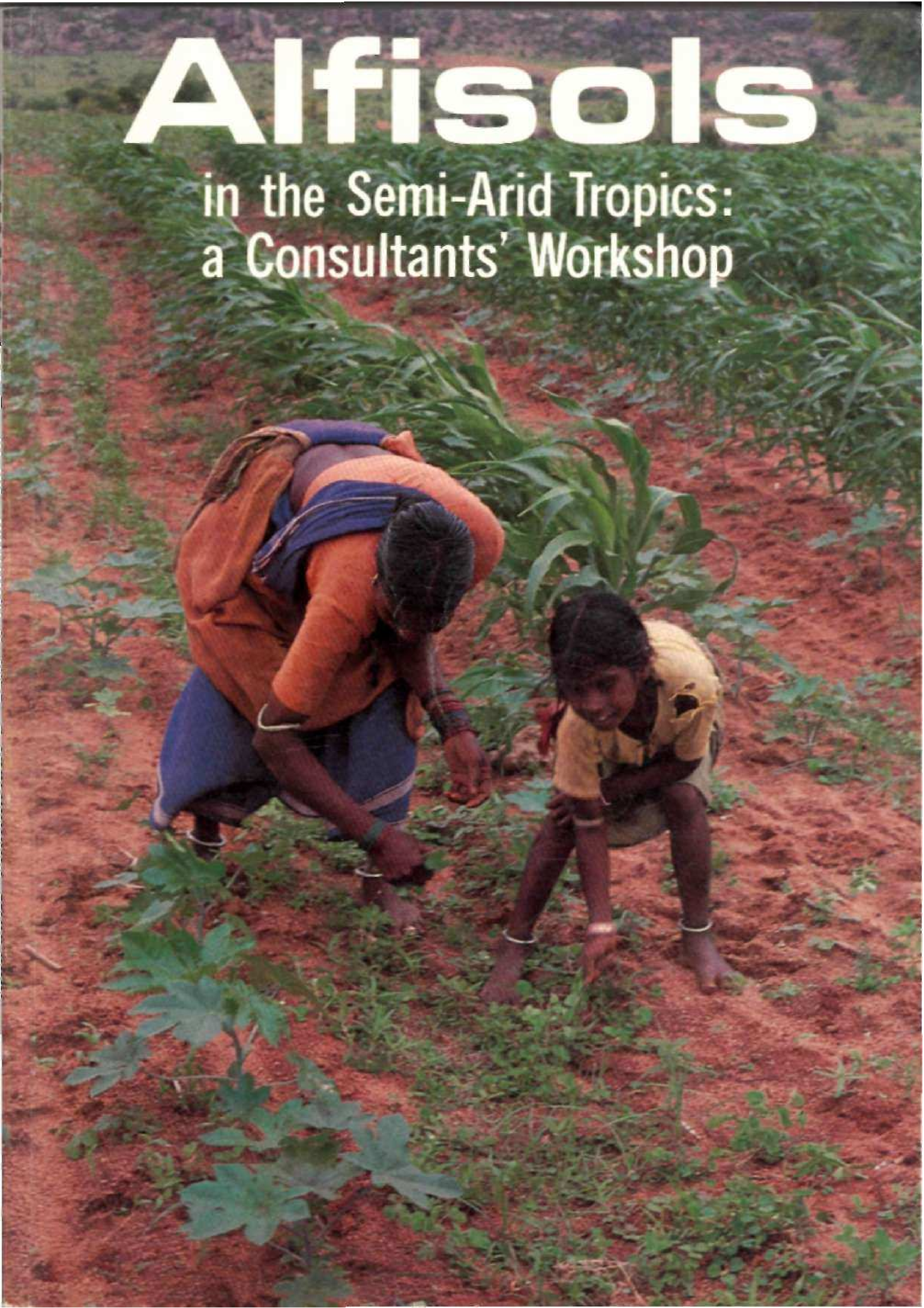
Alfisols

in the Semi-Arid Tropics: a Consultants' Workshop



A summary of the principal findings of this Workshop was published in 1984, and is available from ICRISAT under the following reference:

El-Swaify, S.A., Walker, T.S., and Virmani, S.M. 1984. Dryland management alternatives and research needs for Alfisols in the Semi-Arid Tropics. An interpretive summary of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils held at ICRISAT Center, India, 1-3 December 1983. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. 44 pages. ISBN 92-9066-079-1.

Cover: Mother and daughter weeding intercrops on an Alfisol, Aurepalle, India.

ALFISOLS
in the Semi-Arid Tropics

Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils

1-3 December 1983
ICRISAT Center, India

ICRISAT

International Crops Research Institute for the Semi-Arid Tropics
Patancheru, Andhra Pradesh 502 324, India

1987

Correct citation: ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 Dec 1983, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

Scientific Editors

Prabhakar Pathak, S.A. El-Swaify, and Sardar Singh

Publication Editors

N. Raghavan and S.R. Beckerman

ISBN 92-9066-103-8

The International Crops Research Institute for the Semi-Arid Tropics is a nonprofit scientific educational institute receiving support from donors through the Consultative Group on International Agricultural Research. Donors to ICRISAT include governments and agencies of Australia, Belgium, Canada, Federal Republic of Germany, Finland, France, India, Italy, Japan, Netherlands, Norway, People's Republic of China, Sweden, Switzerland, United Kingdom, United States of America, and the following international and private organizations: Arab Bank for Economic Development in Africa, Asian Development Bank, Deutsche Gesellschaft far Technische Zusammenarbeit (GTZ), Global 2000 Inc., International Development Research Centre, International Fertilizer Development Center, International Fund for Agricultural Development, The European Economic Community, The Ford Foundation, The Leverhulme Trust, The Opec Fund for International Development, The Population Council, The World Bank, United Nations Development Programme, and the University of Hohenheim. Information and conclusions in this publication do not necessarily reflect the position of the aforementioned governments, agencies, and international and private organizations.

Contents

Foreword

This consultants' workshop, hosted by ICRISAT, had the following objectives.

1. To review the important environmental, physical, chemical, and biological characteristics of SAT Alfisols and related soils, and identify major constraints to their effective agricultural utilization.
2. To assess the current state of the art on effective management of SAT Alfisols under rainfed conditions, with particular reference to the following:
   a. Soil and water conservation and management.
   b. Optimum requirements for effective crop establishment and growth.
   c. Water-supply development and efficient use for supplemental irrigation.
   d. Fertility and nutritional requirements.
   e. Alternative cropping systems.

A summary report of the workshop was published in 1984 (for details, see the note given inside the front cover) in order to acquaint scientists with the principal findings of the workshop without significant delay.

In this publication we present the full proceedings of the workshop, with the objective of informing the scientific community in detail about alternatives and research needs for the management of Alfisols in the semi-arid tropics, as presented and discussed during the workshop.

I am pleased to state that the workshop's findings have greatly influenced ICRISAPs direction of research on Alfisols. I am therefore sure that researchers elsewhere will similarly be able to make good use of the material presented in this volume, for the benefit of those dryland farmers who depend upon rainfed agriculture on Alfisols for their livelihood.

J.S. Kanwar
Deputy Director General
ICRISAT

Inventory of SAT Alfisols, Related Soils, and Environmental Characteristics

Classification Requirements of Red Soils of India for Transfer of Technology

S.R. Naga Bhushana, H.S. Shankaranarayana, and C.R. Shivaprasad[1]

Abstract

Distribution, classification, and the major characteristics of red soils of India are described, and the various constraints to crop production reviewed. The problem of identifying argillans to designate argillic horizon in the field is brought out. Characteristic activities of fauna in soil formation, and lack of evidence of clay illuviation in red soils, classified as Alfisols on the basis of micromorphological studies, are highlighted. A detailed soil map of Chagalhatti village near Bangalore is featured to show that soils differ in their physical characteristics within a village; their quality varies with depth, occurrence, and amount of gravel in the profile; texture of the subsoil and nature of soil-forming materials; and surface texture variations, slope, and erosion. Finger millet yields, with two levels of management under rainfed and irrigated conditions, are given. The importance of information on properly classified soils and their distribution in the transfer of technology and for research based on models of soil moisture and other behavioral characteristics of soils, and on the conservation of inputs and their proper use, is brought out.

Introduction

In general, the deterrents to increased productivity of Alfisols have their roots in the physical and chemical nature of these soils, as indicated in the preamble to the theme of this workshop. According to Kampen (1979), intense rainfall, unpredictable droughts, short rainy season, variable rainfall between seasons, high evapotranspiration, low infiltration capacity of soil, great water-erosion hazard, small farms, fragmented holdings, limited capital, use of mainly animal or human labor, severe unemployment in the dry season, limited biological resources, lack of credit facilities, and labor shortages at peak times characterize the farming systems in the SAT. Virmani (1979) has pointed out the importance of analyzing the meteorological conditions of a region for characterizing its agricultural potential. Evaluation of the soil's water-holding capacity and other physical characteristics, water-balance calculations using rainfall and potential evaporation data in conjunction with soil water storage, are points for consideration. Shankaranarayana and Hirekerur (1978) computed weekly rainfall data along with moisture-holding capacity of some soils in the northern Indian plains where soil profile characteristics differ according to textural composition.

In this paper we have attempted to review the information available on the distribution, classification, major characteristics, and production constraints of red soils, and highlighted the soil classification requirements of red soils of India for technology transfer.

Distribution of Red Soils

Red soils are associated with tropical and subtropical climates, which are characterized by high temperatures and humidity (Digar and Barde 1982). They occur in the states of Tamil Nadu, Karnataka,

1. National Bureau of Soil Survey and Land Use Planning (1CAR), Regional Centre, Hebbal, Bangalore, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultanu Workshop on the Sute of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Kerala, Maharashtra, and Andhra Pradesh and in the union territories of Goa and Pondicherry. They are also found in Orissa, Madhya Pradesh, West Bengal, Bihar, and Assam. Figure 1 shows the distribution of red and laterite soils in India.

Sankaranarayana and Sarma (1982), discussing nine red soils including seven Alfisols, state that these Alfisols occur at 50-1000 m above MSL, where the mean annual rainfall varies from 570 to 1550 mm. Data on precipitation, temperature, and water balance for different locations, as well as the associated benchmark soil series, are given in Figure 2.

Climatic variations in the red soils region are mainly due to rainfall. (Temperatures in this region are relatively uniform.) The rainfall-distribution pattern shows wide variation. Figure 2 shows the period of precipitation exceeding potential evapotranspiration in different benchmark soil series

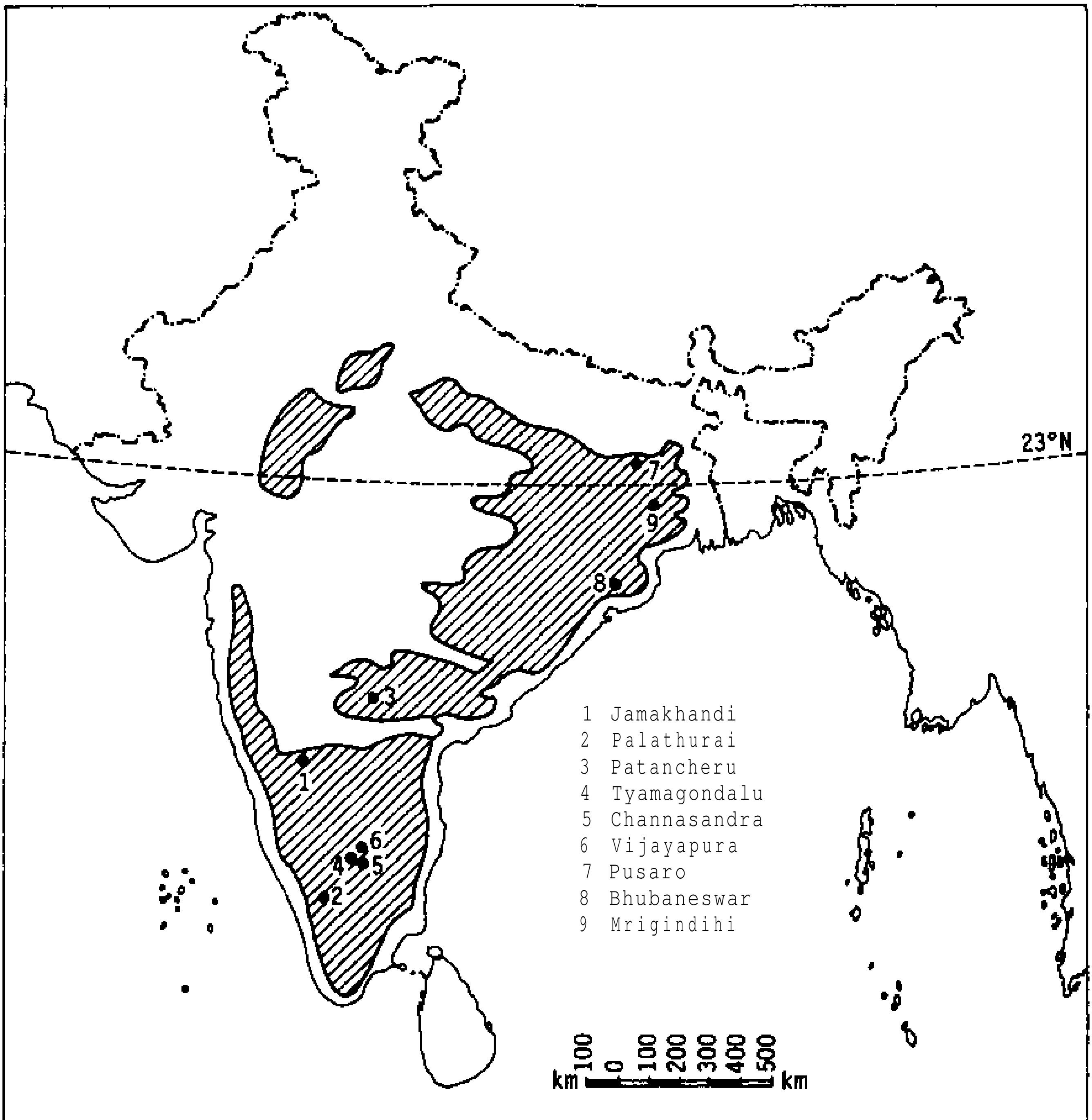


Figure 1. Benchmark toils: red and laterite soil regions in India.

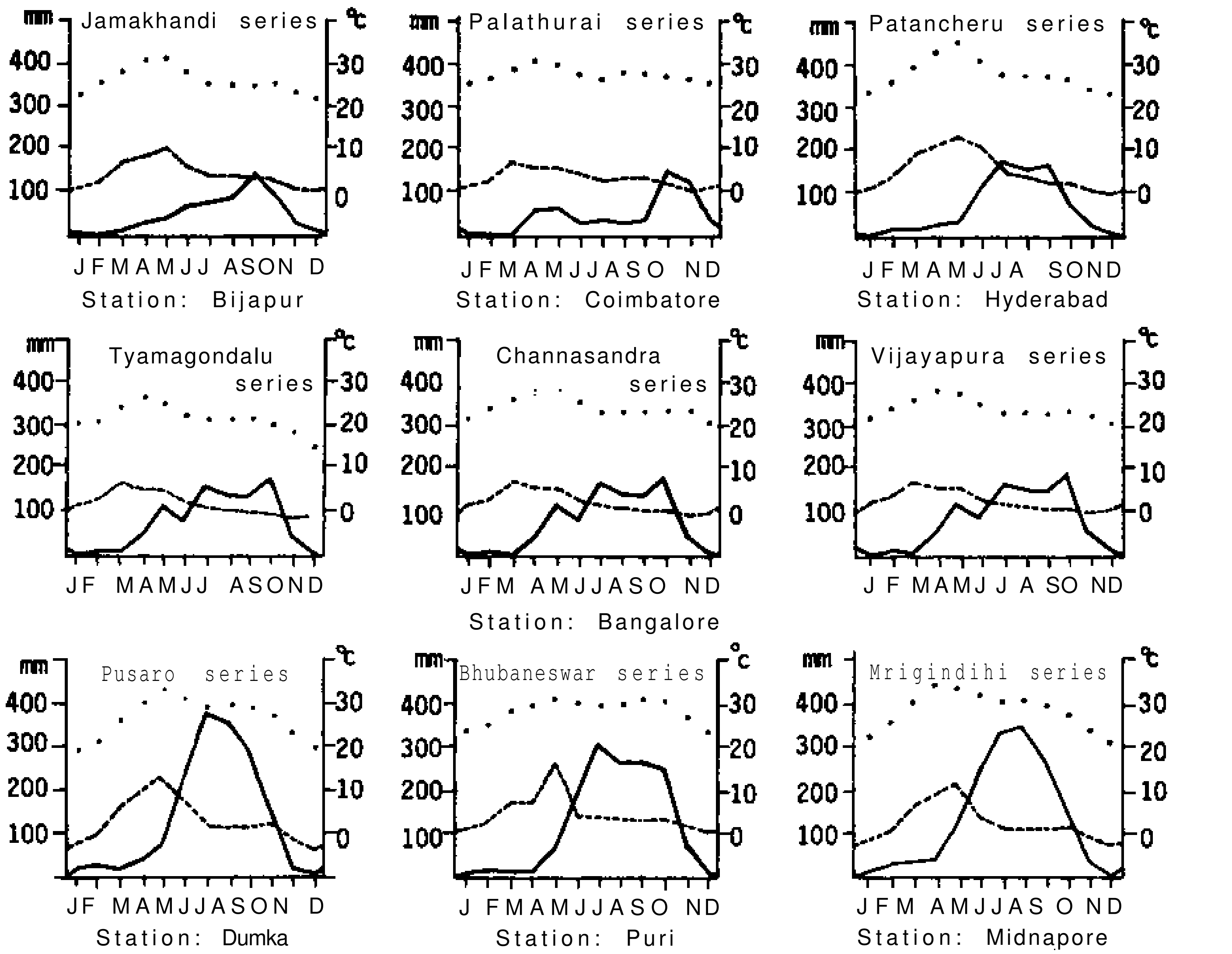


Figure 2. Precipitation, temperature, and potential evapotranspiration for various locations, with associated benchmark soil series. Dotted lines = temperature; broken lines = potential evapotranspiration; continuous lines = precipitation.

areas. Pofali and Shankaranarayana (1982) have charted the rainfall-distribution pattern and potential evapotranspiration at selected stations for three main seasons covering the period Feb-May, Jun-Sep, and Oct-Jan. In most cases, potential evapotranspiration exceeds rainfall except during June to September. Nevertheless, rainfall is highly erratic in different locations. Rainfall varies not only from year to year but from week to week, and the coefficient of variation is high.

