants to the NCARTT headquarters, a farmer near Amman, the variable landscape, and its land use.

After an introduction to OSWU activities during the last year, NARS representatives presented their papers on the impact of research related to optimal soil water use, and on the importance of information technologies in OSWU research in their respective countries.

Dr. B. Ouattara (Burkina Faso) presented an overview of a training workshop on WOCAT (World Overview of Conservation Approaches and Technologies), held in Niamey, Niger, May 3-5, 1999, cosponsored by OSWU. WOCAT aims at collecting, analyzing, presenting, and diffusing knowledge on soil and water conservation (SWC) technologies through an openly accessible database, and provides decision-support on their suitability, profitability, impact, and approaches to implementing them at the global level. It was agreed that the OSWU Consortium should consider participating in the WOCAT initiative, particularly with regard to the importance of impact assessments within the WOCAT approach.

Dr. M. Pala (ICARDA) gave a presentation on the use of cropping systems models, with particular emphasis on their application in optimized soil water use. Models can improve our understanding of mechanisms and processes, mimic different crop management options, and allow the extrapolation of site-specific research results to other locations, considering the prevailing agroecological conditions. However, simulation models cannot completely substitute for agronomic trials. Dr. Pala explained, in particular, the performance of CropSyst and CLIMGEN, which have been used at ICARDA with success. All the participants agreed on the usefulness of using cropping systems simulation models within the OSWU Consortium. The abundance of data available within the consortium allows for the full use of models, so that they can be validated in very contrasting environments and the results can be extrapolated to other regions.

In the following session, research proposals from Zimbabwe, Morocco, Burkina Faso, Turkey, South Africa, and Syria were presented and critically discussed.

Impact Assessment

From the presentations, it became clear that —in contrast to irrigated agriculture— no formal assessment on the impact of OSWU-related research has been made in any of the OSWU member countries. The impacts presented were mainly based on observations at the farmers' level or on specific case studies. It was also stressed that impact relates not only to yields in farmers' fields or adoption rates of certain technologies but also to the effects of such an adoption on the farmers, the overall economy, to human resource development, capacity building, and institutional strengthening. The information available on impact is summarized in Table 2. Although some conditions are not listed in the table, it does not imply that they do not occur in the country.

While the effect of participatory on-farm research is still not substantial in terms of technology adoption, there are countries where the farmers themselves showed great interest in adopting the technology (in Burkina Faso where farmers adopt stone bunds), but again, often no data is available on the number of farms or area covered. It is, therefore, essential that quantitative studies on the impact of OSWU-related research be carried out in all member countries. As a first step, each member country could select a specific project, for which the impact of optimizing soil water use could be analyzed. This would bring about a further integration of disciplines in the OSWU Consortium.

Information Tools

The presentations on information tools clearly showed the importance of these technologies in OSWU member countries. Table 3 lists some of the main models being used (at least in two countries). According to the working group, no differences exist in the level of sophistication of models among the member countries. However, some countries (e.g. South Africa and Morocco) are more advanced in their use of models and GIS for formulating recommendations for farmers and identifying new areas of research.

Table 2. Examples of impact indicators in the WANA and SSA regions from research in optimizing soil water use. X = used but not quantified, BF = Burkina Faso, EG = Egypt, IR Iran, JO = Jordan, KE = Kenya, ML = Mali, MR = Morocco, NE = Niger, SA = South Africa, SY = Syria, TU = Turkey, and ZI = Zimbabwe.

Impact indicator	BF	EG	IR	JO	KE	ML	MR	NE	SA	SY	TU	ZI
Package use*												
Improved varieties	X	X	X	X			X			X	X	
Supplementary irrigation		X	X	X						X	X	X
Fertilization	X	X	X	X			X					
Chemical weed control				X			X					
Fallow replaced by legumes				X							X	
Zai, stone bunds	X											
Tied ridging	X											X
Microcatchment				X								
Tillage	X			X					X			
Drill										70%		
Full package	Low										60%	
On-farm yield increase**												
Cereals	10-100	200	30-50	10-200			50-100		15-45		200-240	
Fruit trees		400		10								
Socioeconomic												
Income increase**				30			X		X			20
Increased food security	X											
Increased tenure security												X
Environment												
Fertilizer rate based on soil analyses												
Reduced erosion							X		X			X
Revegetation							X					
Capacity building												
MSc graduations				14							-	
Creation of center							X					
Miscellaneous												X

* = adoption (% of number of farmers)
** = increase (% as compared to use of traditional package).

Table 3. Common (i.e. at least in two countries) databases, software packages for GIS, simulation models, and decision support systems in OSWU member countries, where X = NARS, (X)= at ICARDA or ICRISAT, X* = at NARS and ICRISAT/ICARDA, BF = Burkina Faso, EG = Egypt IR Iran, JO = Jordan, KE = Kenya, ML = Mali, MR = Morocco, NE = Niger, SA = South Africa, SY = Syria,, TU = Turkey, and ZI = Zimbabwe

Name software	BF	EG	IR	JO	KE	ML	MR	NE	SA	SY	TU	ZI
Databases												
Weather	X	X	X	X	X	X	X	X	X	X	X	X
Soils (e.g. FAO, SOTER)	X	X	X	X	X	X	X	X*	X	X*	X	X
GIS												
ArcInfo	X	X	?	?	X	X	?	X*	X	(X)	?	?
ArcView	X	X	?	?	X	X	?	X*	X	(X)	?	?
Atlas-GIS	X	?	?	?	?	X	?	X*	?	(X)	?	?
Simulation models												
APSIM					X	(X)		(X)				X*
CropSyst										(X)	X	
CERES-Maize, barley					X		X					
NUTSHELL/NUTMON	X				X							
Watershed*			X					X				X
Decision support systems/ bioeconomic models												
Multiscale	X					X		(X)				
Farm model							X					

* Different packages.

However, the presentations revealed the lack of coordination in each country between institutions using crop simulation models and those using different decision support systems. Although standardization of software may help resolve this problem, different groups do need different models or databases because of differences in outputs required.

OSWU members are identifying their own objectives for database and model use (outputs needed, parameters to be variable, etc.), according to their specific needs, and data(bases) and models already available and used. Nevertheless, it was stated that commonly-defined minimum datasets are important to allow for an exchange of modeling experiences and extrapolation to similar regions. Hence, with regard to experiments, it was recommended that all parameters necessary for modeling be collected. Members should identify input parameters needed for the models, search for data within their own institutions, identify other partners working in the domain, and evaluate their capacity to provide information, experience, and data for use in the framework of OSWU. Joint modeling activities could serve the focus of new modeling efforts in the field of optimizing soil water use (e.g. to explain the yield-gap between farmer's and simulated rainfed potential yield). The need for validated models with both nutrient (nitrogen and phosphorus) and water balance subroutines was again underscored.

The working group also highlighted the need for training in the use of crop simulation models and information tools at different levels. To increase knowledge on crop simulation modeling, training workshops in crop simulation models (CropSyst and APS1M) are envisaged. Regarding database development, mentors from experienced NARS (e.g. Egypt and South Africa) will support this in countries less advanced in that domain. The need for training of extension services was also mentioned (e.g. Iran).

Conclusions

The OSWU Consortium, as part of the Soil, Water, and Nutrient Management Program, has a clear role and focus. With its contributions it helps to ameliorate on-going projects in optimizing soil water use within the NARS of member countries, exchange experiences among the five agroecological regions, and avoid duplication of research in similar regions.

The national review papers revealed the enormous experience in this field of research, but also showed that results could be elaborated by using information tools. The review papers allowed an evaluation of the consortium's knowledge base, as well as the identification of specific research and knowledge gaps and priorities, and complementarities and potential synergisms across countries and regions.

The papers also revealed the large gap in impact assessment of research and technologies aimed at optimizing soil water use under rainfed conditions in contrast to irrigated conditions. Quantitative impact studies will, therefore, have to play an important role in OSWU's future activities. In addition changes in yield and in a few cases, increased farmer's income, making use of the outputs and products of past research in the domain of OSWU has resulted in changes in the institutional capability and orientation of the NARES. It seems essential for the OSWU Consortium to follow the approach developed by WOCAT, in order to establish better links between research and development projects implementing soil and water conservation technologies and to assess their impact.

OSWU members are identifying their own objectives for database and model use according to their specific needs, data(bases), and models already used. With regard to experiments, all parameters necessary for the use of models should be collected, while training workshops in modeling are envisaged.

Finally the workshops' eagerness to collaborate between the regions and have some openness among participants, contributed largely in getting equal partners in the consortium. This will help in getting high quality research executed within the consortium.

The Future of the Optimizing Soil Water Use (OSWU) Consortium

M Pala[1], N van Duivenbooden[2], C Studer[1], and M Doumbia[3]

Abstract

The two workshops contributed to a greater coherence and complementarity in OSWU's goal and objectives, and outputs and activities were further focused. Its activities are now based on specific needs and information gaps identified through the national review papers. The assessment of impact of research and technologies aiming at optimized soil water use will have to play a major role in future OSWU activities. For execution of the research program, a large number of possible linkages have been identified. A meeting with stakeholders planned for 2000 will also help in further improving the integration of the four SWNMP consortia. The consortium started in 1999 to support various on-the-ground research projects in the 12 member countries.