Major Characteristics of Red Soils

Red soils are mostly derived from granites, gneisses, and schists of the Archean period (Shankaranarayana and Sarma 1982). Other rock formations from which these soils are derived are sandstones, calcareous schists, basalts, shales, and laterites. Research by Govinda Rajan and Murthy (1971) on red soils of Mysore Plateau, by Govinda Rajan and Datta Biswas (1968) in Orissa, and by Digar et al. (1973) in Orissa, and Andhra Pradesh, has shown the characteristics of red soils as a result of illuviation and transformation, leading to release and dispersion of iron and progressive oxidation and hydration. The red soils are acid to neutral in reaction, and moderate in their cation exchange capacity. Their exchange complex is dominated by a mixture of kaolinite and illite. The morphology, genesis, and classification of red soils of India have been reviewed by Digar and Bardc (1982).

According to Shankaranarayana and Sarma (1982) red soils have well-marked horizons of clay enrichment that are easily discernible in the field. Amorphous material is found in significant proportions in the profiles. Variations in texture, depth, color, and clay mineralogy result from relief and drainage differences. They occur on gently sloping to undulating surfaces and are excessively to moderately well drained. These soils have weak granular or subangular blocky surface A horizons, subangular blocky to prismatic B horizons, and subangular blocky C horizons. The A horizons vary from loamy sand to gravelly clay and clay, but B horizons are generally enriched with clay to give fine loamy or clayey soils. The soils are strongly acid to moderately alkaline in reaction. (Cation exchange capacity of these soils varies from low to high and their organic matter content varies from very low to low.) The chemical characteristics of these soils appear to reflect mainly the effect of soil-forming materials; the other factors that influence these characteristics are rainfall and drainage.

Available water-holding capacity of red soils profiles varies from 5 to 18 cm.

Table 1 gives the major characteristics of the red soil series of the benchmark soils of India from the red- and laterite-soil region.

Micromorphological studies (Kooistra 1982)

Table 1. Major characteristics of red soils of India.

Name of the soil	Source of forming material	Setting and slope	Drainage	Soil characteristics: Surface soil	Soil characteristics: Control section below 15 cm from the surface
1	2	3	4	5	6
Jamkhandi	Alluvium of sandstone and quartzite	Gently slopping valley	Moderately well drained	Loamy sand to sandy	Clayey, subangular blocky to prismatic, moderately alkaline, CEC 17-39 meq 100 g^{-1} soil
Tyamagondalu	Developed on weathered gneiss	Gently sloping upland	Well drained	Loamy sand to sandy loam, neutral, CEC 2 meq 100 g^{-1} soil	Sandy clay to clay, subangular blocky, neutral to moderately acid, CEC 8-9 meq 100 g^{-1} soil
Vijayapura	Developed on weathered granite gneiss	Gently sloping upland	Well drained	Loamy sand to sandy loam, slightly acid, CEC 2-3 meq 100 g^{-1} soil	Sandy clay loam to sandy clay, subangular blocky, slightly to strongly acid, CEC is 3-4 meq 100 g^{-1} soil
Channasandra	Developed on weathered granite gneiss	Undulating to gently sloping upland	Well drained	Gravelly loamy sand to gravelly sandy loam, weak fine granular, CEC 4-5 meq 100 g^{-1} soil, neutral	Clayey skeletal, subangular blocky, neutral to slightly acid, CEC 8-12 meq 100 g^{-1} soil

Continued

Table 1. Continued

Name of the soil	Source of forming material	Setting and slope	Drainage	Soil characteristics: Surface soil	Soil characteristics: Control section below 15 cm from the surface
1	2	3	4	5	6
Bhubaneswar	Developed on weathered ferruginous sandstone	Nearly level to gently sloping upland	Well drained	Loamy sand to sandy loam sub-angular blocky strongly acid	Sandy clay loam to clay loam, subangular, blocky, very strongly acid, CEC 6-9 meq 100 g^{-1} soil. Base saturation less than 40%
Mrigindihi	Developed on old alluvium	Undulating interflue plain	Somewhat excessively drained	Loamy sand to sandy loam weak subangular blocky, strongly acid	Sandy clay loam to clay loam, subangular blocky, strongly to very strongly acid, CEC 5-9 meq 100 g^{-1} soil, base saturation 50-75%
Pusaro	Weathered granite gneiss	Gently sloping plateau	Well drained	Sandy to clay loam, massive to subangular, blocky, strongly acid	Loam to clay loam, subangular blocky to prismatic, slightly to strongly acid, CEC 8-12 meq 100 g^{-1} soil
Palathurai	Developed on weathered calcis gneiss	Gently sloping to undulating upland	Well drained	Loamy sand to sandy loam, weak fine granular, moderately alkaline	Gravelly sand clay loam to clay loam, subangular blocky moderately to strongly alkaline, CEC 13-25 meq 100 g^{-1} soil
Patancheru	Developed on weathered granite	Level to gently sloping upland	WeU drained	Loamy sand to sandy loam, fine granular to subangular blocky, slightly acid	Sandy clay loam to clay, subangular blocky, neutral to slightly alkaline, CEC 8-22 meq 100 g^{-1} soil

Remarks: There are associated and competing red soils (and Alfisois?) of the Benchmark Soils. Main variations are with respect to depth, texture and amount of gravel. Main variations in site characteristics are due to surface texture, slope, and associated erosion and/or runoff.

Source: Benchmark Soils of India, 1982.

show that red soils often contain strongly altered rock fragments and weathered parent material. Faunal activity has resulted in variations in the soils* B horizons and the creation of channels leading to formation of several kinds of voids systems. Faunal channels are often coated with a layer of fine-grained soil material. These coatings are due to plastering with fine-grained soil material (generally excreta) by animals working in the soils. The coatings are often mistaken for argillans. Faunal activity also causes homogenization of soil material in the pedons. A majority of the pedons studied showed soil material to be apedal in the surface; in a few cases features of real argillans and ferri-argillans were seen. In some pedons (Mrigindihi), argillic B horizon was developed but was subsequently destroyed on account of animal activity. In pedons such as Jamkhandi and Palathurai, features of argillans were not seen to indicate illuviation of clay. Illuvation features were not found because of homogenization as was the case with the Bhubaneswar pedon.

Classification

Classification of red soils based on field and laboratory characterization is given in Table 2. Micromorphological studies of the soil (Kooistra 1982) revealed no evidence of argillans, and lack of clay illuviation features because of faunal activity, in some of these soils. Features that are a result of swelling and shrinking can be mistaken for cutans. This is probably the most common mistake made when an argillic horizon is designated in red soils. As stated by Shankaranarayana and Hirekerur (1982), the problem of identifying argillans in the field remains. The problems such as clay activity and surface crusting are common in many red soils. The soils are generally low in organic matter. The structure of the A horizon is influenced by the cultivation practice adopted. A large number of voids partly filled with mineral grains and soil fragments are formed because of cultivation; when these grains and fragments settle down, they pose a physical problem for plants and inhibit their water intake.

Kooistra (1982) concludes that Jamkhandi pedon cannot be an Alfisol because of the absence of clay illuviation. Similarly, the Palathurai pedon did not show any current or previous illuviation features. In the case of the Mrigindihi series, micromorphological studies revealed that current illuviation features were insufficient to classify it as an Alfisol. In the Vijayapura pedon, the illuviation features were reduced because of homogenization of groundmass, and the present clay illuviation is too marginal for it to be classified as an Alfisol.

The problems of identifying illuviation features in the field were confirmed by morphological studies. Further, the authors did not observe that the argillic horizon adversely affected soil-water-plant relationships because of increased clay illuvation. No differences in the general nature or composition of the clay was noticed. Further, even in clayey B horizons, most of the clay was confined to the groundmass.

Table 2. Classification of red soils of India.

Name of the soil	Classification
Jamkhandi	Fine, mixed, Isohyperthermic of Typic Paleustalfs
Tyamagondalu	Fine, mixed, Isohyperthermic family of Oxic Paleustalfs
Vijayapura	Fine, mixed, Isohyperthermic family of Oxic Haplustalfs
Channasandra	Clayey-skeletal, mixed, Isohyperthermic family of Oxic Rhodustalfs
Bhubaneswar	Fine-loamy, mixed, Isohyperthermic family of Typic Haplustalfs
Mrigindihi	Fine-loamy, mixed, Hyperthermic family of Ultic Paleustalfs
Pusaro	Fine-loamy, mixed, Hyperthermic family of Ultic Paleustalfs
Palathurai	Fine-loamy, mixed, Isohyperthermic family of Typic Haplustalfs
Patancheru	Clayey-skeletal, mixed, Isohyperthermic family of Udic Rhodustalfs

Remarks: Most of the classification was done on the basis of reconnaissance soil surveys. Hence other variations are not identified or mapped on majority of the cases.
Source : Benchmark Soils of India, 1982.

Soil Classification Requirement for Technology Transfer

The theme of technology transfer, as laid down in the Benchmark Soils Project report, University of Hawaii (1982), states that innovation-sharing among research centers comprises horizontal transfer whereas innovation diffusion is vertical when it involves the transfer of technology from research centers to farmers' fields. The Benchmark Soils Project is designed to do research on the horizontal component—the first step in the two-step process of technology transfer and innovation diffusion.

Information on the characteristics and classification of red soils and their distribution may nominally serve the purpose of horizontal technology transfer. Gill (1979), while advocating shortcuts such as better models of agroclimates, better models of soil-moisture behavior, and better understanding of crops and cropping systems that utilize available moisture, mentions the need for properly classified soils. In this context, a look into information requirements on soil classification for horizontal and vertical transfer of technology is necessary. Virmani (1979) states that in shallow Alfisols there is little soil moisture storage for use over extended periods, whereas in deep Alfisols moisture storage is sufficient to last for a substantially longer period. Such variations in soil characteristics are likely in areas falling within different agroclimatic models. Shankaranarayana and Venkata Rao (1982) have shown that the most appropriate diagnostic criterion for defining soil capability is availability of moisture in the soil profile at different times in our environment. Shankaranarayana and Venkata Rao (1983) have identified soil quality—determined by available moisture, drainage, toxicity due to acidity, salinity or sodicity, potential to hold nutrients, and erodibility characteristics of soils—as factors in maximizing returns from seed, fertilizer, and other inputs.

The soil map (Fig. 3) shows a detailed distribution of red soils near Bangalore. Reconnaissance mapping of the area on a 1:63 360 base distinguished soil variations due to depth, occurrence of gravel, and soil-forming material. There are eight units associated with different soils. The soils include Entisols, Inceptisols, and Alfisols.

In the detailed soil mapping done on scale 1:7920, there are about 50 units that distinguish soil variations due to depth, occurrence of gravel in the soil profile, texture of the subsoil, and nature of soil-forming materials. These are further classified on the basis of surface-texture variations, slope, and erosion. All the characteristics considered for classifying the soils are important for assessing their quality in terms of their capacity to hold moisture and their recharging ability. The distribution also reveals erodibility and runoff behavior.

A major constraint to horizontal or vertical transfer of technology is lack of information. In India, technology transfer means transfer of research results from the research farm or experimental station to other areas through extension (lab-to-land). For example, finger millet yields with traditional farm practices range from 600 to 800 kg ha^{-1} and, with improved techniques, from 1500 to 2500 kg ha^{-1}. In dryland research experiments in 1982 at the University of Agricultural Sciences (UAS), Bangalore, yields in control plots varied between 1500 kg ha^{-1} and 3400 kg ha^{-1} when farmyard manure and fertilizers were used. The experiments were conducted on Vijayapura series, which has a gravelly layer below 100 cm depth. The control plot yield was nearly twice that derived from plots where traditional methods were employed. Similarly, in experiments during 1982-83 at the university farm, yields of 3300 kg ha^{-1} were obtained in the control plot, with irrigation; yields were 4760 kg ha^{-1} at 90 kg ha^{-1} N as against 3000 kg ha^{-1} obtained by farmers using improved practices. It may be inferred that yields on soil units such as 2bB, 2bC, 2eB, 6aB, 6dB, 9bB, and $9bB_1$ cannot be of the level obtained on experimental plots or even that derived from improved practices. Finger millet is grown in most of the area shown in Figure 3. The total yield that can be achieved by a state cannot be predicted without basic soil data on availability of moisture, runoff, and erodibility characteristics. With the scarcity of land that can be developed in the country, qualitative land evaluation (Singer et al. 1979) should become the rule not only for economic use of inputs but also for conserving soil and land resources. To elaborate, merely knowing how much area is under finger millet will not serve the purpose of technology transfer and computation of yields; what is needed is information on quality and location-specific distribution of soils on which the crop is grown, and the land available.

It need hardly be emphasized that, for horizontal transfer of technology, knowledge of properly classified soils and their distribution is important. Such information is essential for research based on models of soil moisture and other behavioral characteris-

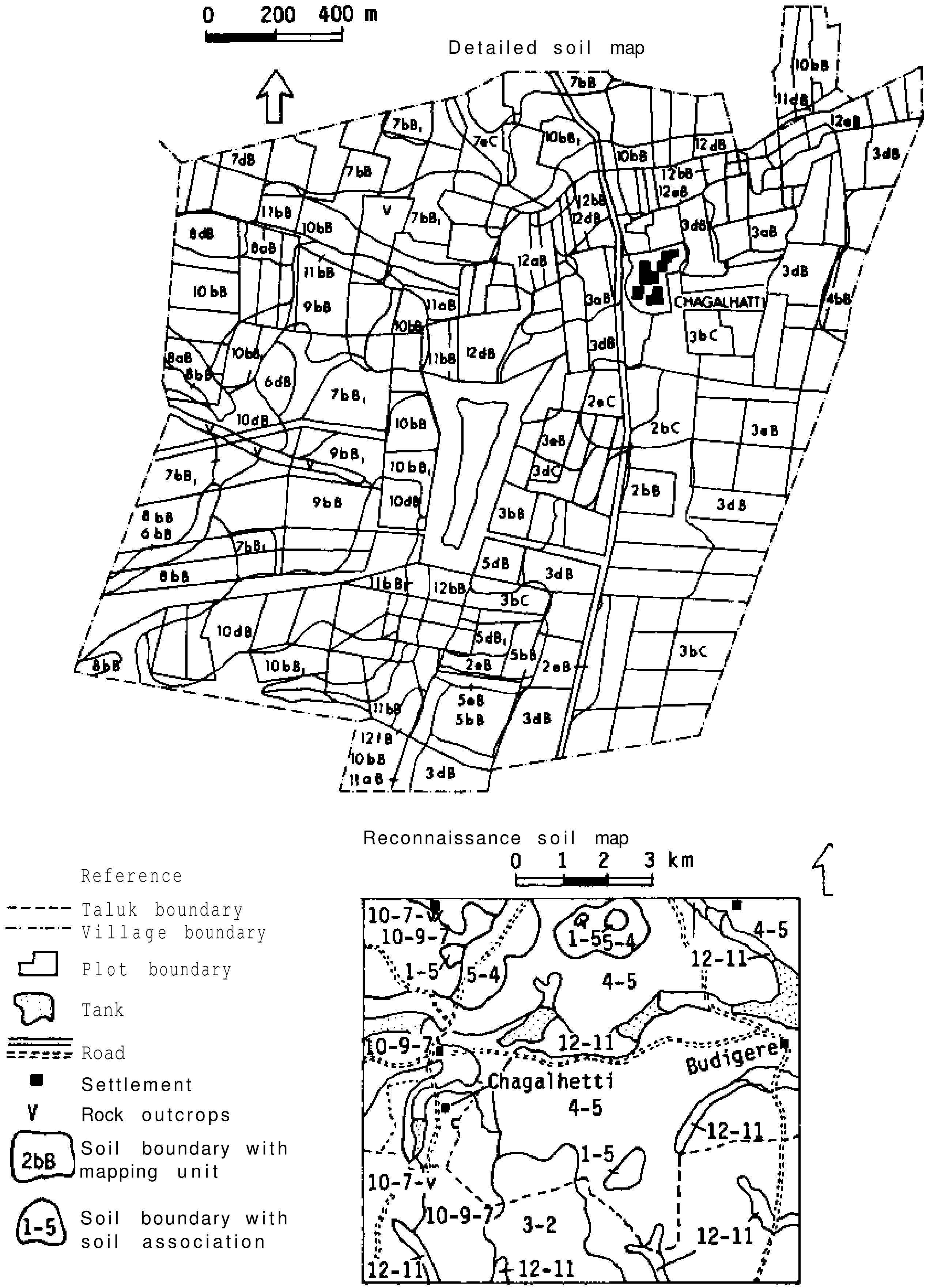


Figure 3. Soil map of Chagalhatti village, Bangalore district, Karnataka. Key to the symbols in the soil map opposite.

Map symbol	Description
1	Clayey skeletal, 2.5YR hue, hard laterite within 40 cm (Lithic Ustorthents)
2	Clayey skeletal, iron gravel horizon between 50-100 cm from the surface (Oxic Haplustalfs)
2bB	Same as 2 with sandy loam surface on 1-2% slope, rapid runoff
2bC	Same as 2 with sandy loam surface on 2-5% slope, moderate erosion and rapid runoff
2eB	Same as 2 with sandy clay surface on 1-2% slope, rapid runoff
2eC	Same as 2 with gravelly clay surface on 3-5% slope, severe erosion and very rapid runoff
3	Clayey, iron gravel horizon between 100-115 cm from the surface (Oxic Haplustalfs): Vijayapura series
3aB	Same as 3 with loamy sand surface on 1-2% slope, rapid runoff
3bC	Same as 3 with sandy loam surface on 2-5% slope, rapid runoff
3bB	Same as 3 with sandy clay loam surface on 1-2% slope, rapid runoff
3eB	Same as 3 with sandy clay surface on 1-2% slope, rapid runoff
3bB	Same as 3 with sandy loam surface on 1-2% slope, moderate erosion and rapid runoff
3dC	Same as 3 with sandy clay loam surface on 2-5% slope, moderate erosion and rapid runoff
3eB|	Same as 3 with sandy clay surface on 1-2% slope, severe erosion and rapid runoff
4	Clayey iron gravel horizon below 150 cm from the surface (Oxic paleustalfs): Hoskote series
4bB	Same as 4 with sandy loam surface on 1-2% slope, rapid runoff
5	Clayey, 7.5YR hue, iron gravel horizon between 100-150 cm from the surface (Udic Haplustalfs)
5dB	Same as 5 with sandy clay loam surface on 1-2% slope, medium runoff
5bB	Same as 5 with sandy loam surface 1-2% slope, moderate erosion, and medium runoff
5dB|	Same as 5 with sandy clay loam surface on 1-2% slope, moderate erosion and medium runoff
5eB	Same as 5 with sandy clay surface on 1-2% slope, severe erosion and rapid runoff
6	Clayey skeletal, lithic contact within 50 cm from the surface (Lithic Ustorthents)
6aB	Same as 6 with loamy sand surface, rocky on 1-2% slope, rapid runoff
6bB	Same as 6 with sandy loam surface, rocky on 1-2% slope, rapid runoff
6dB	Same as 6 with gravelly clay loam surface, rocky on 1-2% slope rapid runoff
7	Clayey skeletal, quartz gravels throughout the depth of 120 cm from the surface (Typic Ustropepts)
7bB	Same as 7 with sandy loam surface on 1-2% slope, rapid runoff
7bB|	Same as 7 with sandy loam surface on 1-2% slope, moderate erosion and rapid runoff
7dB	Same as 7 with clay loam surface on 1-2% slope, moderate erosion, rapid runoff
7eC	Same as 7 with gravelly clay surface on 3-5% slope, severe erosion and rapid runoff
8	Clayey, quartz gravel horizon between 50-100 cm from the surface, thick argillic horizon (Oxic Haplustalfs)
8aB	Same as 8 with loamy sand surface on 1-2% slope, rapid runoff
8dB	Same as 8 with sandy clay loam surface on 1-2% slope, rapid runoff
8bB	Same as 8 with sandy loam surface on 1-2% slope, moderate erosion and rapid runoff
9	Clayey skeletal, quartz gravel horizon between 50-100 cm from the surface, 2.5YR hue (Oxic Haplustalfs)
9bB	Same as 9 with sandy loam surface on 2-5% slope, rapid runoff
9bB|	Same as above, moderate erosion
10	Clayey, very thick argillic horizon (Oxic Haplustalfs)
10bB	Same as 10 with sandy loam surface on 1-2% slope, rapid runoff
10bB,	Same as above, moderate erosion
10dB	Same as 10 with sandy clay loam surface with 1-2% slope, rapid runoff
11	Clayey, 10YR hue (Typic Ustropepts)
1laB	Same as 11 with sand to loamy sand surface on 1-2% slope, medium runoff
11bB	Same as 11 with sandy loam surface on 1-2% slope, medium runoff
11dB	Same as 11 with sandy clay loam surface on 1-2% slope, medium runoff
11 bB,	Same as 11 bB, moderate erosion
12	Clayey, gray-colored mottles below 50 cm (Aquic Ustropepts)
12bB	Same as 12 with sandy loam surface on 1-2% slope, slow runoff
12dB	Same as 12 with sandy clay loam surface on 1-2% slope, slow runoff
12eB	Same as 12 with sandy clay surface on 1-2% slope, slow runoff
12fB	Same as 12 with clayey surface on 1-2% slope, slow runoff

tics of soils, and for technology diffusion through vertical transfer and conservation of inputs or their proper use. Without authentic data on soil classification and soil distribution, neither transfer of technology nor computation of input requirements and yield is possible. According to Bridges (1970), by the turn of this century we shall have to depend on soil characteristics for increasing food production. Detailed soil maps are therefore essential. Although time-consuming in its acquisition, knowledge on the distribution of soils and their physical and chemical properties permits accurate planning of fertilizer use, soil- and water- conservation measures, and irrigation. Unfortunately, we are still lacking such information. Considerable time has already been lost and it is imperative that efforts are initiated to compile detailed soil survey data if transfer of technology is to be meaningful in a country such as India, where pressure on land is extreme and where there are no arable lands that remain to be brought under cultivation.

Acknowledgments

The authors express their thanks to Dr L. R. Hirekerur, Officiating Director, NBSS & LUP (ICAR), Nagpur, for giving the opportunity to make this presentation. Thanks are also due to Dr B. R. Hegde, Chief Scientist, Dry Land Agriculture Project, UAS, Bangalore, for providing data on finger millet yields in the dry farming experiments; to Dr B. K. Linge Gowda, millet specialist, UAS, Bangalore, for providing data on finger millet yields under irrigated conditions; and to Mr P. S. A. Reddy, Scientist S-2, NBSS & LUP, Regional Centre, Bangalore, for data on available soil moisture for some red soils. Thanks are also due to Mr Prabhakara, Scientist S-l, and Mr C. Srinivasan, Technician-1, for help in preparing the maps. The contribution made by Mr C. S. Harindranath, Scientist S-l, who guided fieldwork under the training program, is acknowledged.

References

Bridget, E.M. 1970. World toils. Cambridge, UK: Cambridge University Press.

Digar, S., Haldar, A.K., and D M , AX. 1973. Classification of the Soils of the Machkund Catchment according to U.S. soil taxonomy. Journal of the Indian Society of Soil Science 21:491.

Digar, S., and Barde, N.K. 1982. Morphology, genesis, and classification of red and laterite soils. Pages 498-507 in Review of soil research in India. Pt2. New Delhi, India: Indian Society of Soil Science.

Gill, T.S. 1979. Benchmark soil studies: a means for transfer of agrotechnology. Pages 103-109 in Proceedings of the International Symposium on Development and Transfer of Technology for Rainfed Agriculture and the SAT Farmer, 28 Aug-1 Sep 1979, ICRISAT, Hyderabad, India. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics.

Govinda Rajan, S.V., and Datta Biswas, N.R. 1968. Classification of Indian soils and their mapping. International Geographical Congress, India 1:374-376.

Govinda Rajan, S.V., and Murthy, R.S. 1971. Characteristics of some important soils identified in the Mysore plateau of peninsular India. Indian Journal of Agricultural Chemistry 4(1): 1-7.

Kampen, J. 1979. Farming systems research and technology for the semi-arid tropics. Pages 39-56 in Proceedings of the International Symposium on Development and Transfer of Technology for Rainfed Agriculture and the SAT Farmer, 28 Aug-1 Sep 1979, ICRISAT, Hyderabad, India. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics.

Kooistra, M.J. 1982. Micromorphological analysis and characterization of seventy benchmark soils of India. Wageningen, Netherlands: Netherlands Soil Survey Institute.

Pofali, R.M., and Shankaranarayana, H.S. 1982. Physiography, climate, natural vegetation and land use planning. Pages 3-40 in Benchmark soils of India: morphology, characteristics and classification for resource management (Murthy, R.S. et al., eds.). Nagpur, Maharashtra, India: National Bureau of Soil Survey and Land Use Planning.

Shankaranarayana, H.S., and Hirekerur, L.R. 1978. Interpretation of small- and large-scale soil maps for arid and semi arid north Indian plains. Pages 117-129 in Soil-resource data for agricultural development (Swindale, L.D.ed). Honolulu, Hawaii, USA: University of Hawaii, Hawaii Agricultural Experiment Station.

Shankaranarayana, H.S., and Hirekerur, L.R. 1982. Use of soil survey information and soil maps for land use planning. Pages 72-89 in Benchmark soils of India: morphology, characteristics and classification for resource management (Murthy, R.S. et al., eds.). Nagpur, Maharashtra, India: National Bureau of Soil Survey and Land Use Planning.

Shankaranarayana, H.S.,and Sarma, V.A.K. 1982. Soils of India: B. Brief description of the benchmark soils. Pages 50-70, in Benchmark soils of India: morphology, characteristics and classification for resource management (Murthy, R.S. et al., eds.). Nagpur, Maharashtra, India: National Bureau of Soil Survey and Land Use Planning.

Shankaranarayana, H.S., and Venkata Rao, B.V. 1982. Need for detailed soil maps as relevant to developing countries like India. Page 127-128 in Abstracts of voluntary papers. Transactions of the 12th International Congress of Soil Science, 8-16 Feb 1982, New Delhi 110012, India. New Delhi 110012, India: Indian Agricultural Research Institute.

Shankaranarayana, H.S., and Venkata Rao, B.V. 1983. Soil quality—factor in maximising returns for seed, fertiliser and other inputs. Agricultural Technology 1(3).

Singer, M J., Tanji, K.K., and Snyder, J.H. 1979. Planning uses of cultivated cropland and pastureland. Pages 225-271 in Planning the uses and management of land (Beatty, M.T., Petersen, G.W., and Swindale, L.D., eds.). Agronomy no. 21. Madison, Wisconsin, USA: American Society of Agronomy.

Unlveristy of Hawaii, Benchmark Soils Project. 1982. Assessment of agrotechnology transfer in a network of tropical soil families. Progress report 3 (Jul-Sep 1982). Honolulu, Hawaii, USA: University of Hawaii, College of Tropical Agriculture and Human Resources.

Virmani, S.M. 1979. Climatic approach to transfer of farming systems technology in semi-arid tropics. Pages 93-101 in Proceedings of the International Symposium on Development and Transfer of Technology for Rainfed Agriculture and the SAT Farmer, 28 Aug-1 Sep 1979, 1CRISAT, Hyderabad, India. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics.

Agroclimatic Aspects in Planning for Improved Productivity of Alfisols

M.V.K. Sivakumar[1], Piara Singh[1], and J.H. Williams[2]

Abstract

Crop yields on Alfisols, the most abundant soils in the semi-arid tropics, have remained low and unstable due to aberrant weather and soil-related constraints. With suitable examplesfrom India and West Africa, variations in the amount and distribution of rainfall as well as its intensity were described. However, crop planning on Alfisols should take into account the length of the growing period, involving an assessment of rainfall as well as potential evapotranspiration. The role of soil constraints, such as depth, soil water storage capacity, particle size distribution, and soil moisture release characteristics in making water available for crop growth on Alfisols, was illustrated. At soil depths below 30 cm in Alfisols the recharge and depletion of soil water occurred on an annual basis whereas, in the upper 30 cm, the process occurred repeatedly with a periodicity determined by the depth, amount, and frequency of rainfall. In the upper 30 cm soil layers with decreasing capillary potential there was a large decrease in the water content, while in the lower layers this decrease was considerably less. The effect of short-term intraseasonal droughts on crop moisture status was shown to differ depending on soil depth. The timing and intensity of water stress is an important factor in assessing the crop response to drought on Alfisols. Studies conducted at ICRISA T Center showed that crop water-use efficiency on Alfisols could be improved through appropriate management practices, including the selection of suitable genotypes, crops, and cropping systems.

Introduction

Alfisols are the third most important soil order in the world, covering 13.1% of the world area (Buringh 1982). Compared with Vertisols (which have been the major focus of attention at ICRISAPs Farming Systems Research Program), Alfisols cover a much larger area of potentially arable and grazeable land. These soils are most abundant in the semi-arid tropics (SAT) (Kampen and Burford 1980).

Due to aberrant weather and soil-related constraints to production, crop yields on Alfisols have remained low and unstable. Experimental evidence from research, however, shows that these soils are capable of producing more food with appropriate soil- and water-management systems. Since successful crop production depends heavily on environmental factors, the combined influence of climate and soil on plant growth must be considered before land use is planned. In order to take advantage of the advances made in science and technology, Kanwar (1982) advocated that soil scientists should work with agroclimatologists to predict more accurately the interactions between the weather, the soil, and the plant.

About 62% of the Alfisols in the SAT are located in West Africa and India. The agroclimatic aspects that need to be considered in planning for improved productivity of Alfisols are illustrated in this paper, with suitable examples from India and West Africa.

1. Farming Systems Research Program (now Resource Management Program). ICRISAT, Patancheru, A.P. 502 324, India.
2. Groundnut Crop Improvement Program (now Legumes Program), ICRISAT, Patancheru, A.P. 502324, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils. 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502324. India: ICRISAT.

Rainfall

Rainfall amounts

In SAT countries, Alfisols are distributed over a wide range of rainfall regimes. The annual rainfall, for instance, varies from less than 500 mm in Botswana to more than 1400 mm in Nigeria. In West Africa, which accounts for 36% of the global area under Alfisols, the mean annual rainfall varies from 400 to 1250 mm. The rainfall isohyets run parallel to the equator, and the farther south the location of bands or zones, the more is the rainfall (Cocheme and Franquin 1967). KowaJ and Knabe (1972) have shown that annual rainfall for the northern states of Nigeria decreases by 119 mm for every degree of latitude.

In peninsular India, which accounts for a major portion of the area under Alfisols in India, the annual rainfall varies from 500 mm in a narrow zone that covers southwestern Andhra Pradesh and eastern Karnataka, to over 1000 mm in southwestern Tamil Nadu and Kerala. The rainfall is also over 1000 mm a^{-1} in the Alfisol area of eastern Madhya Pradesh and western Orissa.

To provide a description of the rainfall characteristics, we have chosen 24 stations in 5 different rainfall zones in India and Africa (Table 1) for which long-term rainfall data are available on tape from the Agroclimatology unit of ICRISAT. Annual rainfall statistics for these stations are given in Table 2. The coefficient of variation of annual rainfall varies from 9 to 45%, with the largest variation at Mahalapye, which has the lowest rainfall.

Rainfall distribution and probabilities

In most Alfisol regions of West Africa and India, rainfall is restricted to a short growing season (in the northern hemisphere summer). In West Africa, the rainfall increases gradually from the beginning of the rainy season (in late spring or early summer), to reach a maximum in the rainy season. Seasonal distribution of rainfall for different stations in the Alfisol areas of India and Africa is shown in Table 3. Over 80% of the annual rainfall occurs in the rainy

Table 1. List of stations in different rainfall zones used In the description of climatic aspects.

Rainfall zone (mm a^{-1})	Station	Country	Latitude O'	Longitude O'	Elevation (m)
<500	Mahalapye	Botswana	23 04	26 48	
500-600	Anantapur	India	14 41	77 37	350
	Birni N'Konni	Niger	13 48	05 15	272
	Coimbatore	India	11 00	76 58	709
	Mourdiah	Mali	14 28	07 28	314
	Yeliman	Mali	15 07	10 34	97
600-800	Diema	Mali	14 33	09 11	252
	Cuddapah	India	14 29	78 50	130
	Fatick	Senegal	14 20	16 24	6
	Hyderabad	India	17 27	78 28	545
	Kayes	Mali	14 26	11 26	46
	Kurnool	India	15 50	78 04	281
	Kaya	Burkina Faso	13 06	01 05	313
800-1000	Bangalore	India	12 58	77 35	921
	Foundiaugne	Senegal	14 07	16 28	6
	Gaya	Niger	11 59	03 30	160
	Kolokani	Mali	13 35	08 02	399
	Lilongwe	Malawi	13 57	33 48	1029
	Madurai	India	09 55	78 07	133
	Salem	India	11 39	78 10	278
>1000	Bougouni	Mali	1125	07 30	350
	Gaoua	Burkina Faso	10 20	03 11	333
	Bamako	Mali	12 38	08 02	332
	Raipur	India	22 14	8139	296

Table 2. Annual rainfall (mm) for different stations in Alfisol areas of India and Africa.

Station	Mean annual rainfall	CV (%)	Maximum rainfall	Minimum rainfall	Range (mm)
Mahalapye	494	45	1765	191	1574
Anantapur	591	26	866	259	607
Birni N'Konni	565	26	990	289	701
Coimbatore	602	31	1047	238	809
Mourdiah	545	21	814	337	477
Yeliman	572	24	976	316	660
Diema	652	20	962	424	538
Cuddapah	751	28	1226	299	927
Fatick	775	27	1220	295	925
Hyderabad	784	27	1431	457	974
Kayes	723	22	1136	361	775
Kurnool	630	27	1065	281	784
Kaya	704	20	1008	184	824
Bangalore	831	18	1282	588	694
Foundiaugne	835	26	1427	416	1011
Gaya	836	17	1108	451	657
Kolokani	813	24	1226	352	874
Lincongeue	880	26	1260	198	1062
Madurai	883	25	1443	411	1032
Salem	955	24	1496	534	962
Bougouni	1090	12	1309	844	465
Gaoua	1259	29	2359	440	1919
Bamako	1022	9	1297	942	355
Raipur	1337	20	2175	714	1461

Table 3. Seasonal distribution of rainfall (mm) for different stations in Alfisol areas of India and Africa.

Station	Prerainy season	Rainy season	Postrainy season	Dry season	Annual rainfall
Mahalapye	38	395	68	3	494
Anantapur	34	502	33	22	591
Birni N'Konni	30	507	10	18	565
Coimbatore	18	197	64	323	602
Mourdiah	32	461	27	25	545
Yeliman	15	516	24	17	572
Diema	19	584	31	18	652
Cuddapah	57	634	37	23	752
Fatick	32	709	25	9	775
Hyderabad	51	631	65	37	784
Kayes	16	667	26	14	723
Kurnool	47	517	34	32	630
Kaya	31	626	15	32	704
Bangalore	22	755	27	27	831
Foundiaugne	46	752	24	13	835
Gaya	32	768	15	21	836
Kolokani	24	745	18	26	813
Lilongwe	32	785	45	18	880
Madurai	213	590	46	34	883
Salem	24	865	34	32	955
Bougouni	0	1047	17	26	1090
Gaoua	60	1152	20	27	1259
Bamako	32	933	32	25	1022
Raipur	111	1174	33	19	1337

season. It is recognized, however, that the amount of rainy-season rainfall cannot by itself provide a good index of productivity, because the potential evapotranspiration, or water loss, and the soil's water-holding capacity, dictate the amount of rainfall available for crop growth.

More important than the quantity of rainfall in a given season, is the question of persistency in receiving a specified amount of rainfall over a short interval (for instance, 1 week). In the case of Alfisols, which are known to dry rapidly and develop a surface crust, information on rainfall probabilities is important for agricultural planning. The probability of receiving 10 mm of rainfall, and the weekly rainfall amount, for three locations in the peninsular Indian Alfisol zones are shown in Figure 1. Although there is little difference in the amount of annual rainfall at Hyderabad and Bangalore, the rainy season rainfall at Bangalore extends over a much longer period, albeit at a lower probability than at Hyderabad. Coimbatore—located farther south in peninsular India—has a bimodal rainfall distribution, with the two rainfall peaks separated by an 8-week dry period.