Resume

Les deux ateliers ont contribui a une meilleure coherence et complementarite dans les buts et objectifs d'OSWU, et les produits et les activites ont ete mieux focalisees. Ses activites sont a present bastes sur les besoins specifiques et les manquements dans les connaissances identifies au travers des revues nationales de litterature. L'evaluation de l'impact de la recherche et des technologies visant l'optimisation de l'utilisation de l'eau du sol jouera un role majeur dans les activites futures d'OSWU. Un grand nombre de liens possibles ont ete identifies pour l'execution des programmes de recherche. L'integration des 4 consortia devrait egalement beneficier de l'organisation d'une reunion des parties prenantes prevue pour l'an 2000. C'est en 1999 que le consortium a commence a soutenir divers projet de recherche dans les 12 pays membres.

1. ICARDA, P O Box 5466, Aleppo, Syria.
2. ICRISAT, B P 12404, Niamey, Niger.
3. IER, B P 438, Bamako, Mali.

N. van Duivenbooden, M. Pala, C. Studer and C.I., Bielders (eds.). 1999. Efficient soil water use: the key to sustainable crop production in the dry areas of West Asia, and North and Sub-Saharan Africa. Proceedings of the 1998 (Niger) and 1999 (Jordan) Workshops of the Optimizing Soil Water Use (OSWU) Consortium. Aleppo, Syria: ICARDA; and Patancheru, India: ICRISAT. pp 447-463.

Introduction

During the Workshop and Steering Committee Meeting at Sadore, Niger, some fundamental issues relating to the future of the OSWU Consortium were discussed. The main discussions comprised (1) the goal and objectives of OSWU, (2) the uniqueness of OSWU and its focus and approach, (3) functioning and characteristics of the OSWU Consortium, (4) identification and prioritization of activities and comparative advantages of OSWU member institutions, and (5) linkages with other consortia. It was also felt that the last consortium proposal (1997) could be improved on the following points: (1) the specificity of a consortium approach, and (2) the specific outputs, which should be "cutting-edge" and not "more of the same/old wine in a new bottle".

The Workshop and Steering Committee Meeting in Amman, Jordan, focused on the evaluation of impact of research and technologies aiming at optimized soil water use, potential links to WOCAT, and the use of cropping systems models within OSWU. In addition, funds were allocated to specific research proposals discussed during the workshop.

In this paper, the new specifics of OSWU are being described, as well as the way forward of the Consortium.

OSWU Specifics

Goal and Objectives

The long-term goal of the OSWU Consortium is:

Sustainable and profitable agricultural production in dry areas based upon optimal use of the restricted available water at different scales.

The overall objective is:

To develop and promote adoption of integrated land management strategies and techniques that capture and retain rainwater with crop husbandry techniques that maximize productive transpiration and minimize evaporative and drainage losses, within water-efficient, productive, and sustainable cropping systems.

Specific Objectives for Research

- **Adaptive and participatory:** Land-surface and soil/crop husbandry practices developed and under test on farmers' fields that optimize output per unit of available water within sustainable production systems that match climate characteristics (especially patterns of rainfall and evaporative demand) and production and livelihood aspirations at household, community, and national level, integrating;

- the management of land surfaces to optimize the retention of rainwater;
- the management of cropped soils and crops to minimize losses of water to deep drainage, surface evaporation, and weed transpiration;
- choices of crops (and cultivars), crop and fallow sequences, and cropping practices to optimize the efficiency of soil water use in the production of economic yield.

- **Applied and generic.** Research activities established at selected locations to study key problems of soil-water-plant processes common to dry-area cropping systems.

Specific Objectives for Strategic and Development Activities

- Spatially-referenced databases at national and regional levels, developed from research and development experience and from national statistics and environmental information; and appropriate data-handling and modeling systems with which to use them.
- Increased capacity in national agricultural research and extension systems (NARES) to identify and advise on appropriate management systems for enhanced water-use efficiency in dry-area cropping sequences, based upon relevant research and development experience, at national and international level, and supported by access to spatially-referenced information on the biophysical environment, farming systems, production practices, and relevant research and development experience.
- Increased opportunity to communicate new insights and successful techniques among national researchers in dry-area agriculture.
- Enhanced human skills and practical knowledge, within national and regional research, development and extension institutions, and at farm level.
- Guidelines for national and regional policies to promote efficient and acceptable water-use management techniques within the development of dry-area agriculture.

Research Approach

The OSWU research program will combine different levels of research, conducted at different scales in key target areas, as a matrix of activities across national, regional, and international research institutions. The main venues for applied and adaptive research will be subsets of field experiments, on both research stations and farmers' fields, ongoing or newly established with project support, undertaken by national institutions in participating countries in ways that match local conditions, priorities, and research strengths.

These activities will be conducted in multidisciplinary, systems contexts, with the participation, where appropriate, of the farming community and extension services. Care will be taken to ensure that all experimental sites are well-characterized in respect of climate, soil, and utilization history. Strategic research will be limited to a very small number of institutions where there is existing experience and relevant expertise to support appropriate activities. The research program will comprise:

1. Farm-level activities (within catchment and community contexts)
   - appraisal of farmers' cropping practices (the constraints and perceptions that determine them and possible options for their improvement) and their effect on water capture and utilization efficiency in relation to environmental potential;
   - on-farm, farmer-participatory research, to test the effectiveness and acceptability of selected techniques that improve water capture and utilization efficiency.
2. Back-up research
   - field activities, on-station and on-farm (with researcher management) to test and quantify promising techniques within a range of appropriate biophysical conditions;
   - laboratory/field studies of soil physical properties.
3. Support and technology-transfer activities, comprising
   - inventory, review, and appraisal of previous work;
   - development of geographical, agroclimatic, and biophysical information bases (with modeling, where appropriate) to facilitate (1) the testing and utilization of models to better define crop/environmental potentials and identify the reasons why actual production fails to match potential; and (2) the targeting, generalization, and subsequent transfer of effective field techniques.

Across all research venues, encouragement will be given to recognition of the occurrence of problems at different scales, the interrelation of those different scales, and the selection of scale-related research designs.

Research teams in different countries will be encouraged to focus on different problems, optimizing the comparative advantage of each institution to maximize the coverage and complementarity across OSWU as a whole. Data exchange, and more general interaction, between field teams and information-support groups will be an important integrating process. A major aim will be to build up national awareness of scale linkages and national capabilities to analyze and generalize field research data through spatially-referenced information systems and well-focused modeling tools.

Wherever appropriate, linkages will be established (particularly in data exchange) to other initiatives, consortia, and projects promoting research and development activities involving land and water use in dry-area agriculture.

In summary, the OSWU Consortium tries to take into account economic (growth, efficiency), social (equity, poverty reduction), and ecological (natural resource management) objectives of development (McNeill 1998).

Uniqueness of OSWU

With water being one of the principal sources of (agricultural) production, an overlap with other ecoregional projects, networks, or consortia within and outside the Soil Water Nutrient Management Program (SWNMP) is unavoidable. The four programs which are closest to the OSWU Consortium are the Desert Margin Program (DMP) convened by ICRISAT (DMI 1996), the Combating Nutrient Depletion Consortium (CNDC, Chude et al. in these proceedings), SWNet (in SADCC countries), and the On-Farm Water Harvesting Consortium convened by ICARDA (OFWH 1995). The linkages are the subject of a separate section later in this paper. Like most of these consortia or networks, OSWU has an integrated and participatory research and systems approach, includes different levels of scale (e.g. farmer and community/ watershed), capitalizes on existing knowledge, works with development projects, and uses different models. The *uniqueness* of OSWU, however, lies in the following:

- Water is the cross-cutting issue among five different agroecological regions (WANA: West Asia and North Africa, and SSA: West, East, and Southern Africa) which allows exchange of experience and generation of new solutions for resource-poor farmers in regions where water is the most scarce natural resource;
- Emphasis is on optimizing the water balance at the farmer and community (watershed) level to increase water availability for intensified and increased agricultural production;
- Increase the awareness of farmers on the environmental issues related to optimizing soil water use (i.e., biological, physical, and chemical soil degradation);
- OSWU puts particular emphasis on rainfed crop production (in contrast with other similar programs such as the On-Farm Water Harvesting Consortium);
- The different level of the member countries NARS's capacities allows the less developed to profit from and capitalize on the experience of the more advanced NARS;
- Standardization of documentation to facilitate exchange and achieve comprehensive coverage of the subject;
- Linkages and collaboration among different organizations and institutions working in the domain.

Functioning of OSWU: Consortium Versus Network

The Consortium should have a strong networking role. It should help in the creation of regional databases and dissemination and sharing of experience, and have a backstopping role for the submission of proposals.

Rather than having all countries working on all possible topics, research themes should be identified and carried out by a single country or group of countries within the Consortium. The allocation of research themes to specific countries should be done according to needs and priorities as well as on the basis of a genuine assessment of the strengths and weaknesses of the different member countries or, for instance, the predominance of a certain production system in a given country. The assignment of themes to countries should not be exclusive, and duplication is permissible as long as there is a clear framework allowing for the sharing of experience and results. The national reviews are a good start from which the strengths and weaknesses of the countries can be identified and the network built up on.