The rainfall probabilities for Yeliman (Mali), Gaya (Niger), and Gaoua (Burkina Faso) in Africa are shown in Figure 2. These weekly rainfall probabilities, as well as the amounts, are more sharply defined than those relevant to Alfisol locations in India. In the higher-rainfall locations of Gaya and Gaoua, the cropping opportunities appear more promising. For Lilongwe (Malawi) and Mahalapye (Botswana), the peak probabilities (Fig. 3) occur in December and January. At Mahalapye, the rainy season is short and the probabilities are low.

Rainfall intensities

It is known that Alfisols, because of their poor structural stability at the surface, are susceptible to erosion. In spite of this recognition, rainfall intensities

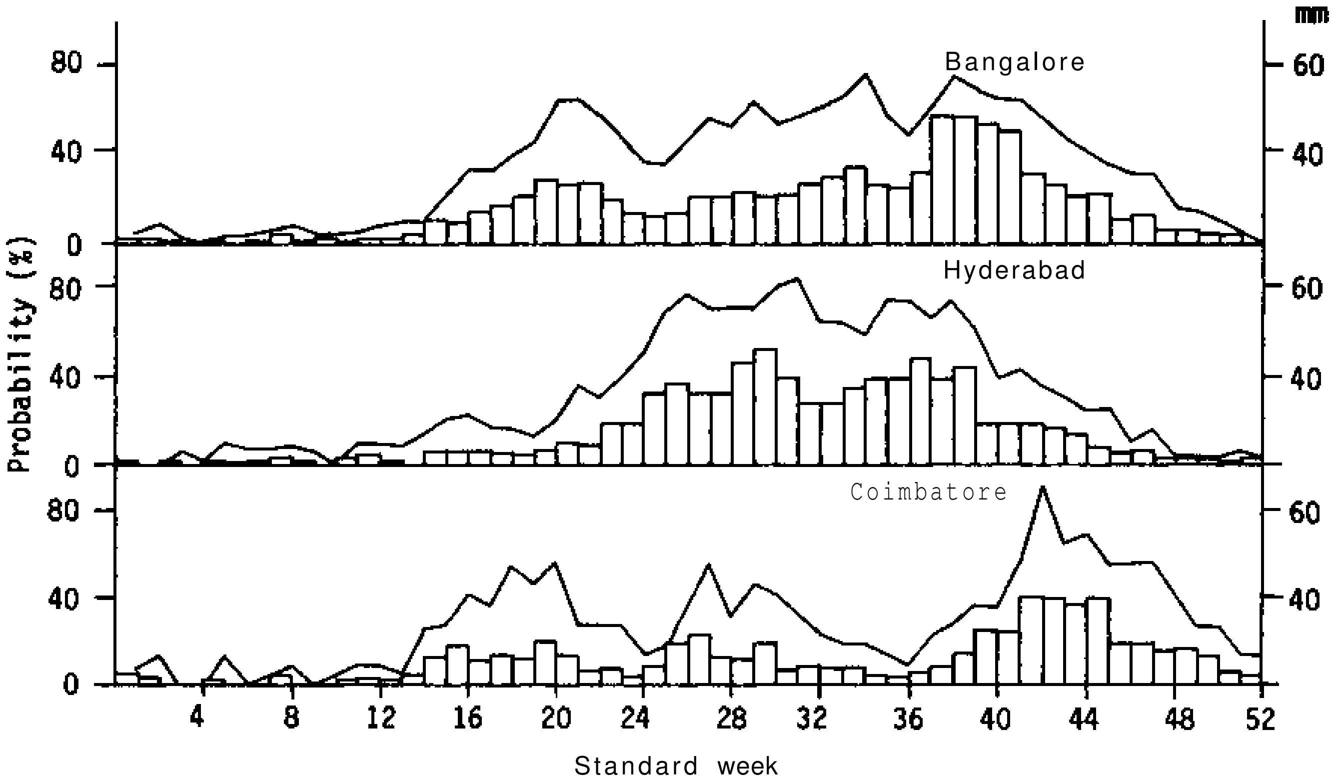


Figure 1. Weekly probability of receiving 10 mm of rainfall (line) and rainfall amount (bars) for three locations in Alfisol areas in peninsular India.

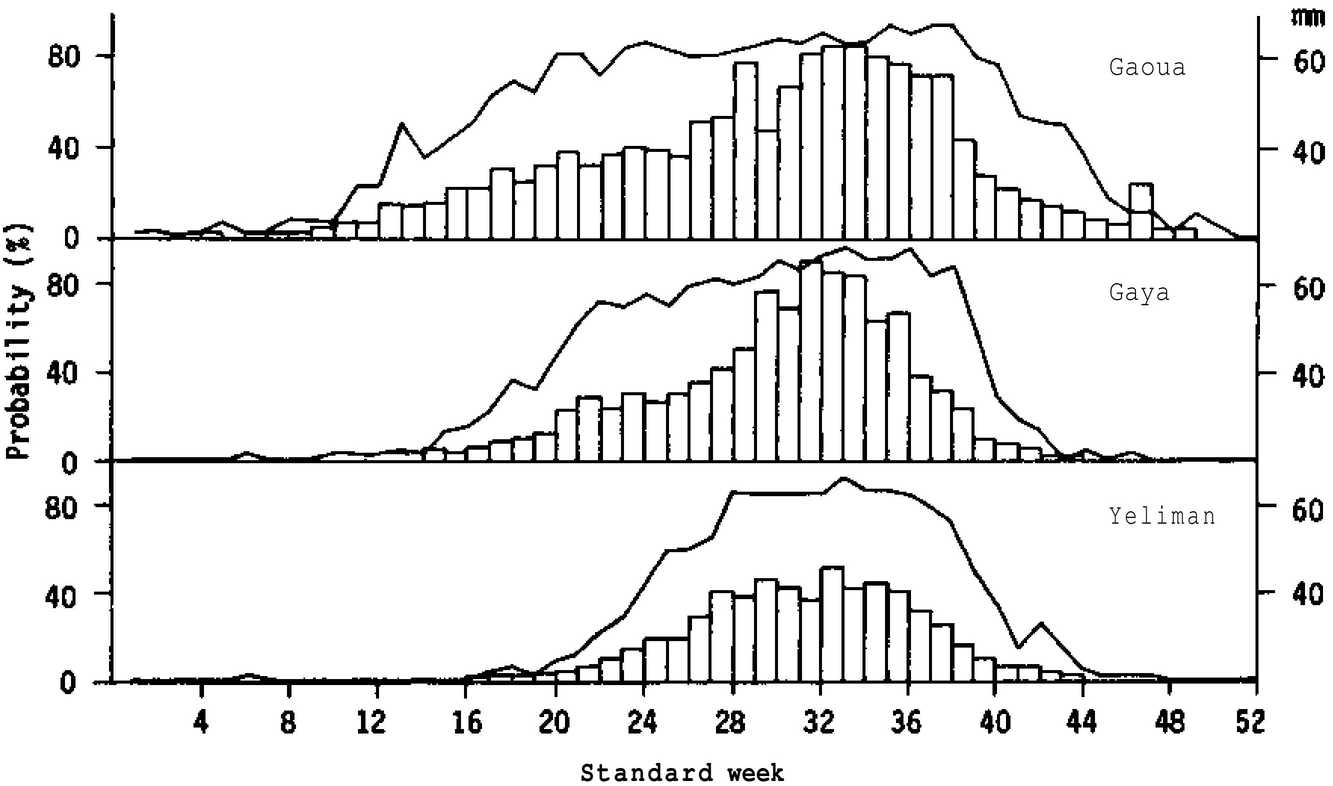


Figure 2. Weekly probability of receiving 10 mm of rainfall (line) and rainfall amount (bars) for three locations in Alfisol areas of Africa.

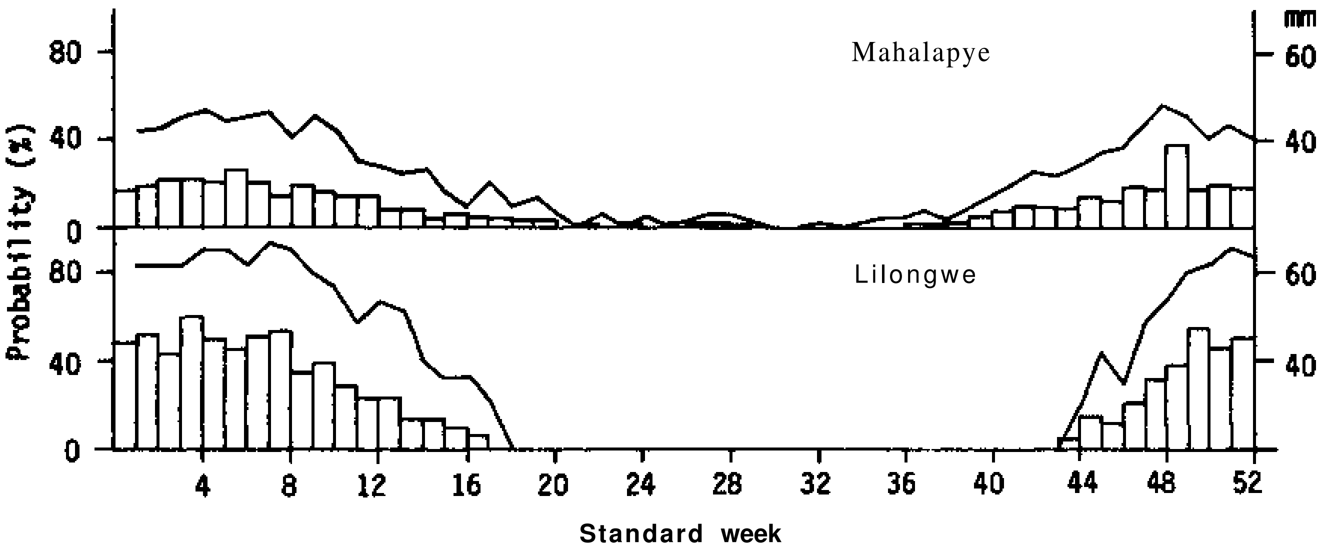


Figure 3. Weekly probability of receiving 10 mm of rainfall (line) and amount of rainfall (bars) for Mahalapye (Botswana) and Lilongwe (Malawi).

in Alfisol areas are seldom measured. At Bambey (Senegal), Charreau and Nicou (1971) reported that 75% of the total volume of rainfall had an intensity distribution of 8.6 mm h^{-1}, and 25% recorded intensities less than 52 mm h^{-1}.

Hoogmoed (1981) reported that, at Niono (Man), 75% of the rainfall received had intensities of 10 mm h^{-1} or lower, while 25% had intensities of 58 mm h^{-1} or more (Fig. 4). Peak intensities in 1977,1978, and 1979 were reported to be 190,230, and 300 mm h^{-1} respectively.

At ICRISAT Center, the rainfall intensities are lower than those reported for Africa. Rainfall intensities at ICRISAT Center for 1975 are shown in

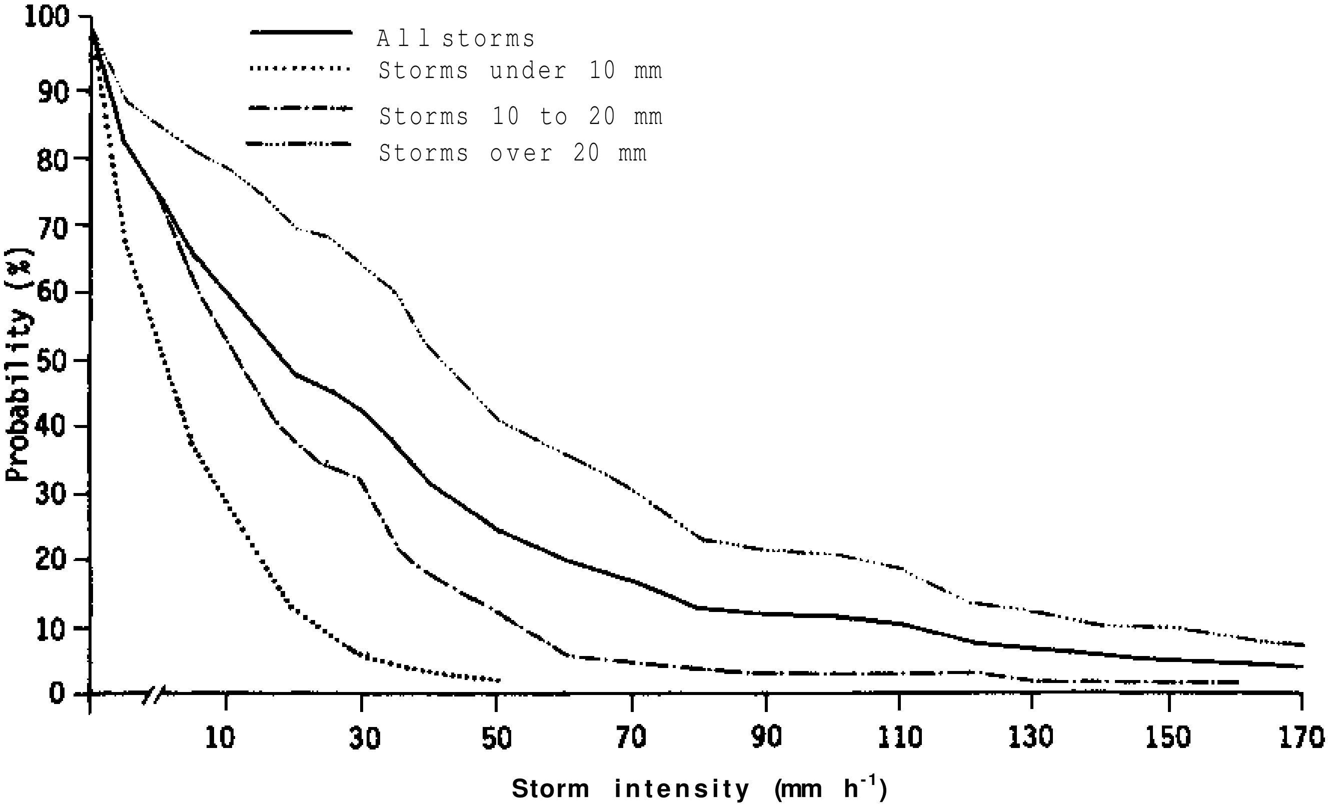


Figure 4. Distribution of storm intensities in different storm sizes at Niono, Mali (Hoogmoed 1981).

Figure 5. Peak intensities in 1974, 1975, 1976, and 1977 were reported to be 134,155,92, and 57 mm h^{-1} respectively (Hoogmoed 1981).

Length of the Growing Period

Plans for improved productivity on Alfisols should take into account the period available for crop growth. Using different average rainfall potential evapotranspiration (PE) ratios, Cocheme and Franquin (1967) evolved a procedure to determine the beginning and end of the growing period as well as its length. We have used the average rainfall and PE for different stations in the Alfisol areas to determine the average dates of the beginning, end, and the length of the growing period. It should be understood that this analysis provides only approximate data, because in the SAT the variability in these dates could be large. As shown in Table 4, the beginning and end of the growing period show a wide fluctuation across the different rainfall zones, reflecting thereby the need to consider different management strategies. Kowal and Kassam (1973) showed that in the Sudanian and Northern Guinean zones of Nigeria, due to abnormality in the amount and distribution of rainfall, the start of the rainy season of 1973 was delayed, and the delay was most accentuated north of U°N latitude. The length of the growing period was reduced from 120 days at 11.2°N latitude, and to 70 days at 12.3°N latitude. The minimum reduction in groundnut yield was estimated to vary from 0% at 11.2° latitude to 56% at 12.3° latitude.

Temperature

Air temperature

The air temperatures in Alfisol areas in India and Africa are consistently high, and can be considered above optimum for most crops (Table 5); in low-rainfall zones, the temperatures can exceed 40° C. Information on the probabilities of occurrence of lethal and stress-inducing temperatures would be useful in planning alternative cropping strategies for Alfisols; but the long-term records on air temperature recorded at shorter intervals are insufficient. Table 6 shows, as an example, the probability of the temperatures rising to the point of becoming lethal

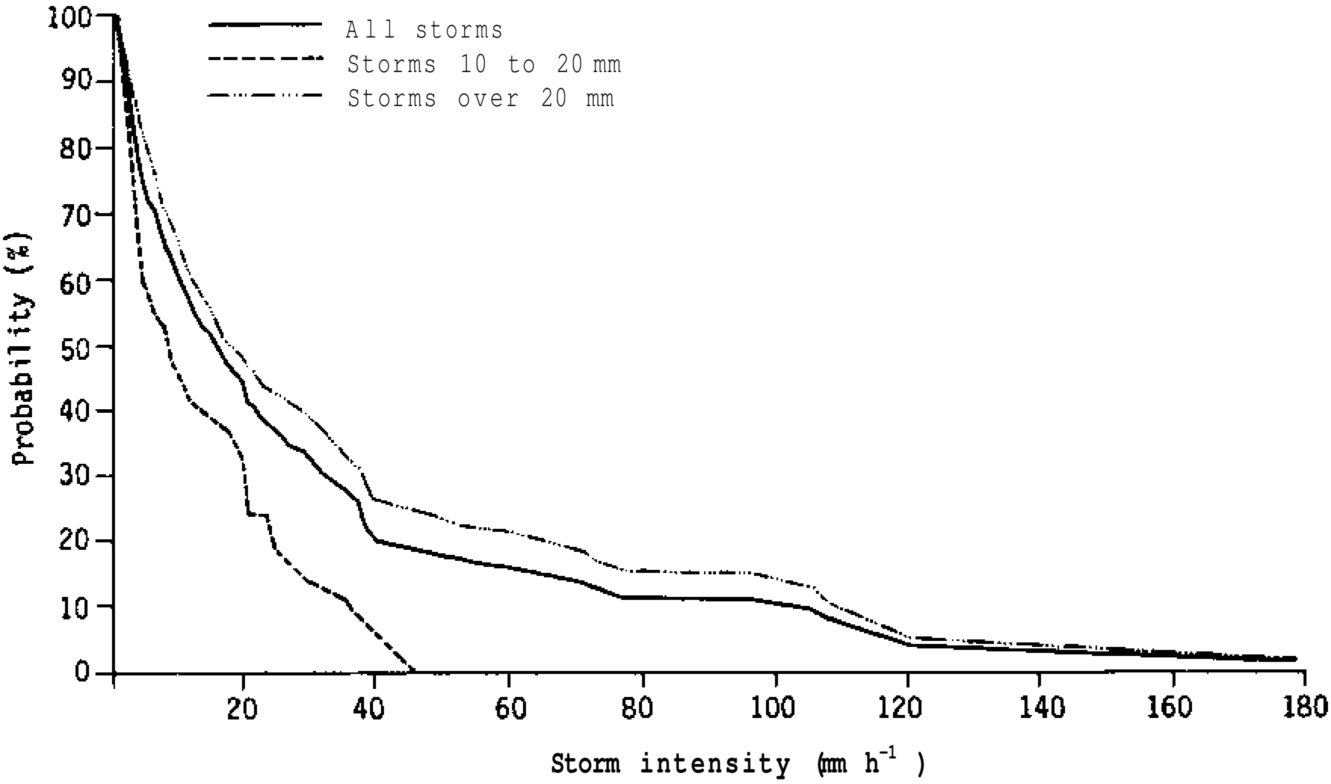


Figure 5. Distribution of storm intensities in different storm sizes at ICRISAT Center, 1975 (Hoogmoed 1981).

Table 4. Dates of beginning and end of the period and length of the growing period for different stations in Alfisol areas of India and Africa.

Station	Growing period Date of beginning	Date of ending	Length (days)
Mahalapye	13 Nov	17 Apr	155
Anantapur	09 May	24 Nov	199
Birni N'Konni	01 Jun	07 Oct	128
Coimbatore	24 Aug	23 Dec	121
Mourdiah	07 Jun	10 Oct	125
Yeliman	07 Jun	13 Oct	128
Diema	05 Jun	15 Oct	132
Cuddapah	16 May	13 Dec	211
Fatick	13 Jun	30 Oct	139
Hyderabad	26 May	15 Nov	173
Kayes	01 Jun	22 Oct	143
Kurnool	23 May	12 Nov	173
Kaya	18 May	12 Oct	147
Bangalore	12 Apr	08 Dec	240
Foundiaugne	13 Jun	29 Oct	138
Gaya	08 May	12 Oct	157
Kolokani	21 May	21 Oct	153
Lilongwe	02 Nov	28 Apr	177
Madurai	03 Jul	08 Jan	189
Salem	09 Apr	20 Dec	255
Bougouni	19 Apr	04 Nov	199
Gaoua	25 Mar	11 Nov	231
Bamako	08 May	08 Nov	184
Raipur	23 May	05 Nov	166

and stress-inducing in Kayes, Mali. High temperatures are known to effect germination and establishment, leaf-area development, stem growth, tillering, root growth, panicle initiation, photosynthesis, and respiration (Peacock 1982).

Table 5. Averagee monthly air temperature (°C) for different stations in Alfisol areas of India and Africa.

	Jun	Jul	Aug	Sep	Oct	Nov
Station	Nov'	Dec	Jan	Feb	Mar	Apr
Anantapur	29.7	28.0	27.9	27.8	26.9	24.7
Birni N'Konni	31.2	28.2	26.8	27.7	29.5	27.3
Coimbatore	26.5	25.5	26.0	26.3	26.2	25.2
Cuddapah	31.9	30.0	29.7	29.1	28.2	25.8
Hyderabad	29.1	26.0	25.8	25.6	25.0	22.3
Kayes	31.6	28.3	27.2	27.5	28.7	28.2
Kurnool	30.3	28.1	27.8	27.6	27.4	25.1
Bangalore	24.3	23.2	23.2	23.2	23.2	21.7
Lilongwe	15.5	15.0	16.5	19.4	22.3	23.4
Madurai	31.5	30.7	30.2	29.9	28.5	26.8
Salem	29.6	28.5	28.3	28.2	27.3	25.8
Bougouni	27.2	25.6	25.2	25.7	26.6	26.5
Gaoua	26.8	25.5	25.5	25.7	27.2	27.8
Bamako	28.5	26.6	26.0	26.3	27.3	26.7
Raipur	32.1	27.2	27.1	27.5	26.3	22.5

1. Months in the lower row refer to Lilongwe which is south of the

Table 6. Statistical analysis of maximum air temperatures for Kayes, Mali.

Month	Mean max. temp. (°C)	SD	CV	Probability of exceeding max. temp. (°C) >25	>30	>35	>40	>45
Jan	33.8	1.6	5	100	100	26	0	0
Feb	36.6	1.5	4	100	100	85	3	0
Mar	39.6	1.2	3	100	100	100	33	0
Apr	41.7	0.9	2	100	100	100	100	0
May	42.0	1.0	2	100	100	100	100	3
Jun	38.1	1.3	3	100	100	98	3	0
Jul	33.5	1.0	3	100	100	10	0	0
Aug	31.8	1.1	3	100	100	3	0	0
Sep	32.9	0.8	3	100	100	0	0	0
Oct	35.9	1.3	4	100	100	73	0	0
Nov	36.7	1.0	3	100	100	90	0	0
Dec	33.7	1.1	3	100	100	13	0	0
Annual	36.3	0.5	1	-	-	-	-	-

Soil temperature

Soil temperatures, particularly the extremes, adversely influence germination of seed, functional activity of roots, the rate and duration of plant growth, and the occurrence and severity of plant diseases (Chang 1968). The soil temperatures observed at any given location depend (Monteith 1979) on:

a. The rate at which radiant energy is absorbed;
b. the fraction of energy that is available for heating the soil and atmosphere (sensible heat), i.e., the fraction not used for evaporation (latent heat); and
c. the partitioning of sensible heat between soil and the atmosphere.

We measured the soil temperature, at 10 cm depth, of a medium-deep Alfisol planted to a postrainy-season sorghum crop at ICRISAT Center. Three mositure regimes were imposed on the crop.

1. No drought stress (by irrigating the crop every 10 days).
2. Drought stress imposed 35 to 65 days after emergence (DAE) (by withholding irrigations during this period and irrigating thereafter every 10 days).
3. Drought stress imposed from 65 DAE (by withholding irrigation) to maturity.

Soil temperatures were also measured on a nonirrigated, bare soil. Maximum soil temperatures under different treatments are shown in Figure 6. Treatment 1 showed the lowest soil temperatures to range between 21 ° and 24°C, up to 95 DAE. Because all irrigations were withheld thereafter, the soil temperatures showed a sudden increase. Treatment 2, which was under stress up to 65 DAE, showed soil temperatures that were, on an average, about 4°C higher than in treatment 1. In treatment 3, the temperatures were high, occasionally approaching those for the bare fallow in treatment 4.

Van Wambeke (1982) computed the mean annual, mean summer, and mean winter soil temperatures for selected stations in Africa from the mean air temperatures (see Table 7). According to the USDA Soil Conservation service (1975), Alfisol regions can be classified as Hyperthermic or Isohyperthermic.

In crops, the shoot meristem has been indentified as the site of temperature perception (Kleinendorst and Brouwer 1970; Peacock 1975). At the start of the growing season, the meristem may be at or just below the surface, so that the rate of leaf expansion is determined by surface soil temperature (Monteith 1979). As the shoot extends, the meristem moves away from the soil surface but, if transpiration is fast enough, its temperature may still be modified by the temperature of the root system and, therefore, of the water the roots absorb.

In relating the response of a crop plant to soil (or air) temperature, Monteith (1979) advocates that it is essential to record the duration of each developmental stage. Several management practices (e.g., mulching) aimed at favorably altering the soil-temperature regimes of Alfisols will be discussed during the course of this workshop, and the forementioned suggestion of monitoring the duration of growth in addition to the rates is worth considering.

Soil Water

Soil water storage capacity

The above discussion on rainfall, PE, and the length of the growing season provides rough solutions to

Table 7. Computed soil temperatures and soil taxonomy definition of the temperature regime for different stations in Alfisol areas of Africa.

Rainfall zone (mm a^{-1})	Station	Mean soil temperature (°C)			Temperature regime
		Annual	Summer	Winter	
<500	Mahalapye	23.0	25.7	18.5	Hyperthermic
500-600	Birni N'Konni	31.0	30.6	28.3	Isohyperthermic
600-800	Kayes	32.0	31.4	29.4	Isohyperthermic
800-1000	Lilongwe	22.4	23.6	19.3	Isohyperthermic
>I000	Bougouni	29.5	28.5	28.3	Isohyperthermic
>1000	Gaoua	30.0	28.3	30.2	Isohyperthermic

Source: van Wambeke 1982.

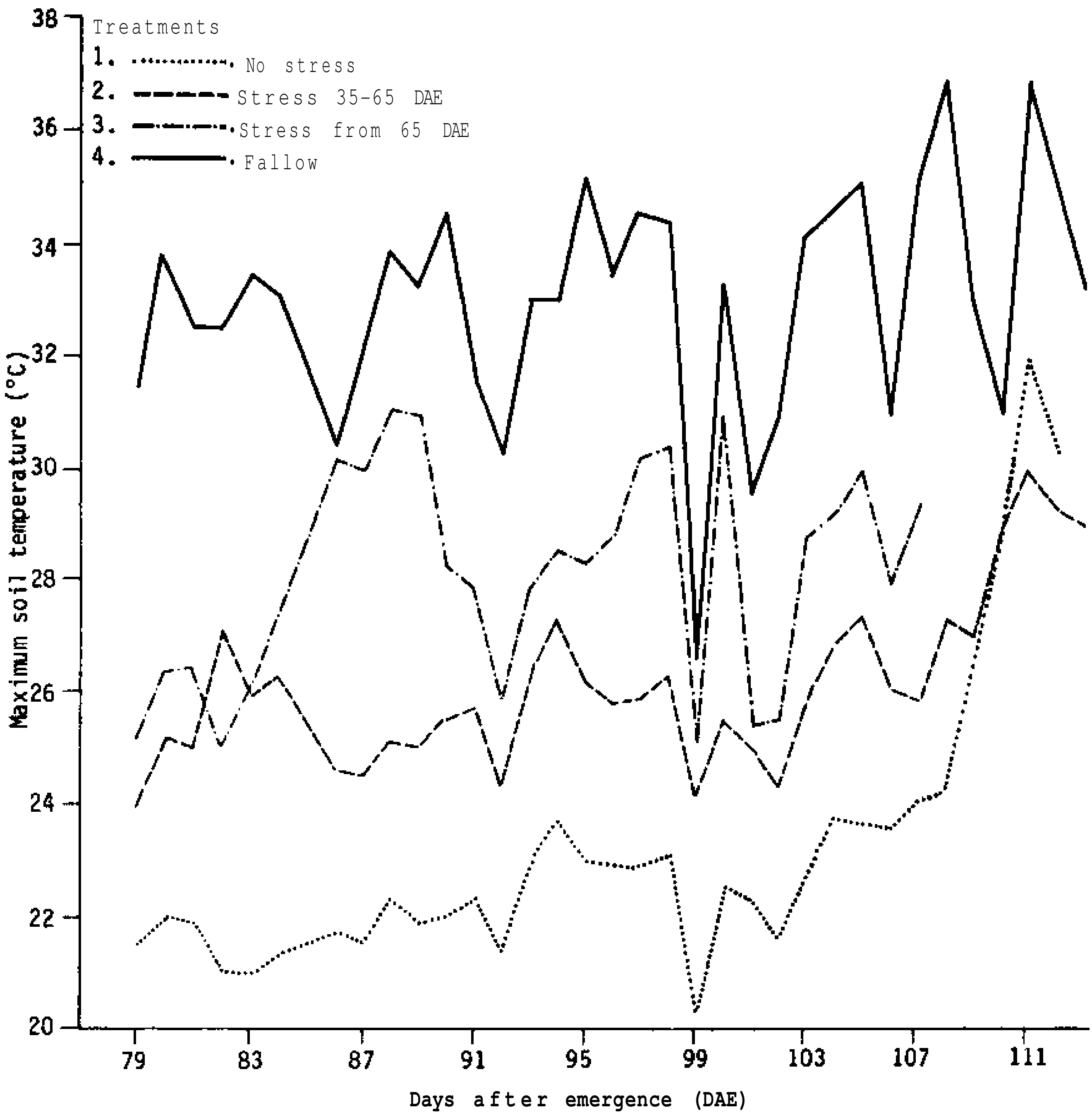


Figure 6. Seasonal variation in maximum soil temperature under different treatments in sorghum grown during the postrainy season at ICRISAT Center.

broad, region-specific problems in agricultural planning. But the soil characteristics of the region are by themselves very important since the soil serves as a storage reservoir when rainfall exceeds PE. Availability of stored water is crucial for the successful harvest of a crop in SAT Alfisols, where water deficits during the growing season are frequent.

Traditionally, the water-storage capacity of a soil profile is determined by using the limits of water extraction at field capacity and -15 bars (permanent wilting point). The lower limit used in this procedure has come under criticism of late, because the proportion of the soil profile tapped by the crop is difficult to ascertain (Hsiao et al. 1980). By growing sorghum, pigeonpea, and chickpea under good management during the postrainy season on water stored in the soil, generalized estimates of crop-extractable water in deep and medium-deep Alfisols at the ICRISAT Center were determined. (Sec Fig. 5, El-Swaify et al. 1987, in this volume).

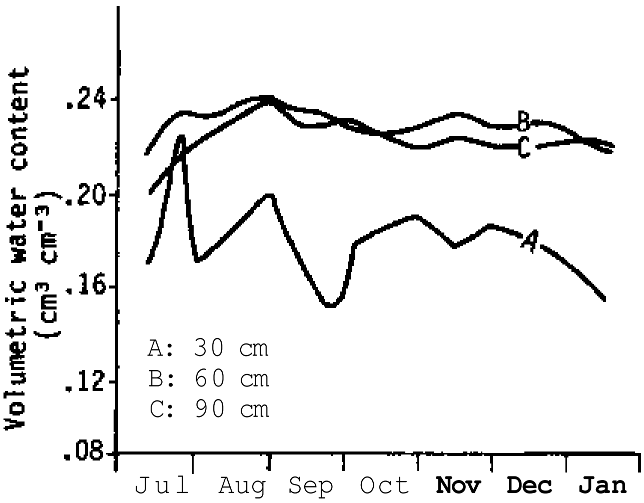


Figure 7. Seasonal changes in water content at three soil depths in an uncropped deep Alfisol.

Soil texture and soil moisture changes

The particle size distribution of selected Alfisols at ICRISAT Center are reported in El-Swaify et al. 1987 (in this volume).

Soil-moisture changes at depths of 30, 60, and 90 cm in an uncropped deep Alfisol (Fig. 7) clearly reflect the dynamic changes in profile-water recharge and depletion in the top 30 cm during the rainy and postrainy seasons. At depths below 30 cm, recharge and depletion occur annually, whereas in the upper 30 cm the periodicity of recharge and depletion is determined by depth and by the size and frequency of rainfall. The water regime of the upper 30 cm of the profile is highly dynamic, evaporation from the soil surface being the primary cause of depletion.

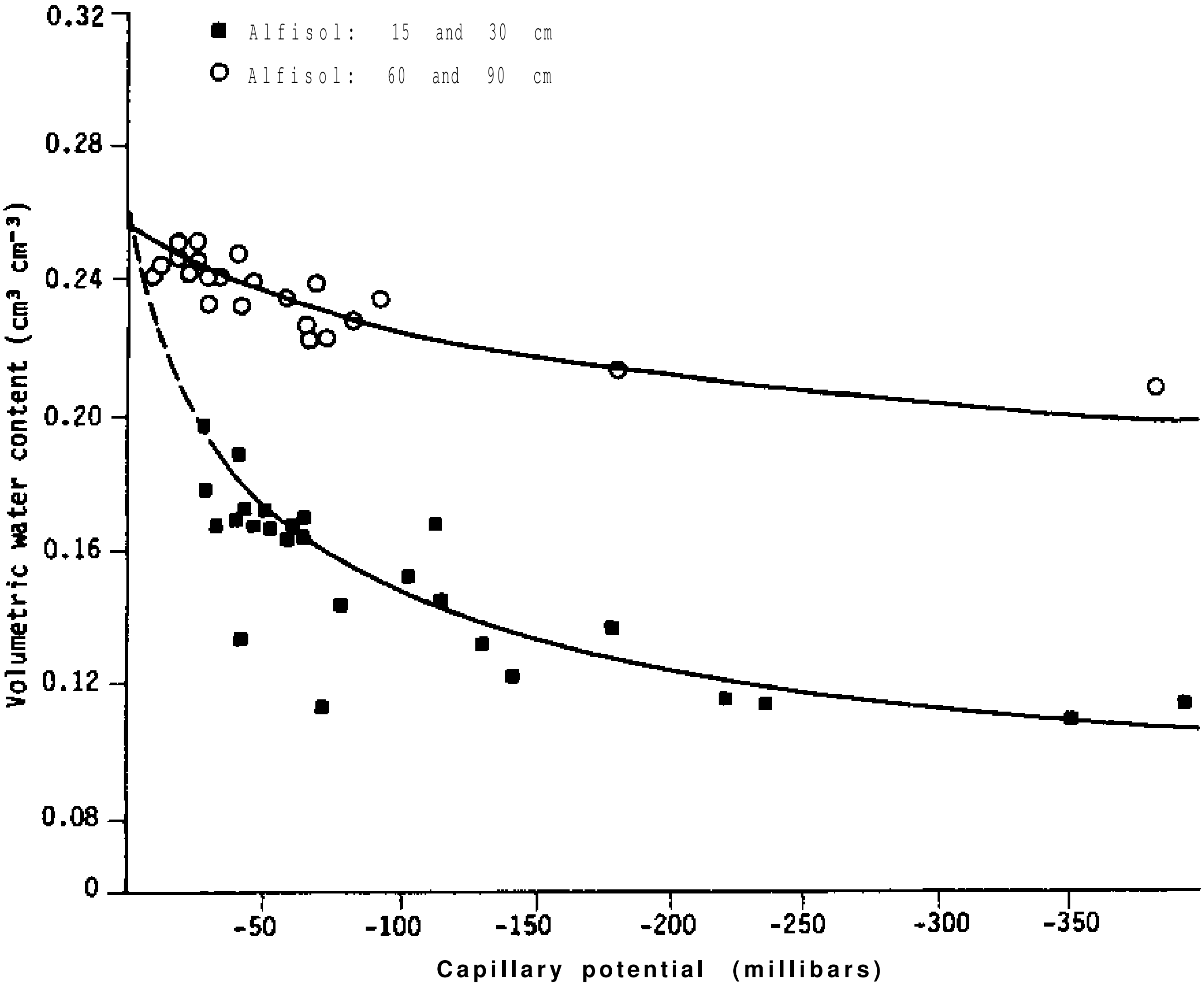


Figure 8. Moisture characteristic curves determined from in-situ field measurements on an Alfisol at ICRISAT Center.