Focus, Target Groups, and Scales

It was unanimously expressed that the OSWU Consortium should not be doing 'old wine in new bottle' research, and it should not be a network on a theme that links national research programs. The list of potential research subjects, as developed during the Aleppo meeting in 1996 is no longer the only basis for further development of OSWU's research agenda. Instead, the National Review and Impact Papers on the optimization of soil water use (Parts A and C in these proceedings) are used to identify existing research gaps and priorities (next section).

The target groups of OSWU are small-holder and commercial farmers as well as rural communities (villages). As a consequence, OSWU will carry out research and development activities at scales up to the watershed level. The watershed approach should not be an objective as such, but should derive in a logical way from the definition of the objectives. The scale of approach comes with the implementation of the work. Taking into consideration the goal and also the unique features of OSWU, the Consortium will focus on optimizing soil water use through on-farm and farmer-participatory research at the field and watershed (community) level.

Identification and Prioritization of Activities

Table 1 lists the activities as identified and developed in the general OSWU Consortium proposal. Out of these issues, the top research priorities in each of the member countries were identified in the Niamey Workshop in 1998 (Table 2). To avoid duplication of efforts and to make optimum use of resources (e.g. knowledge), the comparative advantage of the various member institutions/countries was identified (Table 3).

The 1999 Workshop in Amman clearly revealed that there is a large gap with regard to impact assessments of research and technologies aiming at optimized soil water use. It is therefore essential that quantitative impact studies on this subject will be performed. This is very much in line with the demand of several donor countries and organizations to put more emphasis on impact.

Linkages with Other Consortia and Networks

Figure 1 shows the linkages and cementing role of OSWU, while Figure 2 shows the linkages of the SWNMP. Through collaboration in relevant topics and exchange of progress and planning reports, duplication of efforts should be avoided. Some of those linkages are real collaborations, while others are still in the drawing-board phase.

Table 1. Proposed activities and outputs of the OSWU Consortium (OSWU 1998).

Outputs	Activities
Research	
A1 Appraisals of climate, farming systems and farm-level constraints, from technical and farmer points of view, with particular reference to water-use efficiency in selected target areas.	A.1.1. Review of secondary information and local professional expertise.
	A.1.2. Data analysis to provide information on seasonal patterns of precipitation (amounts and intensities) and evaporative demand.
	A.1.3. Participatory rural appraisal (followed, where necessary, by more detailed survey and/or on-farm monitoring) to detail modes of water capture and utilization, and associated (socioeconomic) problems and success of improved OSWU technologies.
A2 On-station tested techniques for arable land management (and data quantifying them), compatible with local rainfall patterns, farming systems and household constraints, that improve interception and retention of rainwater.	A.2.1. Investigations of soil infiltration characteristics and surface crust formation in relation to soil type, rainfall characteristics and land utilization history.
	A.2.2. Adaptation and testing of techniques (e.g. tillage, chemical amendments, plant cover, mulching, residue management) to control soil surface crusting and promote infiltration.
	A.2.3. Adaptation and on-farm testing of in-field water harvesting systems to improve rainwater-use efficiency.
A3 On-station-tested production practices for individual crops	A.3.1. Comparison of crop varieties with different morphological and phenological characteristics with respect to water-use efficiency.
	A.3.2. Evaluation of the effects of plant density, geometry and row orientation on water-balance components.
	A.3.3. Evaluation of appropriate weed control techniques.

Continued

Table 1. *Continued.*

Outputs	Activities
A4 Sustainable on-farm-tested management practices that maximize the productivity of the farming systems per unit of available water.	A.4.1. Farmer-participatory identification and testing of integrated land management interventions at field and watershed level to improve the well-being of rural households by means of a more efficient use of available water resources.
	A.4.2. On-farm quantification of the agronomic, socioeconomic and environmental impact of existing and improved water, soil, and crop management technologies on the overall efficiency of water use at farm and community level.
A5 General principles of optimal soil water use in dry-area cropping systems, integrating the best practices.	A.5.1. Analysis, interpretation, and integration of biophysical and socioeconomic data outputs (A.1-4; e.g. using Bayesian Belief Networks).
	A.5.2. Use of data outputs from A.1-4 to adapt and validate available models of soil-crop-water management.
	A.5.3. Linkage of validated models to selected environmental databases to quantify local yield potentials and identify mechanisms underlying major yield gaps, and test spatial extrapolation of site-specific plot results.
Strategic and developmental activities	
B1 Publication of national- and regional-level reviews and detailed research results in the OSWU domain	B.1.1. Inventory, analysis, and synthesis of available information of past and ongoing research and development of initiatives directed at optimizing soil water use in dry-area arable cropping systems.
	B.1.2. Exchange of results obtained within OSWU with other SWNMP and other relevant consortia (e.g. CNDC, DMP, On-farm Water Harvesting Consortium)

Continued

Table 1. ***Continued***

Outputs	Activities
B2 Accessible sets of spatially referenced data for dry arable farming areas.	B.2.1. Data acquisition and database building.
B3 Staff of research, development, and extension institutions with (a) enhanced understanding of OSWU techniques, and (b) enhanced capability to work together to identify and transfer the most locally appropriate techniques to farmers.	B.3.1. Involvement of technical and socioeconomic scientists and extension specialists in farmer-participatory research activities. B.3.2. Workshops (at project, regional, and national levels). B.3.3. Formal technical training courses.
B4 Dry-area farmers using locally appropriate techniques of land, soil, and crop management for efficient soil water use for sustainable and profitable agricultural production.	B.4.1. Farmer-participatory research and development activities. B.4.2. Farmer support through formal extension activities and, where necessary, the recommendation of appropriate policy measures to support the adoption of improved techniques.
B5 Reliable guidelines on efficient and acceptable water-use management techniques for the development of dry-area agriculture available to, and accepted by, relevant government planners and policy-makers.	B.5.1. Involvement of policy-unit staff in field-level problem identification and research planning. B.5.2. Joint seminars between research and policy/planning staff to review research results and their implications. B.5.3. Publication (workshop proceedings, final project report/ recommendations).

Table 2. Needs in research activities in the various countries of the OSWU Consortium, X = need; number indicates priority; * = completed before this workshop; ! = activities being carried out by national funds.

Countries	A1 *	A2	A3	A4	A5	B1	B2	B3	B4	B5
Zimbabwe	1.3	X		X						X
Egypt		X		X			X		!	X
Iran		X		X	X				!	X
Jordan		X		X	X				!	X
Morocco			X		X		X		!	X
Mali		X		X			X			X
Niger		X					X		X	X
South Africa	1.3	2.2		X	X		X			X
Syria		X		X					X	X
Turkey			3.1	X		*			4.1	X

Table 3. Comparative advantage of the member institutions in OSWU.

Country	Field of expertise
Burkina Faso	Soil and water conservation technologies
Egypt	CIS and database development
Iran	-[1]
Jordan	Supplementary irrigation
Morocco	Water harvesting technologies; dryland farming
Mali	Agroc limatology
Niger	Cropping strategies
South Africa	Soil water balance management; agroclimatology; databases and CIS
Syria	-
Turkey	Cropping strategies
Zimbabwe	-

1. Not specified.

Within the SWNMP, the one closest to OSWU is the Combating Nutrient Depletion Consortium (CNDC) because of its rainfall and target area (i.e., the humid and subhumid tropics of sub-Saharan Africa). It has been mentioned in various papers of these proceedings that nutrient depletion has associated negative consequences for water-use efficiency.

The Managing Soil Erosion Consortium (MREC) has its mandate primarily in Asia (focus on Thailand, Indonesia, and the Philippines) where there is much higher rainfall; links will therefore relate mainly to methodological issues.

Linkages with the Managing Acidic Soils (MAS) Consortium will be limited, because of the much more acidic nature of the soils and the ecoregional zone, which is the hillside, savanna, and forest margin agroecosystems of Latin America. However, this consortium started recently activities in Africa.