Capillary potential: water content relationships

One of the basic relationships used to describe and analyze the interactions of water with soils is the functional relationship between volumetric water content and capillary potential. From the tensiometric data and volumetric water contents measured at different depths on an Alfisol at ICRISAT Center, it was shown (Fig. 8) that with decreasing capillary potential there was a large decrease in the water content in the top 30-cm soil layer, while, in the lower layers, this decrease was considerably less. This reflects the large difference in texture between the soil layer at 0-30 cm and the deeper layers of Alfisols.

Water balance

Once the extractable water-holding capacity of an Alfisol is determined, water-budgeting or water-balance techniques can be used to determine the pattern of changes in profile moisture during the crop-growing season. The changes in profile moisture in deep and medium-deep Alfisols were estimated for five locations in Africa and India, using a simple water-balance model (Keig and McAlpine 1974). The results, shown in Figures 9a and 9b, indicate that, under identical rainfall conditions, the effect of short-term intraseasonal droughts on crop moisture status will differ with the depth of the Alfisols. The effect of changes in seeding dates, and the influence of different phenological characteristics on crop performance, could be assessed on a first-approximation basis using such analysis.

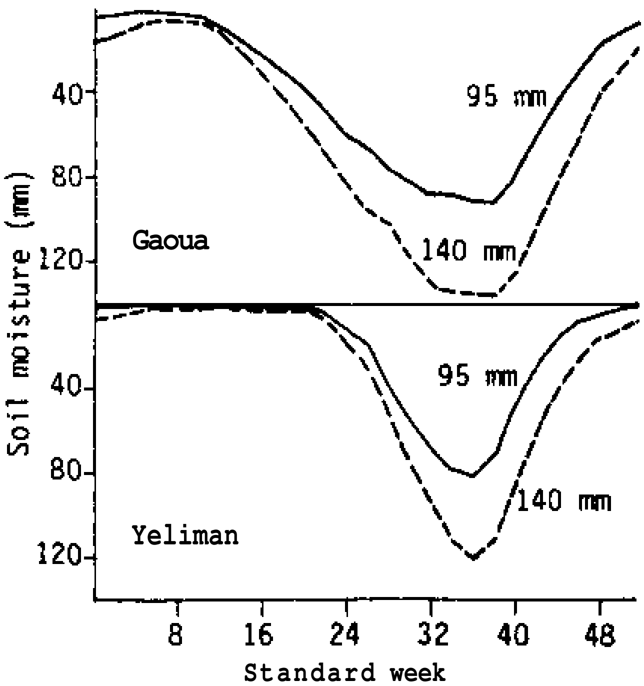


Figure 9a. Simulated profile moisture changes under two assumed available soil water storage capacities (95 and 140 mm) for two locations in Africa.

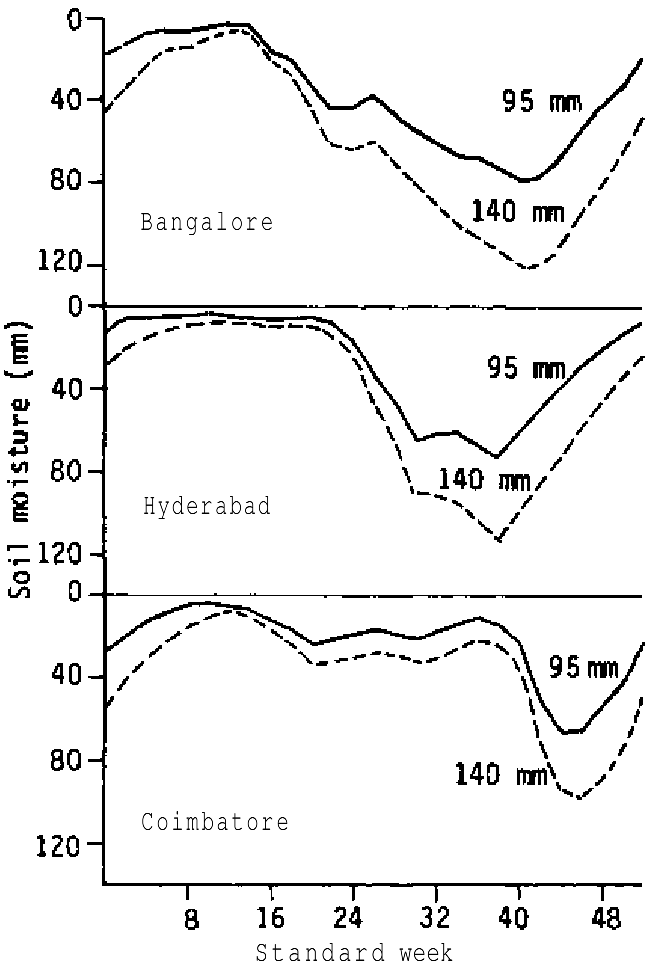


Figure 9b. Simulated profile moisture changes under two assumed available soil water storage capacities (95 and 140 mm) for three locations in India.

Crop Response to Drought Stress on Alfisols

Timing and intensity of drought stress

From the description of the climatic and soil characteristics of Alfisols, it is apparent that improved productivity on these soils would largely depend on the nature of the crops' response to drought. We have conducted several studies on the effects of timing and intensity of drought stress on groundnut grown during the postrainy season on Alfisols at ICRISAT Center. The timing of stress on the crop was found to be much more important than the intensity of stress. This is reflected in the yields achieved, as shown in Figure 10. The final yields were greater from the crops that experienced drought stress during the preflowering stage.

It is worth noting the yield advantages obtained from early stress and considering whether or not this can be exploited. The merit of conditioning groundnuts to early stress to enable them to withstand a second stress has been demonstrated by Rao and Williams (1983), who found that the damage due to stress may be halved.

Water x nutrient interactions

Aborted and stunted groundnut seeds result from inadequate calcium uptake by the pod. Calcium deficiencies can develop in soils with low calcium-

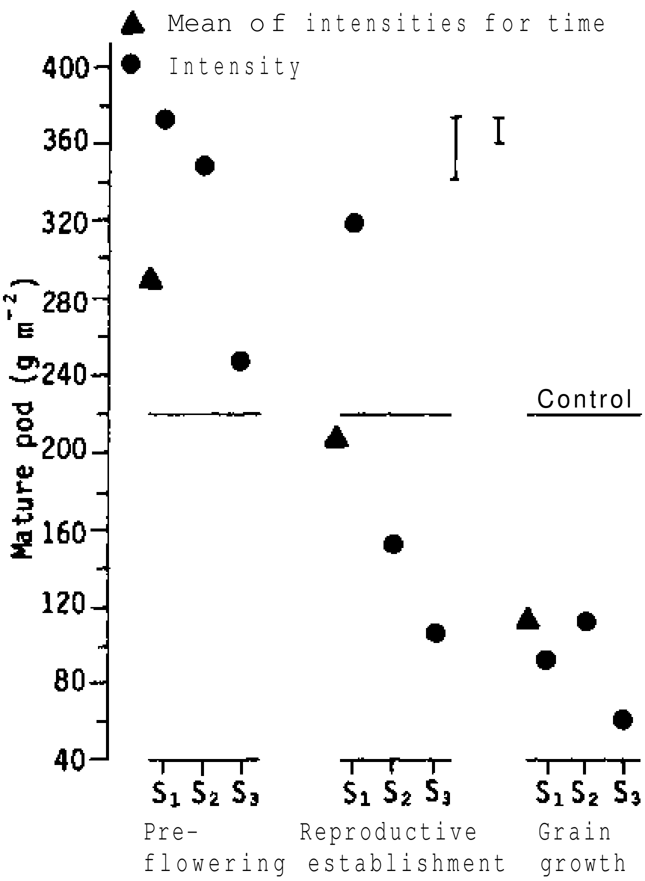


Figure 10. The effect of time and intensity of drought on groundnut yield (Robut 33-1). S_1 = mild stress; S_2 = intermediate stress; S_3 = severe stress.

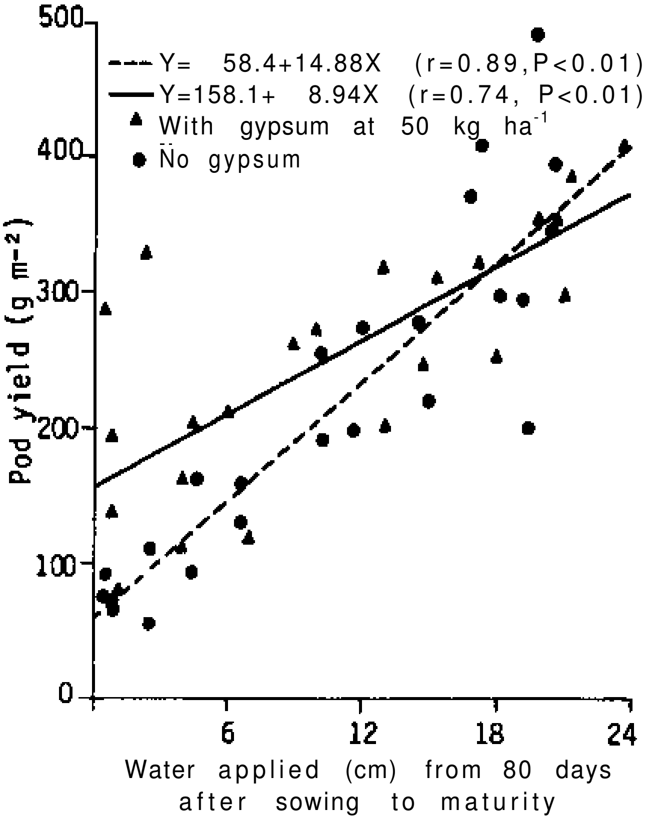


Figure 11. Effect of gypsum on the relationship between applied water and pod yield in groundnut (ICG 4601) at ICRISAT Center.

exchange capacity, or when drought restricts calcium movement in the soil solution. The effects of gypsum application on yields of different groundnut genotypes under varied intensities of drought stress on a medium-deep Alfisol were studied at ICRISAT Center. Although the Alfisols utilized would, normally, not be considered deficient in calcium, gypsum application did increase the yields under drought (Fig. 11).

Crop water-use efficiency on Alfisols

Since water is the most limiting factor for crop production on Alfisols, its efficient use is important. Water-use efficiency can be increased by decreasing evaporation from bare soils (£) between crop rows, and by increasing transpiration (T) and the transpiration efficiency of crops. Various soil and crop management practices employed for improving productivity on Alfisols (El-Swaify et al. 1987) can alter either or both the components of ET. The variation in the £ and T components of sorghum and millet crops was studied under both irrigated and nonirri-

Table 8. Water balances for rainfed and irrigated sorghum on an Alfisol during the rainy and postrainy seasons of 1977-78 at ICRISAT Center.

Dates	Days	P	Eo	M	L	E	Tm	E/Trn
				Rainy-season sorghum				
13 Jul to 18 Jul	5	50	37	29	21	10	11	0.91
18 Jul to 28 Jul	10	56	92	10	46	36	4	9.00
28 Jul to 04 Aug	07	16	37	-16	32	19	12	1.58
04 Aug to 16 Aug	12	97	54	6	91	10	27	0.37
16 Aug to 05 Sep	20	124	73	7	17	13	50	0.26
05 Sep to 12 Sep	7	0	38	-42	42	1	31	0.03
12 Sep to 26 Sep	14	0	83	-16	16	1	15	0.07
Total	75	343	364	-22	365	90	150	0.60
				Postrainy rainfed sorghum				
07 Nov to 16 Nov	9	5	53	-17	22	12	10	1.20
16 Nov to 01 Dec	15	28'	61	6	22	10	12	0.83
01 Dec to 28 Dec	27	2	125	-44	46	7	39	0.18
28 Dec to 18 Jan	21	17	90	-20	37	9	28	0.32
Total	72	52	329	-75	127	38	89	0.43
				Postrainy irrigated sorghum				
07 Nov to 16 Nov	9	5	53	-11	16	12	4	3.00
16 Nov to 01 Dec	15	28[1]	61	0	28	11	17	0.65
01 Dec to 15 Dec	14	41[2]	65	18	23	13	10	1.30
15 Dec to 23 Dec	8	0	37	-33	33	5	28	0.18
23 Dec to 04 Jan	12	34[3]	55	- 4	38	9	29	0.31
04 Jan to 18 Jan	14	35[4]	58	- 8	43	13	30	0.43
Total	72	143	329	-38	181	63	118	0.53

P = Rainfall (mm).
Eo = Open-pan evaporation (mm).
M = Change in water in 127 cm profile (mm).
L = Total water loss (mm).
E = Soil evaporaton (mm).
Tm = Transpiration by mass balance (mm).
1. = Including 22 mm irrigation.
2. = Including 39 mm irrigation
3. = Including 34 mm irrigation.
4. = Including 18 mm irrigation.

gated conditions on Alfisols in the rainy and postrainy seasons at ICRISAT Center. Data in Table 8 show that the £/ Tm ratio was high in the early stages of sorghum growth in both the rainy and postrainy seasons. In the rainy season, evaporation accounted for 60% of the total transpiration, and about 24% of the total water loss.

In the postrainy season, for nonirrigated sorghum, the proportion of E to Tm was lower than that for the rainy season. Under irrigation, the E/Tm ratio increased to 0.53. Early-season losses in water due to evaporation were high during the postrainy season also, indicating the need to check evaporation in the early stages of plant growth. For pearl millet (Table 9), the E/Tm ratio, averaged over the season, was 0.25—considerably lower when compared with sorghum.

Early canopy growth and development of maximum leaf area increase the canopy demand for water through increased transpiration. For a postrainy-season groundnut crop grown on Alfisols, stress imposed from emergence to appearance of first pegs considerably reduced the canopy transpiration through reduction in leaf area index (LAI), but did not reduce the water-use efficiency (WUE) (Table 10). However, when stress was imposed after full

Table 9. Water balances for rainfed and irrigated pearl millet on an Alfisol during the postrainy seasons of 1977-78 at ICRISAT Center.

Dates	Days	P	Eo	M	L	E	Tm	E/Tm
				Rainfed pearl millet				
31 Oct to 10 Nov	10	18	52	-12	30	12	18	0.67
10 Nov to 25 Nov	15	10	67	-46	56	5	51	0.10
25 Nov to 05 Dec	10	2	42	- 5	7	1	6	0.17
05 Dec to 15 Dec	10	0	49	- 3	3	I	2	0.50
Total	45	30	210	-66	96	19	77	0.25
				Irrigated pearl millet				
31 Oct to 10 Nov	10	18	52	-15	33	12	21	0.57
14 Nov to 23 Nov	9	5	38	-42	47	6	41	0.15
25 Nov to 05 Dec	10	2	40	-29	31	9	22	0.41
12 Dec to 28 Dec	16	0	63	-30	30	3	27	0.11
28 Dec to 05 Jan	8	0	37	-14	14	1	13	0.08
Total	52	25	240	-130	155	31	124	0.25

P = Rainfall (mm).
Eo = Open-pan evaporation (mm).
M = Change in water in 127 cm profile (mm).
L = Total water loss (mm).
E = Soil evaporation (mm).
Tm = Transpiration by mass balance (mm).

Table 10. Effect of stage of growth at which drought stress is imposed on leaf growth and water-use efficiency of groundnut.

Stage of growth at which stress is imposed	LAI[1] before imposition of water stress	LAI' at maturity	Water-use efficiency (kg ha^{-1} cm^{-1})
1. Emergence to peg initiation	-	3.60	29.61
2. Flowering to last pod set	1.90	3.90	10.47
3. Pod filling to maturity	3.39	1.35	2.95
4. Continuous drought stress	-	1.42	1.73

1. LAI = leaf area index.

leaf-area development, the transpirational demand was very high; the moisture supply was inadequate and the WUE was low.

Selection of varieties that produce more yield for a given amount of water has been made at ICRISAT Center. It seems possible to increase groundnut yields under drought conditions on Alfisols utilizing appropriate genotypes (Fig. 12).

Because various cropping systems differ in their capacity to cover the ground quickly, and in their sensitivity to drought stress at different stages of growth, WUE also usually differs. The differences in the WUE of three sole crops and an intercrop grown on Alfisols at ICRISAT Center are shown in Table 11.

Conclusions

Planning for improved productivity of Alfisols should take into account the interactions between climate, soil, and plant in different areas of the world where these soils are situated. Information on the intensity, amount, and distribution of rainfall does help provide a general idea about the cropping potential and soil erosion, but this information should be combined with potential evapotranspiration data to assess the available length of the growing period for crops. Air and soil temperature data for crop-growing seasons are equally important, in view of the dynamic changes in soil moisture that occur in the surface soil layers of Alfisols. The depth

Table 11. Water use and water-use efficiency of crops/cropping systems grown on Alfisols during the rainy season at ICRISAT Center.

Crop/cropping system	Water use (cm)	Yield (kg ha')	Water use efficiency (kg ha^{-1} cm^{-1})	Reference
Sorghum	24.0	3700	154	ICRISAT (1978)
Pearl millet	15.9	2226	140	Reddy and Willey (1981)
Groundnut	19.6	1185	60	Reddy and Willey(1981)
Pearl millet/groundnut	22.8	1227/840	91	Reddy and Willey(1981)

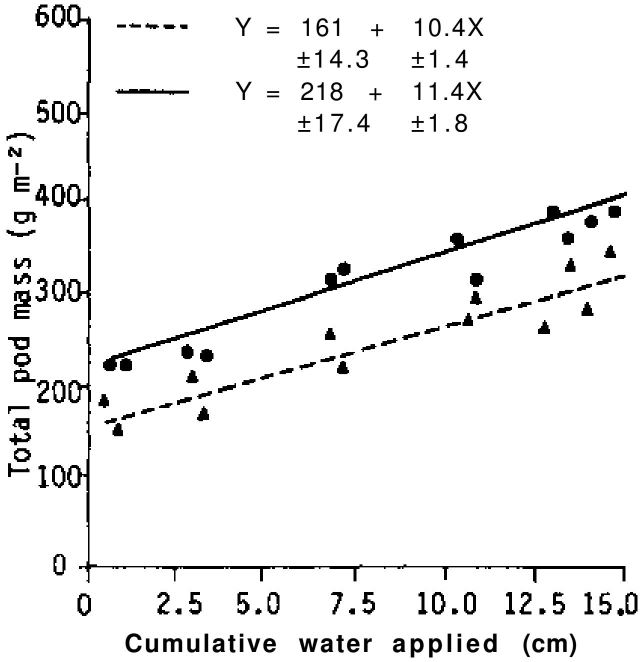


Figure 12. The response of pod yield to variations in applied water during pod set to pod filling for groundnut (ICG 4743), at ICRISAT Center.

of Alfisols being variable, various soil physical characteristics related to moisture storage and its release should be quantified. First-approximation information on profile water changes, employing simple models that use soil and climatic data, should prove useful in planning.

The crop's response to water shortages—so common on Alfisols—should be studied carefully, taking into account the timing and intensities of water stress. Water x nutrient interactions play an important role in drought responses. Crop WUE on Alfisols could be improved through appropriate management practices, selection of genotype, crops, and cropping systems.

References

Buringh, P. 1982. Potentials on world soils for agricultural production. Pages 33-41 in Managing soil resources. Plenary session papers. Transactions of the 12th International Congress of Soil Science, 8-16 Feb 1982, New Delhi, India. New Delhi, India: Indian Agricultural Research Institute.

Chang, J.H. 1968. Climate and agriculture. Chicago, USA: Aldine Publishing Company.

Charreau, C., and Nicou, R. 1971. L'amelioration du profil cultural dans les sols sableux et sablo-argileux de la zone tropicale seche ouest-africaine et ses incidences agronomiques (d'apre's les travaux des chercheurs de I'IRAT en Afrique de l'Ouest). Agronomie Tropicale 26:209-255; 565-631; 903-978; 1183-1247.

Cocheme, J., and Franquin, P. 1967. An agroclimatological survey of a semi-arid area in Africa south of the Sahara. Technical Note no. 86. Geneva, Switzerland: World Meteorological Organization.

El-Swaify, S.A., Singh, S., and Pathak, P. 1987. Physical and conservation constraints and management components for SAT Alfisols. (In this volume.)

Hoogmoed, W.B. 1981. Development of criteria and methods of improving the efficiency of soil management and tillage operations with special reference of arid and semi-arid regions. Appendix 5. Analysis of rainfall in some locations of West Africa and India. Wageningen, Netherlands: Agricultural University, Tillage Laboratory, and Rehovot, Israel: Hebrew University.

Hsiao, T.C., O'Toole, J.C., and Tomar, V.S. 1980. Water stress as a constraint to crop production in the tropics. Pages 339-370 in Priorities for alleviating soil-related constraints to food production in the tropics. Los Banos, Laguna, Philippines: International Rice Research Institute.

ICRISAT (International Crops Research Institute for the Semi-arid Tropics). 1978. Report of work for the year 1977-78, Environmental Physics Subprogram, Farming Systems Research Program. Patancheru, A.P. 502324, India: ICRISAT. (Limited distribution.)

Kampen,J., and Burford, J.R. 1980. Production systems, soil-related constraints and potentials in the semi-arid tropics with special reference to India. Pages 141-165 in Priorities for alleviating soil-related constraints to food production in the tropics. Los Banos, Laguna, Philippines: International Rice Research Institute.

Kanwar, J.S. 1982. Managing soil resources to meet the challenges to mankind: presidential address. Pages 1-32 in Managing soil resources. Plenary session papers. Transactions of the 12th International Congress of Soil Science, 8-16 Feb 1982, New Delhi, India. New Delhi, India: Indian Agricultural Research Institute.

Keig, G., and McAlpine, J.R. 1974. Watbal: a computer system for the estimation and analysis of soil moisture from simple climatic data. 2nd edn. Australian Division of Land Research Technical Memorandum 74/4. Melbourne, Australia: Commonwealth Scientific and Industrial Research Organization. 45 pp.

Kleinendorst, A., and Brouwer, R. 1970. The effect of temperature of the root medium and of the growing point of the shoot on growth of maize leaves. Netherlands Journal of Agricultural Science 18:148.

Kowal, J.M., and Kasaam, A.H. 1973. An appraisal of drought in 1973 affecting groundnut production in the Guinea and Sudan savanna areas of Nigeria. Savanna 2:159-164.

Kowal, J.M., and Knabe, D.T. 1972. An agroclimatalogical atlas of the northern states of Nigeria: with explanatory notes. Samaru, Zaria, Nigeria: Ahmadu Bello University Press.

Monteith, J.L. 1979. Soil temperature and crop growth in the tropics. Pages 249-262 in Soil physical properties and crop production in the tropics (Lal, R., and Greenland, D. J., eds.). Chichester, UK: John Wiley.

Peacock, J.M. 1975. Temperature and leaf growth in Lolium perenne . II. The site of temperature perception. Journal of Applied Ecology 12:115-123.

Peacock, J.M. 1982. Response of tolerance of sorghum to temperature stress. Pages 143-160 in Sorghum in the eighties: proceedings of the International Symposium on Sorghum, 2-7 Nov 1981, ICRISAT Center, India. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

Rao, R.C.N., and Williams, J.H. 1983. Effect of timing and intensity of droughts on groundnuts. Groundnut Physiology Progress Report no. 3. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

Reddy, M.S., and Willey, R.W. 1981. Growth and resource use studies in an intercrop of pearl millet/groundnut. Field Crops Research 4:13-24.

USDA (United States Department of Agriculture), Soil Conservation Service, Soil Survey Staff. 1975. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. Agriculture Handbook no. 436. Washington, D.C., USA: U.S. Government Printing Office.

van Wambeke, A. 1982. Calculated soil moisture and temperature regimes of Africa. Ithaca, New York, USA: Cornell University Press.

Production Constraints and Management Requirements

A: Physical and Hydrological

Physical and Conservation Constraints and Management Components for SAT Alfisols

S.A. El-Swaify, S. Singh, and P. Pathak[1]

Abstract

The Alfisols of the semi-arid tropics are well-drained soils, but possess low water-storage capacities. They are, therefore, cropped only during the rainy (monsoon) season. With traditional rainfed farming, the soils are both unproductive and prone to excessive runoff and erosion. Efforts to improve management of these soils for conventional cropping have succeeded in increasing crop yields over traditional management systems, but effective practices for improved soil and water conservation remain to be formulated. This is primarily because of the extreme structural instability of the soils. Physical components of improved management have been subject to many investigations and many promising trends have emerged, but no integrated set of practices can, as yet, be confidently recommended for sustaining agricultural productivity on small farms. In this background paper, evidence primarily from research at ICRISAT is used as a basis for discussion of the physical constraints and the promising developments that have been made in improving the conservation and management of these soils.

Introduction

The diversity of soils in the semi-arid tropics (SAT) is clearly indicated by the fact that 8 of the 10 orders in Soil Taxonomy (USDA Soil Survey Staff 1975) are represented in this region. Table 1 shows that nearly 33% of the land area in the SAT is occupied by Alfisols (6.96 million km^2). Associated soils are primarily the Aridisols (5.20 million km^2), Entisols (2.72 million km^2), Oxisols (1.88 million km^2), and Vertisols (1.31 million km^2). The Aridisols and Entisols may be considered as related soils, particularly in the African SAT. SAT environments are identified at the suborder level within the ustic moisture regime. This term implies dryness during parts of the year, but "moisture is present at a time when conditions are suitable for plant growth" (USDA Soil Survey Staff 1975). The specific definition of ustic is based on mean annual soil temperature, and duration of the period in which the control section of the profile remains moist or dries out. By this definition, the ustic regime occurs in tropical regions, with a monsoon climate that has at least one rainy season lasting 3 months or more in a year.

Table 1. Soils of the semi-arid tropics.

	Area (million km^2)			
Soil order	Africa	Latin America	Asia	Total
Alfisols	4.66	1.07	1.21	6.96
Aridisols	4.40	0.33	0.47	5.20
Entisols	2.55	0.17	-	2.72
Inceptisols	0.38	-	0.28	0.66
Mollisols	-	0.78	-	0.78
Oxisols	1.88	·	-	1.88
Ultisols	0.24	0.08	0.20	0.52
Vertisols	0.51	-	0.80	1.31
Others	-	0.70	0.23	0.93
Total	14.62	3.13	3.19	20.94

Source: Kampen and Burford 1980.

1. Farming Systems Research Program (now Resource Management Program), ICRISAT, Patancheru, A.P. 502 324, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the Sute of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502 324. India: ICRISAT.

All the forementioned soils are used for agricultural production, and come under a wide variety of "traditional", "improved", or "developed" methods of farming. These, together with general reviews of soil resources in the tropics and the SAT are given in Sanchez (1976), Swindale (1982), and Kanwar (1983). The major characteristics of several tropical soil orders, including Alfisols, are provided in a recent document on soils of variable charge (Theng 1980). These inventories, however, do not specifically document the experiences that have been acquired in recent years on major constraints to productivity and optimized management of SAT Alfisols.

This paper reviews recent studies on the physical constraints and the developments that have been made in soil and water management and conservation to optimize productivity of these soils under rainfed conditions.

Alfisols are represented within the experimental farm of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) by the Patancheru soil series. This soil, a Udic Rhodustalf, will therefore be central to the discussions that follow. Its major characteristics are shown in Table 2. Available information from other locations in the SAT will be presented where relevant.

Relevant Characteristics of SAT Alfisols

Alfisols possess an argillic horizon within the profile. Hence the clay content of these soils increases with depth, although shallow and gravelly Alfisols are also common as a result of erosion. The enrichment of surface layers with coarse particles is assumed to be the result of clay migration with percolating water, termite activity, and/or selective removal of fine particles by erosion. The soils may contain distinct layers of gravel and weathered rock fragments at lower depths (often called murrum). How the presence of stone in these layers effects several Alfisol properties is shown in Fig. 1. Effective rooting depths of crops are restricted either by the limited soil depth imposed by the presence of such layers, or by the compact argillic horizon that may restrict root penetration. Restricted root development on these soils prevents many crops from withstanding even moderate droughts. Hence, poor crop yields are common.

Alfisols—at least those cultivated in the SAT-are characterized by lack of structural development;

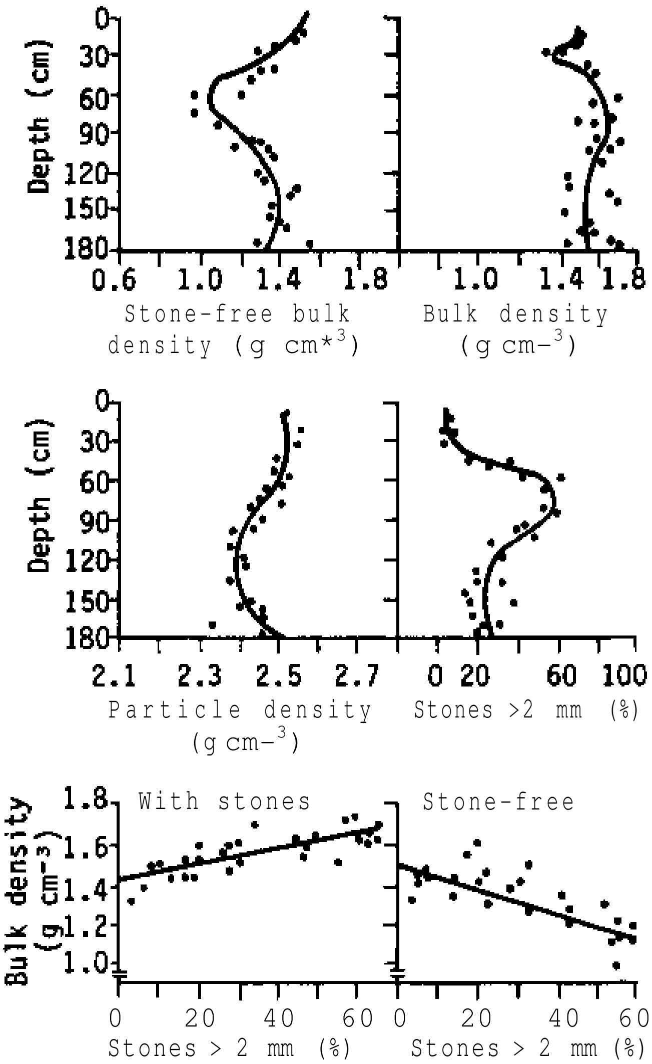


Figure 1. Bulk density, particle density, and the percentage of stones in Alfisols.

this results from a low content of fine (clay-sized) particles, particularly in the surface horizon, clay minerals of low activity (kaolins with varying but small proportions of 2:1 layer-lattice clays and sesquioxides), and—with the cropping systems prevalent in the SAT—the tendency to stabilize only minute amounts of decomposed organic matter within the soil mass. The increased clay content with depth often distinguishes these soils from other "sandy" soils, (e.g., Entisols). However, since soils in many SAT regions have not been described according to Soil Taxonomy, it is difficult to retrieve from the literature precise global information on experiences with these soils.

A major consequence of the lack of aggregation, or unstable aggregation, is the tendency of these soils to display rapid surface-sealing following rainfall, and crusting with subsequent drying cycles. This

Table 2. Major characteristics of the Patancheru soil series, a Udic Rhodustalf, at ICRISAT Center.

Horizon	Depth (cm)	Sand (2.0-0.02)	Silt (0.02-0.002)	Clay (<0.002)	Coarse fragments (>2 mm) % of whole soil	Organic carbon (%)	pH (1:2.5) H_2O	E.C. (1:2.5) suspension	Water retention 1/3-bar Gravimetric %	Water retention 15 bar Gravimetric %
		........% of 2 mm soil particle........								
Ap	0-5	79.3	6.4	14.3	17	0.55	6.0	0.1	16.2	6.3
B 1	5-18	66.7	5.5	27.8	17	0.52	6.9	0.1	20.0	12.4
B 2_1	18-36	41.6	6.8	51.6	36	0.63	6.9	0.1	21.9	13.9
B 2_2	36-71	45.0	4.4	50.6	54	0.40	6.8	0.1	24.8	17.4
B 2_3	71-112	54.1	7.4	38.5	50	0.10	6.5	0.1	23.6	16.2
B 3	112-140	70.6	4.1	25.3	63	0.18	6.2	0.2	18.7	11.5

Depth (cm)	Extractable bases Ca	Mg	Na	K	Sum	CEC NH_4OAC	Base saturation (%)	CEC/Clay ratio	Clay fraction mineralogy[1] Am	KK	MI	SM	QZ	Sand fraction mineralogy[2] QZ	FDM	FE	HE	FDP	Others
	....................meq 100 g^{-1}....................																		
0-5	2.6	0.5	-	0.4	3.5	4.8	74	0.34	11	37	12	17	17	35	25	10	10	5	15
5-18	3.8	0.9	-	0.5	5.2	8.2	64	0.29	12	37	10	19	14	45	20	5	5	10	15
18-36	5.8	3.8	-	0.6	10.2	14.8	69	0.29	14	37	10	23	13	40	30	10	-	10	10
36-71	7.9	3.1	-	0.6	11.6	14.1	82	0.28	12	38	11	20	16	30	30	5	5	15	15
71-112	5.4	2.5	0.3	0.4	8.6	9.8	88	0.25	12	44	8	18	16	40	20	5	-	10	25
112-140	5.7	1.9	0.5	0.3	8.4	9.1	92	0.36	10	39	8	21	16	35	25	5	-	15	20

1. Clay fraction mineralogy: Am = Amphibole; KK = Kaolinte; MI = Mica; SM = Smectite; QZ = Quartz.
2. Sand fraction mineralogy: QZ = Quartz; FDM = Feldspar-microline; FE = Magnetite; HE = Haematite; and FDP = Feldspar-plagioclase.

crusting can adversely affect plant establishment (Figs. 2 and 3). It often extends deeper than the immediate soil surface, resulting in consolidation of the soil profile (slumping) to a depth that is determined by several factors. Apparently the particle-size distribution (and mineralogy) favors slaking, packing, and compaction. Thus, although the soils permit easy tillage when wet, they become hard and difficult to till when dry. Tillage when the soil is too wet may result in excessive compaction. Hence only a limited soil moisture range is available for producing optimum tilth. El-Swaify (1983) attributes the lack of consistent success in managing these soils under rainfed conditions to several physical factors as discussed below.

Alfisols generally possess inherently low water-retention characteristics because of their particle-size makeup and mineralogical composition. This is often compounded by the shallow depth of the soil zone available for water storage. Lack of water storage combines with mechanical impedence problems in these hardening soils to limit crop-root proliferation. Improvements in medium characteristics as a result of tillage are only temporary because of the lack of structural stability. The structural instability and subsequent frequent failures in land-surface configurations lead to a reduction in surface roughness (useful for maximizing infiltration) and enhancement of surface-sealing and crusting (Weststeyn 1983). These on the one hand induce excessive runoff even early in the season and, on the other, directly affect seedling emergence. Direct effects on crops are more drastic with small-seeded crops such as pearl millet, finger millet (Eleusine coracana) and sorghum. Localized droughts are also very likely in the seed environment, i.e., in ridges or beds into which water entry by infiltration is restricted by surface-sealing. Crusted soil surfaces are also presumed to be prone to increased evaporative water loss.