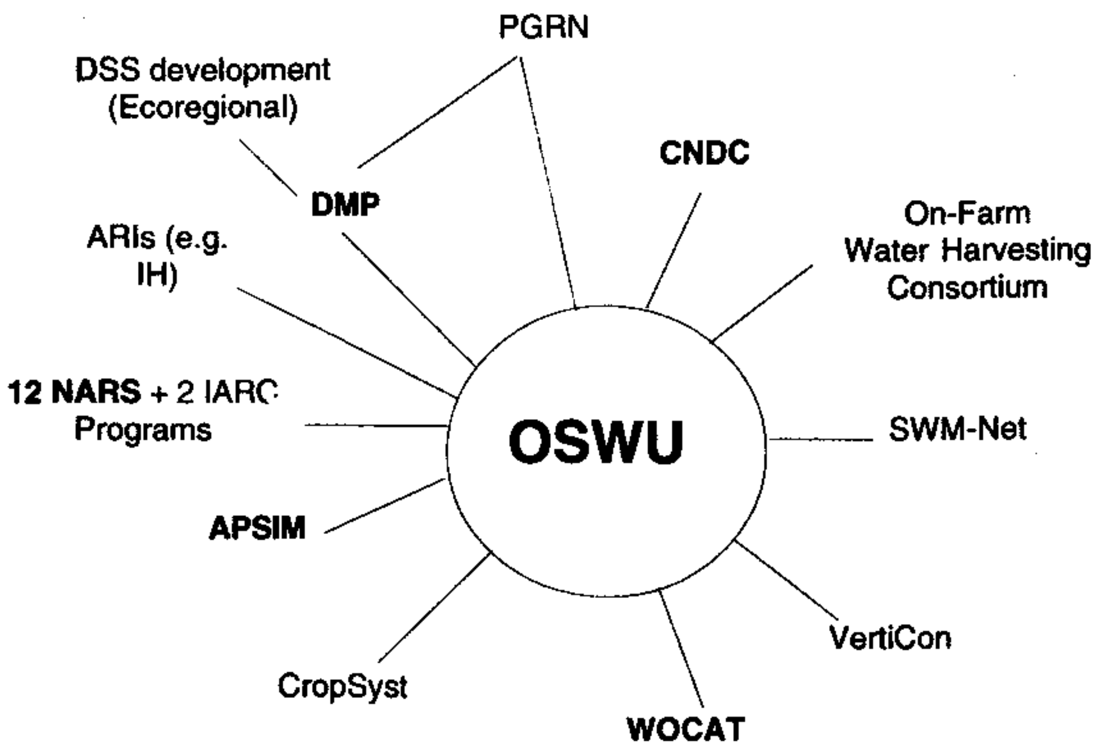


Figure 1. Simplified diagram of the role of OSWU in linking related research in the domain of soil water use. DSS: Decision-support system development project; WOCAT: World Overview of Conservation Approaches and Technologies; APSIM: Group at ICRISAT that works with this model; CropSyst: Group at ICARDA that works with this model; DMP: Desert Margins Program; SWM-Net: Network on soil water management in East Africa; PGRN: Network on Natural Resource Management in West Africa.

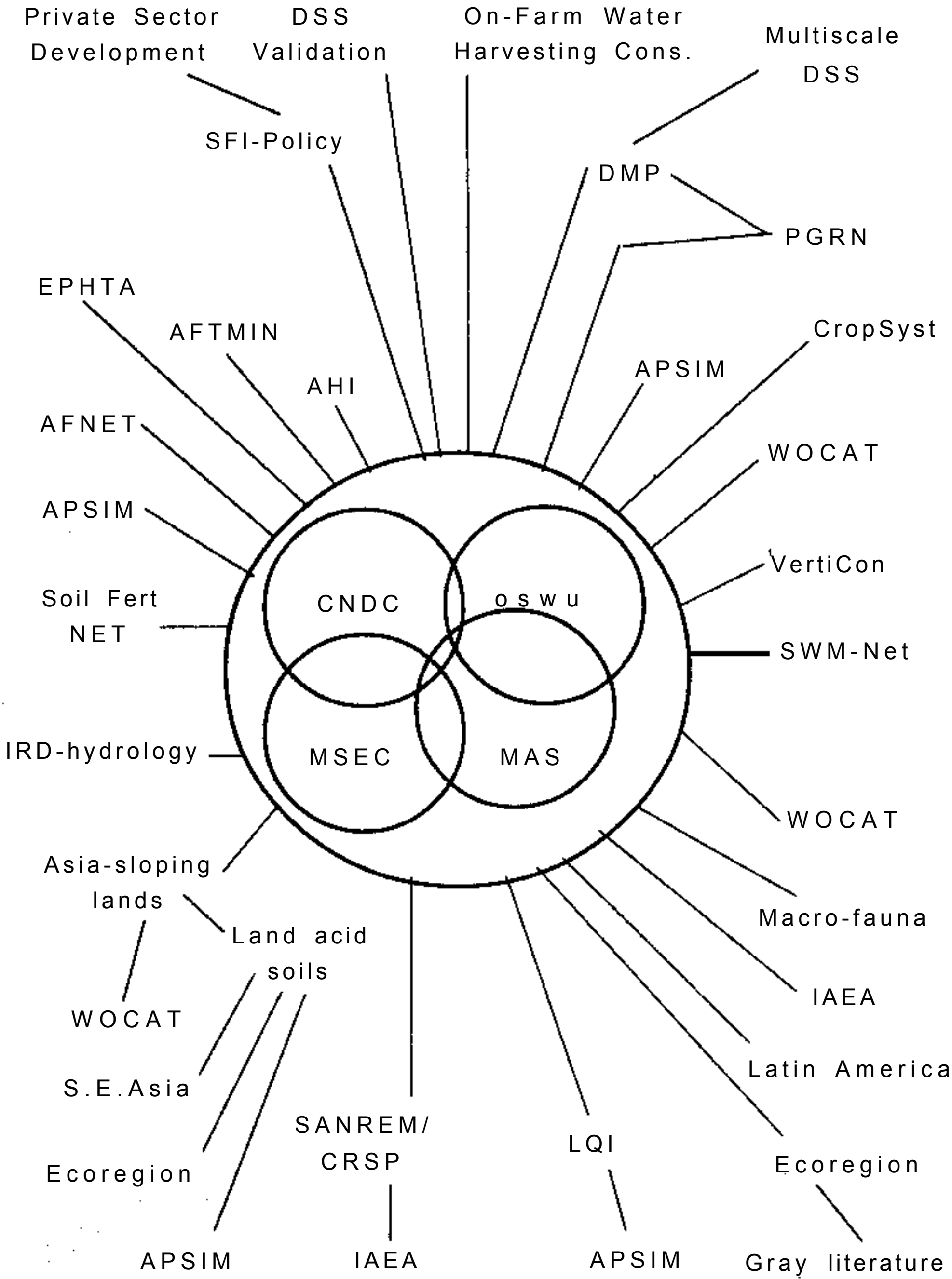


Figure 2. Simplified diagram of the role of the Soil Water Nutrient Management Program with its four consortia in linking research in this domain. Acronyms are listed in Appendix 3

In most countries, OSWU members have links to specific projects dealing with the same problems of water management [e.g. CRISP in Mali and PGRN in West Africa, especially related to use and conservation of rainwater, selection of varieties related to climatic constraints, and soil and water conservation (Lompo 1999)]. Results of the OSWU Consortium will also be of importance to the Convention to Combat Desertification (CCD 1998), especially in the formulation of sustainable farming systems (e.g. van Duivenbooden et al. 1999).

In the WANA region, links with the On-Farm Water Harvesting (OFWH) Consortium could comprise mainly water harvesting techniques and their development, dissemination, and impact.

In SSA, links seem to be also very natural with the Desert Margins Program (DMP), especially in the field of soil water conservation technologies. Currently, overlapping countries include Burkina Faso, Kenya, Mali, Niger, and South Africa.

In East and southern Africa, another potentially important link could be with the ASARECA network on Soil and Water Management (SWM-Net). Currently, overlapping countries include Kenya, Zimbabwe, and South Africa.

In West Africa, a possible link could also be established with the Consortium for Sustainable Use of Inland Valleys (IVC; Jamin et al. 1997), with OSWU focusing on the upland part of the watershed. Current overlapping countries include Burkina Faso and Mali.

At the same spatial scale, collaboration with IWMI in sub-Saharan Africa could be useful (e.g. also on supplemental irrigation). IWMI works currently in the OSWU member countries South Africa and Kenya (IWMI 1999). If financial means permit, inviting countries who have experience with watershed management (e.g. Tunisia: Laajila Ghezal et al. 1998; Senegal: Perez et al. 1997) may also be an option.

So far, links with projects and consortia acting mainly in developing countries have been mentioned. Linkages with Advanced Research Institutes (ARIs) in the developed world are also envisaged (e.g. Institute of Hydrology, UK; see Batchelor, in these proceedings). For instance, farmers in the USA too need to increase water-use efficiency, as recently underscored (e.g. Farahani et al. 1998).

The WOCAT Training Workshops in Niamey (May 1999) revealed a great opportunity for linking OSWU to WOCAT. OSWU members from Burkina Faso and Niger, and ICRISAT participated. The OSWU convenors will, in collaboration with WOCAT resource persons, stimulate the use of the WOCAT approach within the Consortium, especially to monitor implementation of developed technologies in the various countries.

In summary, OSWU is an open-structured consortium, and linkages with partners will be determined by demand and supply from the participating partners on the basis of commonly-set goals that increase alignment (Fig. 2) and research efficiency.

Near Future of OSWU

With the limited funds that were acquired in the last few years, OSWU has placed itself and has started research 'on the ground'. Member countries have sent their

Table 4. Prerequisites for project selection within the OSWU Consortium.

Criteria
Part of OSWU proposal
Aspects from the national reviews
Linking WANA and SSA (both intra-and interlinks)
Proof of NARS' capacity to implement the proposed work
Proof of impact assessment of the proposed work
Availability of matching funds
Linking to SWNMP consortia
Meeting CGIAR criteria
Linking to other consortia (DMP, Water Husbandry Consortium, etc.)
Including training component

project proposals under the umbrella of OSWU to the convenors for a first review. Subsequently, proposals were brought to the Steering Committee Meeting for approval. To facilitate evaluation of project proposals in the framework of OSWU, criteria were retained (in order of importance) at Ethe 1998 workshop (Table 4). The first six criteria are essential, and the others are 'guidelines'.

During the Steering Committee Meeting in 1999, funds were allocated to the following projects:

- Linking of existing databases. During the workshop in Amman, the absence of comprehensive and openly accessible databases was considered a major limiting factor in increasing the impact of past research. The proposed activity entails linking of existing databases to increase transparency on existing data and experience and to avoid duplication of efforts (it is not to fill in/populate the databases), which will also allow better impact assessment and use of simulation models and GIS to extrapolate results to larger areas. It will be carried out tentatively in Burkina Faso, Egypt, Iran, and South Africa for one year first. Backstopping to Burkina Faso and Iran will be provided by South Africa, Egypt, and/or convenors. The original proposal for the development of a database as developed by South Africa and Egypt was considered too large to be funded with existing OSWU funds; OSWU will seek other funding sources to finance this project proposal.

- In-field water harvesting techniques: The way to increase yields in water-scarce areas. The existing joint project proposal developed by South Africa and Jordan was adapted with a 1.5 year phase to quantify soil evaporation (representing the major water loss). The entire project proposal—considered too large to be funded with existing OSWU funds—has been approved by the Steering Committee and will be submitted separately to donors.

- No-till and change of rotation. On the basis of the national review carried out in Turkey, no-till and change of rotation seems a promising alternative management strategy for larger parts of the country.. Linking field work with use of crop simulation models should enable identification of target zones and impact assessment at later stages. OSWU's contribution to the total project will be 50% of the total costs for the four-year period.

- **Optimizing soil water use through changing cropping systems.** The proposal submitted to OSWU fits in the national strategy of Morocco and Niger. Funds are used to complement existing work as well as to initiate new work. Work in Morocco will be carried out.by INRA-Settat and in Niger by INRAN and ICRISAT.
- **Training scientists in information tools.** The need was expressed by NARS participants to have more training in the domain of. crop simulation models, database development and management. Proposed activities include training workshops in crop simulation modeling (CropSyst for WANA and APSIM for SSA; their performance to be compared at a later stage) and in the use of the WOCAT database. OSWU already cosponsored the WOCAT training course in Niamey.
- **Impact assessment.** The 1999 workshop results indicate that there is promising information available. However, the workshop has also revealed that no proper (formal) studies on the impact of research on optimization of soil water use have been conducted in any country. Therefore, funds will be allocated to carry this out within a two-year period. This will then also be the topic of the workshop in 2001, linked to the Steering Committee Meeting.

The general OSWU project proposal (OSWU Consortium 1998) will be further improved with inputs from the various country reviews to highlight aspects in one of the five agroecological zones within OSWU. This improved proposal will then be submitted to various donors.

Conclusions

The two workshops contributed to a greater coherence and complementarity in the Consortium goal and objectives, and outputs and activities were further focused.

The OSWU Consortium activities are now based on specific needs and information gaps identified through the national review papers (detailed current knowledge and knowledge gaps, and identified priority areas for action), assisted by input from other members and invited external soil-water specialists.

A large number of possible linkages have been identified. They include, for instance, another SWNMP consortium (CNDC), the Desert Margins Program (DMP) in SSA, the Water Husbandry Program in WANA, and WOCAT

The-assessment of impact of research and technologies aiming at optimized soil water use will have to play a major role in future OSWU activities. Using the WOCAT tools will facilitate impact assessments.

The importance of SWNMP needs to be further emphasized by using standardized methods, global testing of products, and establishment and/or strengthening of long-term study sites (Appendix 1). A meeting with stakeholders planned for 2000 will also help in further improving the integration of the four SWNMP consortia.

The Consortium's chances of attracting sufficient funding to support an integrated program of field research across all participating countries have improved by elucidating the uniqueness of OSWU and giving clearer focus. OSWU started in 1999 with support to various projects in the member countries.

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Appendix 1. Main Characteristics of Selected OSWU Sites

In this appendix, the main characteristics of the OSWU research sites in Burkina Faso, Jordan, Mali, Morocco, Niger (ICRISAT), Syria (NARS), Syria (ICARDA), Turkey and South Africa are presented.

Burkina Faso

Farako-ba Research Station

Location:	4°20' West longitude and 11°6' North latitude
Average annual rainfall:	950 mm (April-October)
Average annual evaporation:	1700 mm
Average annual minimum temperature:	15°C
Average annual maximum temperature:	35°C

Soil physical properties:

	Texture (%)						
Depth (cm)	Clay (1/1)	Loam	Sand	Bulk density	PF 2.5 (%)	PF4.2 (%) (wilting point)	Field capacity (mm)
0-20	*6.6*	11.5	84.4	1.6	8.5	2.8	18.4
20-40	22.0	13.9	64.1	1.5	13.1	7.8	34.1
40-60	29.0	13.1	57.9	1..5	17.7	11.9	52.1
60-80	28.8	12.8	58.4	1.6	19.3	13.0	72.8
80-100	28.0	19.6	58.3	1.7	18.6	12.9	111.1

Main cropping system: Maize-based production yield, yield 1000-2500 kg ha^{1}, in rotation with cotton in the cotton-producing areas, use of animal-drawn or motorized cropping system.

Saria Research Station

Location:	Longitude 2°09' West
	Latitude 12°16'North
Average annual rainfall:	700 mm (May-September)
Average annual evaporation:	2000 mm
Average annual minimum temperature:	15°C
Average annual maximum temperature:	40°C

Soil physical properties:

Depth (cm)	Texture (%)			Bulk density	PF 2.5 (%)	PF4.2 (%) (wilting point)	Field capacity (mm)
	Clay (1/1)	Loam	Sand				
0-20	10.7	7.1	82.2	1.7	13.5	6.5	17.9
20-40	14.8	7.0	78.1	1.7	19.1	10.1	40.1
40-60	22,2	8.4	79.4	1.9	20.7	13.9	61.5
60-80	24.9	11.8	63.3	1.8	20,0	14.3	79.7
80-100	33.6	12.8	58.6	1.9	21.7	14.8	102.3

Main cropping system: Traditional sorghum-based production yield, 700-800 kg ha*[1], in rotation or association with millet, cowpea, peanut, etc.

Sabouna (farmers' fields)

Location:	Longitude 2°30' West
	Latitude 14° North
Average annual rainfall:	600 mm (June-September)
Average annual evaporation:	2200 mm
Average annual minimum temperature:	14°C
Average annual maximum temperature:	42°C

Soil physical properties:

Depth (cm)	Texture (%)			Bulk density	PF 2.5 (%)	PF 4.2 (%) (wilting point)	Field capacity (mm)
	Clay (1/1)	Loam	Sand				
0-20	22.3	8.5	69.1	1.4	15.7	8.2	22.2
20-40	31.5	9.4	59.1	1.7	21.4	12..3	53.3
40-60	32.4	9.8	57.8	1.8	23.2	12.8	90.0
60-80	33.2	9.9	56-8	2.4	25.3	13.3	149.8
80-100	34.4	10.2	55.4	1.8	25.9	14.1	236.4

Main cropping system: Traditional millet-based production yield, 500-600 kg ha[1], in rotation or association with peanut, cowpea, etc.

Jordan

Mushaqqer Station

Location:	28 km southeast of Amman
Area:	121.2 hectares
Longitude:	35°47'-35°48'E
Latitude:	32°46'-32°47'N
Altitude:	790 m above sea level
Weather and climate:	Mediterranean climate. Hot, dry summers and moderate, wet winters
Average rainfall:	360 mm
Average lowest temperature:	10.2°C
Average highest temperature:	22.9°C
Relative humidity:	40-70%.
Average wind speed:	126 km day^{-1}. In general, wind movement has a northwestern direction.
Soil taxonomy:	Fine, montmorillonitic, thermic, entic, chromoxerets
Soil order:	Vertisol
Soil colour:	Brown-reddish brown
Soil type:	Clay loam. Clay presence in most layers is 56.5%
Field capacity:	33.5% for the surface layer
Power of Hydrogen (pH):	7.8-7.9
Organic matter content:	0.8%
Permanent wilting point:	23% from 0-12 cm
Electrical conductivity:	0.5 m mohs cm^{-1} on the surface (m mohs = millimohs)
Water availability:	10.5%
Average drainage:	1-5 mm hr^{-1}
Phosphorus content:	5-15 ppm
Potassium content:	1.5 eq.mm 100 $parts^{-1}$ (eq. mm = equivalent millimeter)

Maru Station

Area:	980 dunum
Soil depth:	Shallow to 1.5-1.8 m
Weather and climate:	Mediterranean climate. Moderate, hot, dry summers and cold winters
Average rainfall:	447 mm

Soil taxonomy:

Series 15	Red clay soil which forms moderately wide cracks in the dry season and develops on limestone associated with basalt.
Series 18	Red brown clay soil with good structure and developed on limestone.
Series 15 1A	Deep and nonstony soil and nearly level land, 584 dunum.
Series 15 8A	Shallow, stony, and very stony on nearly level and gently sloping 342 dunum.
Series 38 8 B	Shallow, stony, and very stony soil and gently sloping, 23 dunum.
Series 38 8A	Shallow, stony and very stony soil on nearly level land, 7 dunum.
Series 389 B	Shallow, rocky soil on gently sloping and nearly level land, 24 dunum.

Ramtha Station

Soil depth:	1-1.5 m
Slope:	1-2%
Average rainfall:	200-250 mm

Average temperature:

Month	Highest	Lowest
Jan	13°C	6°C
Feb	14°C	5°C
Mar	16°C	7°C
Apr	24°C	12°C
May	28°C	14°C
Jun	31°C	16°C
Jul	33°C	19°C
Aug	35°C	20°C
Sep	32°C	18°C
Oct	29°C	15°C
Nov	28°C	11°C
Dec	18°C	7°C

Soil texture: Silty clay loam

Rabba Station

Soil depth:	Average 2 m
Soil texture:	Clay (18.56 sand + 22.52 silt + 58.91 clay)
Soil slope:	Average 2%
Soil EC:	0.7-1.2 mmohs
Soil pH:	7.8-8.2
Soil class:	Vertisols
BD:	(Jan-June) 1-1.28 gm m^{-3}

Average temperature:

Month	Highest	Lowest
Oct	26.7°C	13.3°C
Nov	23.0°C	10.6°C
Dec	15.8°C	6.3°C
Jan	14.0°C	5.1°C
Feb	13.0°C	4.6°C
Mar	18.0°C	6.7°C
Apr	22.0C	9.1°C
May	27.7°C	14.5°C
Jun	31.0°C	16.0°C

Mali

Introduction

In the Sudano-Sahelian Zone of Mali, crop yields are heavily dependent on soil water and nutrients (Breman et al. 1998). Increasing the efficiency of these factors is the key issue for the research and extension programs involved in these areas. The locations described below are development/research sites where the LaboSEP of IER and the extension division of CMDT (the cotton company of Mali) are implementing tillage along contour lines coupled with soil amendments for the purpose of reducing runoff (thus increasing water infiltration and use) and increasing both soil water-and nutrient-use efficiencies. Selected properties of these sites were summarized from Sivakumar et al. (1984), Spencer et at. (1995) and PIRT (1986).

Konobougou

About 80 km from Segou, this site is located in the Sudanian Zone of Mali. It receives about 800 mm of rainfall annually. The rainy season lasts about 4 months (from June to Sep). The annual PET reaches 2,000 mm. In general, the maximum average temperature is 35°C (from May to June), while the average minimum temperature is 22°C (from Dec to Jan).

Soils at Konobougou are mostly loamy (Sols Ferrugineux Tropicaux or Plinthic Paleustafs). Heavy crusting is a constraint at some sites.

The cropping system is based on cotton, the major cash crop of Mali. The crop rotation is on a two-year basis (cotton followed by either sorghum or millet). Cotton receives the recommended fertilizers (150 kg ha^{-1} of 14-22-12-8S-1.5B plus 50 kg ha^{-1} of urea), while the cereal crop only takes advantage of the residual effects of the above fertilizers. Manure and other organic sources of plant nutrients are applied on cotton. Other crops include groundnut and fonio. Optimizing soil water use practices include stone line (at the community level and located at the upper part of the toposequence) and tillage by ridging.

Cinzana

About 40 km from Segou, this site is located in the Sahelo-Sudanian Zone of Mali. It receives about 700 mm of rainfall annually. The rainy season lasts about 4 months (from June to Sep). The annual PET exceeds 2,000 mm. In general, the maximum average temperature is 37°C (from May to June), while the average minimum temperature is 23°C (from Dec to Jan).

Soils of the Cinzana area are distributed according to a toposequence of smooth slope, resulting in different soils dominated by a deep sandy soil: Sols Ferralitiques or Grossarenic Paleustafs.

The cropping system is in most cases millet monoculture (millet over millet). Millet or sorghum are inter-sown with cowpea. Manure and other organic sources of plant nutrients are applied. Other crops include groundnut and fonio. Optimizing soil water use practice is essentially tillage by ridging.

Yayadiassa

About 10 km from Sikasso, this site is located in the Northern-Guinean or Sudano-Guinean Zone of Mali. It receives about 1200 mm of rainfall annually. The rainy season lasts about 6 months (from May to Oct). The annual PET reaches 1,700 mm. In general, the maximum average temperature is 30 °C (from May to June), while the average minimum temperature *is* 20°C (from Dec to Jan).

Soils at Yayadiassa also follow a toposequence. The dominant soil is loamy (Sols Ferrugineux Tropicaux or Plinthic Paleustafs).

The cropping system is based on cotton. The crop rotation is in most cases on a three-year basis (cotton-maize-sorghum or millet). Cotton receives the recommended fertilizers, maize receives 100 kg ha^{-1} of urea, while sorghum/millet only takes advantage of the residual effects of the above fertilizers. Manure and other organic sources of plant nutrients are applied on cotton. Other crops include groundnut and fonio. Optimizing soil water use practices include stone line (at the community level and located at the upper part of the toposequence) and tillage by ridging.

Morocco

The site where most of the research and technology transfer activities have been conducted by the Aridoculture Center is located in the Chaouia and Abda regions (32°00' N to 33°30' N and 7°30' W to 9°30' W).

The average annual rainfall varies from 200 mm in the southern part to 400 mm in the northern part with the same distribution gradient in the east-west direction. Temperature fluctuation is less important than rainfall fluctuation. However, the difference between the hottest and the coldest months varies from 9°C to 18°C. Monthly rainfall and temperature averages for over more than 30 years are given in the following table.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T_{max}(°C)	20.1	21.3	23.7	25.3	27.4	30.6	34.4	31.8	31.6	28.7	24.1	21.4
T_{min}(°C)	6.06	7.19	8.67	10.3	12.7	15.9	18	20	18.2	12.8	10.1	8.38
Average temp.(°C)	13.1	14.2	16.2	17.8	20.1	23.3	26.2	25.9	24.9	20.8	17.1	14.9
Rain (mm)	58.5	56.28	45.49	40.34	14.64	3.16	0.67	0.17	5.22	27.40	48.54	57.63

The average annual potential evapotranspiration is around 1800 mm.

The most important soils in the region are:

- Aridisols: Xeric, clay texture with a petrocalcic horizon (crusty at the surface). Organic matter content is very low, less than 1%, with an alkaline pH. P and K contents are also low. Bulk density varies from 1..3 to 1..35.
- Rendolls: Calcareous conglomerate with a granular structure. They present a clay texture with less 3% of organic matter in the surface layer and an alkaline pH. They have low P and high K content. The adsorbing complex is saturated in Ca and Mg. Bulk density varies from 1.3 to 1.4.
- Vertisols: Xeric soils with more than 45% smictite clay type. They are very deep with field capacity of 35% and a wilting point of 13%. Bulk density varies from 1.4 to 1.5.

There are three main cropping systems:

- Wheat system with the main following rotations or successions: wheat/fallow, wheat/cereal and wheat/food legume. One or the other rotation is practised depending on the annual rainfall and the depth of the soil.
- Barley system: It is a precarious system, with low crop and animal production yield due to the lack of valorization and nature of soils (hilly, eroded, low organic matter and fertility). This system is strongly related to livestock.
- Range system: Dominant in zones having low rainfall and with no interest to annual crops. Shallow soils with low water retention, low fertility level and salinity problems are dominant.

Average crop yield in rainfed agriculture: wheat 1500 kg ha^{-1}, barley 1200 kg ha^{-1}, maize 1000 kg ha^{4} chickpea 600 kg ha^{-1}, and lentil 600 kg ha^{-1}.

Niger (ICRISAT)

The ICRISAT Sahelian Center (Sadore) is located in the southwestern part of Niger at .13°15'N latitude and 2°18'E longitude. The center lies within the Sahelian bioclimatic zone.

Average monthly rainfall:

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean (mm)	00	0.2	2.4	6.9	29.4	75.9	156.9	172.7	88.2	11.7	0.4	00

Monthly mean minimum and maximum temperature:

Month	1	2	3	4	5	6	7	8	9	10	11	12
Mean max temp.°C	32.9	35.9	39	40.9	39.9	36.9	33.7	32.1	33.9	37.3	36.4	33.4
Mean min temp°C	15.9	18.7	22.8	26.3	27.4	25.4	23.6	22.9	23.3	23.8	19.3	16.4

Average annual evapotranspiration: 191.13 mm

Water-holding capacity: 100 mm

Decade	ETR (mm)	Decade	ETR (mm)	Decade	ETR (mm)
1	2.34.	13	12.58	25	44.80
2	0.98	14	13.08	26	40.62
3	1.07	15	21.26	27	32.57
4	1.29	16	25.86	28	18.51
5	1.10	17	27.66	29	11.75
6	0.97	18	27.62	30	8.96
7	2.97	19	38.36	31	2.57
8	9.99	20	40.04	32	2.70
9	6.67	21	47.87	33	1.98
10	3.46	22	47.33	34	0.93
11	6.26	23	48.23	35	0.84
12	8.19	24	53.95	36	0.95

Soil characterization laboratory:

Horizon	Depth (cm)	Particle size distribution Sand	Silt	Clay	Texture	Orgm (%C)	Ph (H_2O)	Ph (KCl)	NH4DAC Extr Bases Ca	Mg	Na	K	Al (KCl extr)	EC-EC	Bulk density	Water content 0.10 BAR	15 BAR
A1	0-15	92.5	3	4.5	S	0.25	5.1	4.0	0.2	0.1	0	0.1	0.8	0.9	1.8	8.4	1.3
A2	15-27	91.7	3.2	5.1	S	0.15	4.9	3.9	0.1	0.0	0	0.1	0.7	0.9	1.72	8.4	1.3
BT1	27-44	92.1	3.2	4.7	S	0.11	4.8	3.9	0.1	0.0	0	0.0	0.7	0.9	1.67	5.9	1.4
BT2	44-62	92.7	3	4.3	S	0.08	4.8	3.9	0.0	0.0	0	0.0	0.6	0.7	1.66	11.9	1.2
BT3	62-80	93	2.5	4.5	S	0.08	4.8	4.0	0.1	0.0	0	0.0	0.6	0.7			1.2
BW	80-103	92.5	3.2	4.3	S	0.07	4.8	4.0	0.1	0.0	0	0.0	0.6	0.7	1.65	15.5	1.2
BW	103-126	93.4	2.5	4.1	S	0.09	4.9	4.0	0.1	0.0	0	0.0	0.5	0.7			0.9
BC	126-150	94.5	1.9	3.6	S	0.06	4.8	4.0	0.1	0.0	0	0.0	0.5	0.7	1.68	5.6	1.1
BC	150-173	95	2	3	S	0.05	4.8	4.0	0.1	0.1	0	0.1	0.4	0.7			1.2
C	173-200	94.6	2.9	2.5	S	0.04	4.9	4.1	0.1	0.0	0	0.0	0.4	0.6	1.7	11.8	0.9

Production yield (kg ha^{-1}) of major crops

Crops	Millet	Sorghum	Groundnut	Cowpea
Yield	399	230	862	100

Syria (NARS)

Tweeneh Station

Location: 36°55'N latitude and 40°55'E longitude, located 10 km west of Hassekeh city.

Total area: 100 ha.

Climatic data of the last 25 years.

Month	Rainfall (mm)	Relative humidity (%)	ET (Evanov) (mm)	Mean air temp. (°C)	Min. air temp. (°C)	Max. air temp. CO	Absolute min. temp. (°C)	Absolute max. temp. (°C)
Jan	53	79	35	5.5	0.9	11.2	-8.3	20.2
Feb	39	73	51	7.5	2	13.7	-8	24.2
Mar	41	65	84	11.4	5.1	18.1	-4	29.8
Apr	47	59	128	16.6	9.5	23.8	-1	38.1
May	20	44	228	22.6	14.2	30.5	4.3	41.5
Jun	1	29	365	28.4	19.1	36.4	9.5	44
Jul	0	29	408	31.5	22.3	40.1	14	46.5
Aug	0	31	385	30.7	21.4	39.7	12.5	47
Sep	1	33	310	25.7	16.3	35.3	6.5	43
Oct	10	44	199	19.4	10.8	28.7	-1.5	37.8
Nov	17	63	91	12	5.4	20	-9	32.2
Dec	43	77	42	6.8	1.8	12.8	-9	21.5
Mean/Tot	272	52	2326	18.2	10.7	25.9	-9	47

Temperature fluctuation is less important than rainfall fluctuation. The soil order is Inceptisol, Calcixerollic Xerochrept characteristic of the Mediterranean-type climate, its light reddish-brown colour, well-drained, deep calcareous soil, calcic horizon in the subsoil means a rich layer of $CaCO_3$ and do not contain soft, powdery lime. Soil type is clay loam (44-47% sand, 28-33% silt, and 22-26% clay).

pH:	7.3-7.5
EC:	0.42-0.53 dS m^{-1}
$CaCO_3$:	23-25%
O.M:	0.83-1.32%
CEC:	21-24 meq 100g^{-1}
Available P:	9-17 ppm
Available K:	280-400 ppm
Gypsum:	0.25-2%

Main cropping systems are barley/barley and barley/fallow rotations.

Syria (ICARDA)

ICARDA Tel Hadya Research Farm

Location: 35°55'N latitude and 36°55'E longitude

Altitude: 384 m

Climatic data from 1978 to 1996.

Month	Rainfall (mm)	ET (Class A pan) (mm day)[1]	Min. air temp. (°C)	Max. Air temp. (°C)	Mean no. of frost events
Jan	60.9	1.3	1.7	11.2	9.9
Feb	50.2	2.7	2.1	13.5	8.7
Mar	43.8	4.1	4.6	17.5	4.2
Apr	28.4	6.2	8.0	23.7	0.3
May	14.2	9.3	12.1	29.2	0.0
Jun	3.0	15.5	17.2	33.9	0.0
July	0.0	17.3	20.7	36.7	0.0
Aug	0.1	16.1	21.0	36.7	0.0
Sep	0.5	11.7	17.2	34.4	0.0
Oct	24.5	7.5	11.7	27.3	0.0
Nov	48.5	3.9	6.4	18.6	2.6
Dec	53.8	2.2	2.7	12.9	7.8
Mean/Tot	328	2986	8.7	24.6	34

	Soil depth (cm)				
	0-12	12-45	45-70	70-100	100-145
Texture	Clay	clay	clay	clay	clay
Sand (%)	9.6	9.1	9.2	6.6	6.4
Silt (%)	26.7	24.7	22.8	24.3	23.8
Clay (%)	63.7	66.2	68.0	69.1	69.8
Field capacity (1/3 At) (%)	38.0	38.0	38.0	38.0	38.0
Wilting point (15 At) (%)	23.0	23.0	23.0	23.0	23.0
Saturation (%)	66.0	58.0	57.0	58.0	57.0
Bulk density (g cm^{-3})	1.01	1.06	1.18	1.25	1.25
pH (l:l)(Water)	7.9	8.0	8.0	8.0	8.0
$CaCO_3$ (%)	24.4	24.4	25.9	27.3	26.8
Organic matter (% C)	0.43	0.38	0.31	0.26	0.18
Total N (ppm)	660	580	520	390	315
CEC (me 100 g^{-1})	53	53	50	48	48
EC (ms cm^{-1})	0.42	0.40	0.40	0.40	0.40
K (extractable, me 100 $g)^{-1}$	1.4	1.0	0.8	0.8	0.8
P (Olsen-P, ppm)	9	5	2	2	2

Production of major crops (grain yields, t ha^{-1}).

Crops	Wheat	Barley	Winter chickpea	Spring chickpea	Lentil
Station field	2-2.5	2.5-3.0	1.5	0.8	1.2
Farmers'fields	1.3-1.7	1.5-2.0	1.3	0.7	1.0

Turkey

Location: Latitute 39'40'N and Longitute is 32°39'E

Climatic records (averages of 21 years).

Months	Total rainfall (mm)	Temperature (°C)		
		Maximum	Minumum	Average
Jan	50	0.8	-6.3	-2.1
Feb	26	3.9	-4.5	-1.5
Mar	27	10.2	-1.1	3.7
Apr	41	15.1	3.3	9.0
May	48	19.7	6.6	12.1
Jun	26	24.3	9.9	17.7
Jul	9	27.9	12.2	20.7
Aug	11	27.2	11.9	20.4
Sep	8	23.3	8.6	16.6
Oct	27	18.0	4.9	10.8
Nov	32	10.7	-0.6	4.4
Dec	36	4.4	-3.1	-0.4

Site 1

Soil characteristics	Soil depth (cm)				
	0-10	10-30	30-60	60-90	90-120
Texture	Clay	clay	clay	clay	clay
Sand (%)	20.7	26.6	25.1	25.2	25.1
Silt (%)	21.1	27.7	27.2	25.2	27.6
Clay (%}	58.2	45.7	47.7	49.6	47.3
Field capacity (1/3 At) (%)	38.7	34.2	33.4	32.5	33.8
Wilting point (15 At) (%)	20.5	17.1	17.1	17.2	17.6
Saturation (%)	66.0	58.0	57.0	58.0	57.0
Bulk density (g cm^{-3})	1.1	1.2	1.2	1.3	1.4
Total salt (%)	0.08	0.09	0.09	0.08	0.08
pH	7.8	7.7	7.7	7.7	7.7
$CaCO_3$ (%)	28.0	24.4	20.0	25.4	21.3
Organic matter (%)	1.6	2.2	2.5	3.7	2.1
Total N (%)	0.14	0.12	0.07	0.06	0.04
CEC (me/100 g)	34.5	32.2	33.6	31.5	31.6
K_2O (kg ha^{-1})	866	1572	1572	1528	1572
P_2O_5 (kg ha^{-1})	10	56	45	59	57

Site 2

Soil characteristics	Soil depth (cm)				
	0-10	10-30	30-60	60-90	90-120
Texture	Clay	clay	clay	clay	clay
Sand (%)	19.9	18.1	17.2	17.3	14.7
Silt (%)	29.6	24.6	20.7	24.9	18.9
Clay (%)	50.5	57.3	62.1	60.8	66.4
Field capacity (1/3 At) (%)	31.2	30	30	25.2	32.4
Wilting point (15. At) (%)	20.3	22.6	21.6	22	21
Saturation (%)	NA				
Bulk density (g cm^{-3})	1.04	1.04	1.04	1.04	1.1
Total salt (%)	0.065	0.065	0.060	0.055	0.043
pH	7.8	7.8	7.9	8.0	8.2
$CaCO_3$ (%)	20.3	24.7	24.5	34.1	51.5
Organic matter (%)	1.87	1.28	0.81	0.57	0.45
Total N (%)	NA				
CEC (me/100 g)					
K_2O (kg ha^{-1})	1026	518	324	281	173
P_2O_5(kg ha^{-1})	40	11.5	3.4	1.8	1.8
Specific density (g cm^{-3})	2.6	2.65	2.64	2.58	2.61

Main cropping system is fallow/wheat rotation. Average wheat yield is 3.1 t ha^{-1}.

South Africa

Glen Research Station, Bloemfontein

Located in the summer rain semi-arid part of the country, a large variety of agronomic crop research and technology development experiments are carried out here. The runoff studies of Du Plessis and Mostert (1965) reported in Beukes, Bennie et al. in these proceedings were done at this site. The mean cropping system is maize and wheat in rotation, using conventional mouldboard tillage. Mean long-term annual crop yield is 1 500 kg ha^{-1} for both maize and wheat.

Location:	28°55'44"S; 26°19'35"E
Altitude:	1320 m
Mean annual rainfall:	547 mm
Mean annual Class A pan evaporation:	2248 mm
Mean annual maximum temperature:	24.8°C
Mean annual minimum temperature:	7.6°C

Soil classification: Aridic Haplustalf (USDA); Haplic Luvisol (FAO); Hutton form Ventersdorp series (SA)

Machavie Agricultural Experimental Farm, Potchefstroom

Located in the central summer rain part of the country, a large variety of agronomic crop and livestock research and technology development experiments are carried out here. The tillage studies of Beukes (1987; 1992) reported in Beukes, Bennie et al. in these proceedings were done at this site. Mostly grain sorghum (85%) and sunflower (8%) are grown under dryland on these soils. Tillage practices vary from mouldboard/ disc to tine (minimum) tillage. Long-term annual yields of 3000 kg ha^{-1} (grain sorghum) and 1500 kg ha^{-1} (sunflower) are realized under the given rainfall and soil conditions.

Location:	26°47'58''S; 26°58'24"E
Altitude:	1 353 m
Mean annual rainfall:	582 mm
Mean annual Class A pan evaporation:	2173 mm
Mean annual maximum temperature:	25.6°C
Mean annual minimum temperature:	9.2° C

Soil classification: Typic Endoaquerts (USDA); Pellic Vertisol (FAO); Rensburg form Rensburg series (SA)

Soil profile characteristics at Glen Research Station, Bloemfontein, South Africa.

Hor	Depth (mm)	Colour (moist)	Texture (%)			Structure	Matrix density ($kg\ m^{-3}$)	Water ret (mm)		pH (H_2O)	Nutrients ($mg\ kg^{-1}$)			
			Sand	Silt	Clay			10 kPa	1500 kPa		P	K	Ca	Mg
A1	0-300	Red Br 5YR4/4	81	5	14	Massive	1 538	52	20	6.2	11	120	660	220
B1	300-600	Dk Red 2.5YR 3/6	71	6	22	Weak block	1 700	82	37	6.0	2	80	960	340
B2	600-900	Dk Red 2.5YR 3/6	69	7	23	Med block	1 730	90	39	6.7	1	80	980	450
C	900-1500	Red 2.5YR 4/6	74	7	19	Weak block	1 730	180	79	7.1	1	120	1 020	460

Soil profile characteristics at Machavie Agricultural Experimental Farm, Potchefstroom, South Africa.

	Depth	Colour	Texture (%)				Matrix density	Water ret (mm)		pH	Nutrients ($mg\ kg^{-1}$)			
Hor	(mm)	(moist)	Sand	Silt	Clay	Structure	($kg\ m^{-3}$)	10 kPa	1500 kPa	(H_2O)	P	K	Ca	Mg
A1	0-350	V Dk Grey 10YR 3/1	42	11	47	Strong med block	1310	188	102	7.6	2	90	2330	1365
A2	350-1000	Black 10YR 2/1	36	14	50	Mod med block	1360	442	248	8.6	3	105	3480	1935
G	1 000-1300N	Gray Brown 10YR 5/2	39	10	51	Firm gley	1390	209	117	6.7	4	100	3880	2305

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Appendix 3. Acronyms

AFNET	African Network for Biological Management of Soil Fertility
AHI	African Highlands Initiative
APSIM	Agricultural Production Systems Simulator
APSRU	Agricultural Production Systems Research Unit of CSIRO (Australia)
ARC-ISCW	Agricultural Research Council - Institute for Soil, Climate and Water (South Africa)
ARIs	Advanced Research Institutes
CCD	Convention to Combat Desertification
CGIAR	Consultative Group on International Agricultural Research
CIMMYT	Centro Internacional de Mejoramiento de Maiz y Trigo (Mexico)
CNDC	Combating Nutrient Depletion Consortium
CNRST	Centre National de la Recherche Scientifique et Technologique (Burkina Faso)
CRIFC	Central Research Institute for Field Crops (Turkey)
DFID	Department for International Development, UK (formerly ODA)
DMP	Desert Margins Program
DRSS	Department of Research and Specialist Services (Zimbabwe)
DSS	Decision Support System
EPHTA	Ecoregional Program for the Humid and Sub-humid Tropics of Sub-Saharan Africa
FAO	Food and Agriculture Organization of the United Nations (Italy)
GIS	Geographical Information Systems
GTZ	Deutsche Geselischaft fur Technische Zusammenarbeit (Germany)
IAEA	International Atomic Energy Agency (Austria)
IAERI	Iranian Agricultural Engineering Research Institute
IAR	Institute for Agricultural Research (Nigeria)
IARC	International Agricultural Research Center
ICARDA	International Center for Agricultural Research in the Dry Areas (Syria)
ICRAF	International Centre for Research in Agroforestry (Kenya)
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IDRC	International Development Research Centre (Canada)
IER	Institut d'Economie Rurale (Mali)
IFAD	International Fund for Agricultural Development (Italy)

IFDC	International Institute for Soil Fertility Management (USA)
IFPRI	International Food Policy Institute (USA)
IH	Institute of Hydrology (UK)
IITA	International Institute of Tropical Agriculture (Nigeria)
ILRI	International Livestock Research Institute (Ethiopia and Kenya)
INERA	Institut de l'Environnement et de Recherches Agricoles (Burkina Faso)
INRA	Institut National de la Recherche Agronomique (Morocco)
INRAN	Institut National de Recherches Agronomiques du Niger
IRD	Institut de Recherche pour le Developpement, France (formerly ORSTOM)
ISNAR	International Service for National Agricultural Research (Netherlands)
IVC	Consortium for Sustainable Use of Inland Valleys
IWM	Integrated watershed management
IWM1	International Water Management Institute (Sri Lanka)
KARI	Kenya Agricultural Research Institute
LQI	Land Quality Indicators
MAS	Managing Acid Soils
MREC	Managing Soil Erosion Consortium
NCARTT	National Center for Agricultural Research and Technology Transfer (Jordan)
NARES	National Agricultural Research and Extension Systems
NARS	National Agricultural Research Systems
NDFRC	National Dryland Farming Research Center (Kenya)
NGO	Non-Governmental Organization
OFWH	On-Farm Water Harvesting
OSWU	Optimizing Soil Water Use
PGRN	Pole de Gestion de Ressources Naturelles (Natural Resource Management Network; West Africa)
SADC	Southern African Development Community (Botswana)
SANREM/ CRSP	Sustainable Agriculture and Natural Resource Management/ Collaborative Research Support Program
SFI	Soil Fertility Initiative
SSA	Sub-Saharan Africa
SWERI	Soil, Water, and Environment Research Institute (Egypt)
SWM-Net	Soil and Water Management Network

SWNMP	Soil Water Nutrient Management Program
TSBF	Tropical Soil Biology and Fertility Programme (Kenya)
Verticon	Vertisol consortium
WANA	West Asia and North Africa
WOCAT	World Overview of Conservation Approaches and Technologies

About ICARDA

Established in 1977, the International Center for Agricultural Research in the Dry Areas (ICARDA) is governed by an independent Board of Trustees. Based at Aleppo, Syria, it is one of 16 centers supported by the Consultative Group on International Agricultural Research (CGIAR).

ICARDA serves the entire developing world for the improvement of lentil, barley and faba bean; all dry-area developing countries for the improvement of on-farm water-use efficiency, rangeland and small-ruminant production; and the West and Central Asia and North Africa region for the improvement of bread and durum wheats, chickpea, and farming systems. ICARDA's research provides global benefits of poverty alleviation through productivity improvements integrated with sustainable natural-resource management practices. ICARDA meets this challenge through research, training, and dissemination of information in partnership with the national agricultural research and development systems.

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The semi-arid tropics (SAT) encompasses parts of 48 developing countries including most of India, parts of southeast Asia, a swathe across sub-Saharan Africa, much of southern and eastern Africa, and parts of Latin America. Many of these countries are among the poorest in the world. Approximately one-sixth of the world's population lives in the SAT, which is typified by unpredictable weather, limited and erratic rainfall, and nutrient-poor soils.

ICRISAT's mandate crops are sorghum, pearl millet, finger millet, chickpea, pigeonpea, and groundnut; these six crops are vital to life for the ever-increasing populations of the semi-arid tropics. ICRISATs mission is to conduct research which can lead to enhanced sustainable production of these crops and to improved management of the limited natural resources of the SAT ICRISAT communicates information on technologies as they are developed through workshops, networks, training, library services, and publishing.

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