Raised-land surface configurations, installed as conservation measures, lead to excessive concentrations of induced runoff in the furrows which then undergo rilling and exaggerated erosion. In many SAT Alfisols, workability in the dry state and stoniness appear to be deterrents to effective land preparation. Since the soils are generally well-drained, leaching of water-soluble fertilizers is a common

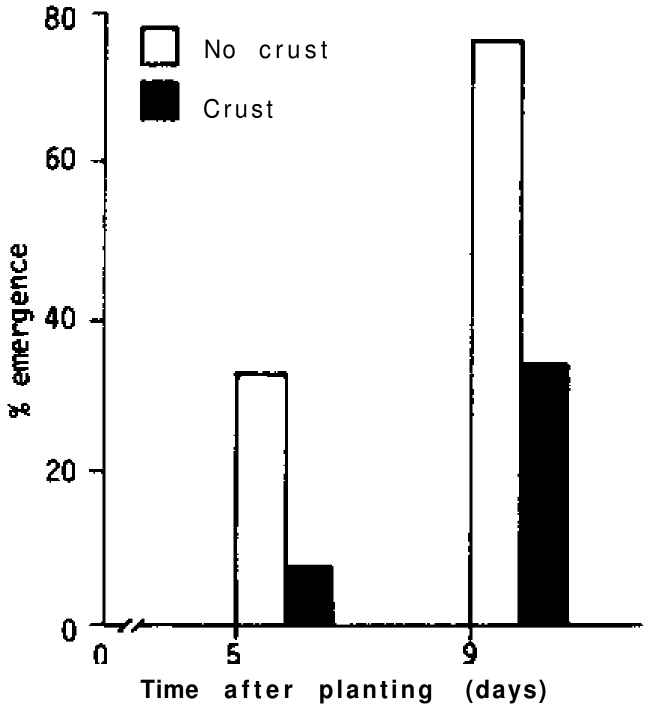


Figure 2. Percentage emergence of sorghum seedlings under crust and no-crust treatments following planting.

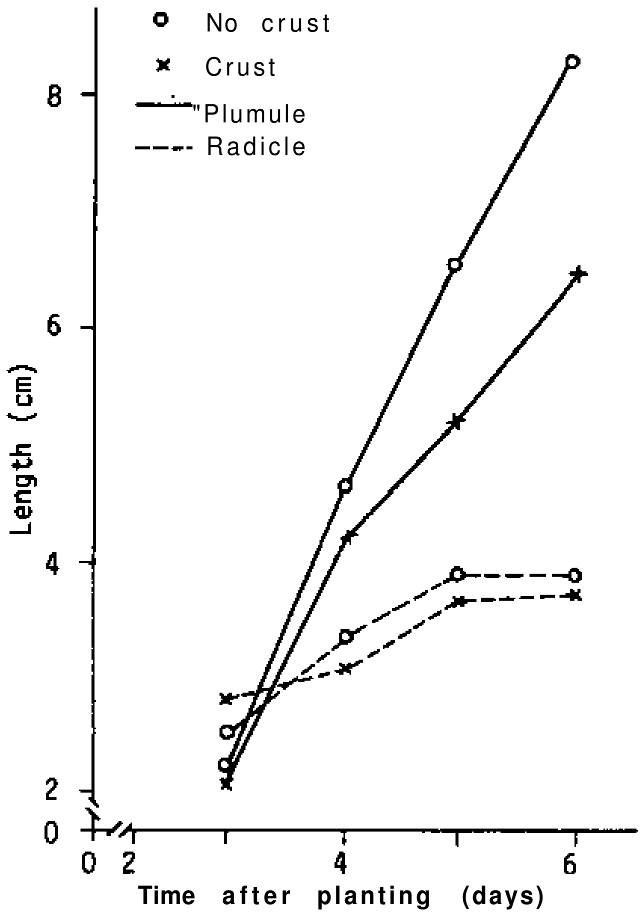


Figure 3. Changes in plumule and radicle lengths of sorghum seedlings under crust and no-crust treatments following planting.

Table 3. Physical properties of two Alfisol profiles at ICRISAT Center.

Depth (cm)	Stone content %[1] ST2	Stone content %[1] RA10	Bulk density (g cm^{-3}) ST2	Bulk density (g cm^{-3}) RA10	Moisture content at[2] 15 bar ST2	Moisture content at[2] 15 bar RAI0	Moisture content at[2] 0.3 bar ST2
0-15	2.4 ± 0.8	10.9 ± 9.1	1.55 ±0.22	1.57 ±0.20	6.0	8.6	8.3
15-30	1.5 ± 0.8	7.7 ± 6.0	1.64 ±0.15	1.72 ±0.19	10.2	10.3	13.5
30-45	0.6 ± 0.8	2.9 ± 1.7	1.59 ±0.07	1.67 ±0.10	14.8	10.4	18.7
45-60	2.2 ± 4.8	1.4 ± 0.5	1.59 ±0.12	1.63 ±0.11	16.1	14.2	20.3
60-75	4.3 ± 10.4	2.3 ± 1.3	1.64 ±0.04	1.71 ±0.10	17.1	15.7	21.1
75-90	5.0 ± 13.0	11.1 ± 19.7	1.60 ±0.04	1.79 ±0.12	17.2	15.8	21.8
90-105	6.6 ± 10.1	16.2 ± 20.2	1.68 ±0.10	1.83 ±0.15	17.7	16.0	21.7
105-120	11.2 ± 13.6	30.3 ± 27.8	1.65 ±0.09	1.85 ±0.14	17.6	16.9	21.5
120-135	12.4 ± 14.5	21.7 ± 18.4	1.75 ±0.10	1.81 ±0.16	16.8	16.6	20.6
135-150	18.1 ± 17.8	28.3 ± 8.1	1.70 ±0.09	1.86 ±0.16	16.4	16.4	20.6
150-165	28.0 ± 14.7	33.1 ± 14.1	1.80 ±0.11	1.86 ±0.05	15.7	16.8	20.1
165-180	30.7 ± 10.0	31.0 ± 15.9	1.74 ±0.08	1.83 ±0.13	14.9	16.4	19.6
180-195	16.6 ± 14.2	35.1 ±21.6	1.80 ±0.14	1.89 ±0.20	15.0	ND	19.6

1. Mass percentage of material >2 mm
2. On a mass basis in stone-free samples.

occurrence with heavy rainstorms (C.W. Hong 1983, ICRISAT, personal communication). Such losses are particularly enhanced by the soils' low nutrient-retention capacities (cation-exchange capacity values range between 1 and 10 meq 100 g^{-1}).

The lack of active clays in Alfisols also indicates that organic matter has an important role in controlling the soil's structural characteristics. This is one important reason why management of Alfisols for sustained agricultural productivity may be comparatively easy in the humid tropics. In the humid tropics, abundant and uniformly distributed rainfall allows continuous biological activity and buildup of organic matter to fairly high levels.

The erodibility of Alfisols appears to vary widely. The universal soil loss equation's K value has been reported to be as high as 0.4 or more, indicating that the soils are quite susceptible to erosion by water (El-Swaify and Dangler 1982).

It is important to emphasize at this point that Alfisols display wide diversity and spatial variability. Therefore, Table 2 may be accepted only as representative of Udic Rhodustalfs at the precise sampling and description site. Even within ICRISAT's farm, much variability is encountered in the properties of the Patancheru series. Tables 3,4a, and 4b include quantitative data for selected physical properties of various Alfisols at ICRISAT Center.

Table 4a. Bulk density (g cm^3) of selected Alfisols at ICRISAT Center.

Depth (cm)	RP17	RCW20	RP1	RUS5
0-15	1.55	1.57	1.54	1.71
15-30	1.64	1.72	1.58	1.74
30-45	1.59	1.62	1.58	1.62
45-60	1.59	1.63	1.56	1.54
60-75	1.64	1.71	1.57	1.56
75-90	1.60	1.79	1.60	1.61

(Column group heading: Location)

Table 4b. Particle size distribution of selected Alfisols at ICRISAT Center.

Depth (cm)	RUS5 Sand	RUS5 Silt	RUS5 Clay	RW2C Sand	RW2C Silt	RW2C Clay	RW3 Sand	RW3 Silt	RW3 Clay
0-15	88	6	8	88	4	8	73	10	17
15-30	69	8	23	85	6	9	55	9	36
30-45	55	6	39	76	5	19	48	10	42
45-60	47	10	43	66	6	28	45	12	43
60-75	46	9	45	59	9	32	47	9	44
75-90	48	9	43	65	8	27	46	9	45

Dryland Management Options for SAT Alfisols

Traditional uses and management

In contrast to Vertisols, rainfed cultivation of Alfisols in the semi-arid tropics is practiced only during the rainy season. The growth period for sequential cropping is extended into the postrainy season where water is available for supplemental irrigation. For certain rainfed intercropping combinations, the season extends to the end of the long-duration crop (e.g., castor). The main traditional crops include sorghum, pearl millet, finger millet, groundnut, pigeonpea, cotton, castor, green gram (mung bean) and black gram (Vigna mungo). These are grown as sole crops, in discrete mixtures or as intercrops. Farmers prefer mixtures or intercropping, especially in low-rainfall regions, because such combinations reduce the risk associated with variable and unpredictable moisture situations, and allow taking maximum advantage of both good and poor rainfall years. Intercropping of cereals with pulses or oilseeds is most common: the farmer requires these for food and cash purposes (Jodha 1980). In the Indian SAT, supplemental irrigation from tanks (small, surface reservoirs) or wells is common on Alfisols. In such cases, farmers prefer paddy rice, sugarcane, tobacco, groundnut, and maize as the main crops.

With their poor water-retention characteristics, rainfed cropping of Alfisols faces the constant threat of deficient soil moisture even during relatively short dry spells. Common crop failures discourage farmers from making substantial investments for improved management (Kampen 1980). Therefore they generally plant traditional crop varieties with little or no chemical fertilizer. Even in dependable-rainfall regions, the average yields are very low. Village-level surveys of some Alfisol areas in India (Rastogi et al. 1982, Sanghi and Rao 1982) have revealed the following average yields for major crops:

Sorghum	300-500 kg ha^{-1}
Pearl millet	300-450 kg ha^{-1}
Castor	300-550 kg ha^{-1}
Pigeonpea	200-300 kg ha^{-1}
Groundnut	400-600 kg ha^{-1}

Since dry soils are quite difficult to handle before the monsoon, all agricultural operations are conducted following the onset of the rainy season. Often, therefore, the fields are relatively bare when the monsoon begins. Further, the nonstable structure of these soils enhances their tendency to develop surface seals that reduce infiltration and profile recharge, even when rains are moderate. These seals harden into crusts during intermittent dry periods. Such conditions deter the establishment of adequate protective crop cover early in the season. As a consequence, the traditional system of farming induces excessive runoff and soil loss. Later in the growing season, poor crop establishment, coupled with continued poor growth, result in very low rainfall utilization.

Hydrologic studies conducted at ICRISAT on the traditional farming system have shown that, of the total rainfall potentially available, an average of about 26% is lost through runoff, 33% through deep percolation, and only the balance 41% is utilized for evapotranspiration by crops (Table 5). For cropped Alfisols—whose physical and fertility status are generally marginal, and the profile often shallow-excessive runoff and soil losses represent further

Table 5. Estimated water-balance components and soil loss observed for the traditional cultivation system[1] on Alfisols at ICRISAT Center.

Year	Rainfall (mm)	Runoff (mm)	Evapotranspiration (mm)	Deep percolation (mm)	Soil loss (t ha^{-1})
1978	1060	391	395	274	5.19
1979	671	113	335	223	1.83
1980	765	149	345	271	1.62
1981	1130	292	415	423	5.61
1978-81[2]	100	26	41	33	3.7P

1. Traditional varieties of sorghum as sole crop, and sorghum/ pigeonpea as intercrop were grown.
2. In percentage of rainfall.
3. Average annual soil loss.

degradation of the resource base and lead to a further decline in productivity.

Developments in improved management for optimized productivity

Our present knowledge about Alfisols—in contrast to that about Vertisols, on which the broadbed-and-furrow (BBF) technology is proving quite promising for optimized management (Kampen 1982)—does not provide a clear and tested approach in management that can be recommended as part of a "technological package" for optimizing the productivity of Alfisols under rainfed conditions. In particular, land- and soil-management techniques that are effective in reducing runoff and erosion, imparting structural stability to the soil, improving water-storage characteristics, and reducing sealing and crusting are yet to be defined.

There are clear indications, however, that most SAT Alfisols do possess a much higher productivity potential than that indicated by yields obtained through traditional farming (shown earlier). Randhawa and Venkateswarlu (1980) report yields of 3500 kg ha^{-1} for hybrid sorghum, 1500 kg ha^{-1} for improved castor, and 2700 kg ha^{-1} for finger millet on Rhodustalfs in southern India. The results of research on physical components that were found promising for improving productivity are discussed below.

Land smoothing and installation of field drains are essential for improved management of Alfisols. Landscapes common in farmers' fields are generally quite uneven, with many depressions of various sizes. Small, surface depressions that are obliterated through normal tillage operations are not subject to waterlogging. But large depressions are generally more stable and act as receiving basins for erosional sediments. Once these sediments are deposited, waterlogging often results. Crop yields from such areas were 10-35% less than that from other areas (Pathak 1981, unpublished report, ICRISAT). Uneven land surfaces also create problems in carrying out various agricultural operations, e.g., tillage or planting, at the proper depth. Higher germination percentages were recorded for pearl millet and sorghum in fields with proper smoothing as compared to those without (Pathak 1981, unpublished report, ICRISAT). To alleviate the influence of such depressions, it is necessary to smoothen the land surface, and this is done most efficiently in the direction of planned cultivation.

Since high runoff is frequent on Alfisols, provision must be made for early and safe removal of excess runoff during the growing (rainy) season. The urgency to reduce runoff must be tempered by the need to improve surface drainage during wet periods, in view of the fact that the profile's capacity for water storage is often very limited. Also, the need to reduce or enhance runoff must be assessed, keeping in view a predetermined strategy for water-resource development and use. Should surface storage of excess runoff water for supplemental irrigation be determined as the feasible alternative, the system should be designed to yield and store sufficient runoff for this purpose. Conversely, maximum water entry into the soil should be facilitated through various ponding techniques when accessible subsurface water storage is possible.

Tied ridging (installation of furrow-dams) has been extensively tried in the African SAT as an in situ soil- and water-conservation system. Under certain circumstances, the system not only helped reduce runoff and soil loss but also increased crop yields (Lawes 1961 and 1963, and Dagg and Macartney 1968). However, during high rainfall years, or in years when relatively long periods within the rainy season were very wet, significantly lower yields were reported from systems using tied ridges than from graded systems that disallowed surface ponding of water (Lawes 1963, Dagg and Macartney 1968). Under such conditions, tied-ridging enhanced waterlogging, development of anaerobic conditions in the rooting zone, excessive fertilizer leaching, and rise of the water table in lower-slope areas (Kowal 1970).

Hudson (1971) expresses serious concern about overtopping of tied ridges, and emphasizes that these systems should be designed so that the ties are lower than the ridges, which should themselves be graded so that excessive runoff is released along the furrow and not down the slope. Further, a support system of conventional contour terraces must be installed to cope with runoff from exceptional storms. Lawes (1961, 1963, and 1966) compared the performance of alternative designs: with open free-draining furrows, alternate cross-tied furrows, all furrows cross-tied, and all furrows cross-tied with mulch. His results showed that tying alternate furrows alone, or tying all furrows in combination with mulching, significantly improved yields of cotton compared with open furrows and tied unmulched furrows in both dry and wet seasons (889 mm and 1303 mm rainfall). With groundnut and sorghum, the effects of treatment were less prominent.

The comparative advantages of other land configurations for effective soil and water conservation have been the subject of many investigations (Pathak et al. 1985). In significant contrast to Vcrtisols, Alfisol watersheds under the BBF system generated decisively more runoff and soil loss than various flat culture designs tested. Table 6 shows the superiority of the flat systems with contour or graded bunds, over BBF and traditional methods. These trends were confirmed for both low- and high-rainfall years (Table 7). These results were attributed to the tendency of BBF-shaped fields to undergo surface smoothing along the slope resulting in low surface depression, and exposure of soil layers with low infiltration rates (e.g., the argillic horizon) while constructing furrows. In the BBF system nearly one-third of the land area is in furrows, with initial infiltration rates about one-third of those on undisturbed soil. Alfisols differ from Vertisols in yet another way: small and moderate storms (arbitrarily defined as those with <90 mm rainfall) contribute a major share of seasonal runoff (34-69%) and soil loss (45-75%) on BBF. For large storms, there was little difference between the various land configurations (Pathak et al. 1985).

The flat-on-grade system was not only most effective in reducing runoff and soil loss but also produced slightly higher crop yield than the other land configurations (Table 8). Raised land configurations (broadbed-and-furrow, narrow-ridge-and-furrow, and wave-type broadbed-and-furrow) offered no particular advantages in terms of

Table 6. Effects of alternative land-management systems on annual runoff, soil loss, and peak runoff rates from Alfisol watersheds (average annual values, 1975-79).

Treatments	Rainfall (mm)	Runoff (mm)	Runoff %of seasonal rainfall	Peak runoff rate[1] (m^3 s^{-1} ha-')	Soil loss (t ha')
Flat with graded bunds at 0.6% slope	837	135	16,1	0.14	1.87
BBF at 0.6% slope	831	238	28.6	0.25	3.40
Flat with contour bunds	836	110	13.2	0.10	0.85
Traditional flat with fanners* field bunds[2]	790	165	20.9	0.15	2.52

1. Maximum peak runoff rate, 1975-79.
2. Watershed monitored from 1976 to 1979. Values reported are based on these 4 years.
Source: Pathak et al. 1985.

Table 7. Annual rainfall, runoff, soil loss, and peak runoff rate for an Alfisol in sa flat, graded-bunds system and a BBF system (1975-79).

	Flat with graded bunds at 0.6% slope				BBF at 0.6% slope			
Year	Rain-fall (mm)	Runoff %of seasonal rainfall	Peak runoff rate (m^3 s^{-1} ha-')	Soil loss (t ha-')	Rain-fall (mm)	Runoff %of seasonal rainfall	Peak runoff rate (m^3 s^{-1} ha-')	Soil loss (t ha^{-1})
1975	1103	15.0	0.13	2.10	1104	27.9	0.20	4.20
1976	662	21.2	0.14	2.00	684	27.9	0.25	2.81
1977	549	5.3	0.06	0.56	563	14.2	0.10	1.13
1978	1048	19.8	0.13	2.81	1060	33.6	0.17	5.00

Source: Pathak et al. 1985.

Table 8. Effects of land management on runoff, erosion, and crop yields on Alfisols. (Average of 1981-82 and 1982-83.)[1]

Land treatments	Crop yield (kg ha-')	Pigeonpea (kg ha-')	Runoff (mm)	Soil loss (t ha-')
Broadbed-and-furrow at 0.4%	2545	775	272	3.56
Narrow ridge-and-furrow at 0.4%	2560	785	296	3.20
Flat-on-grade at 0.4%	2710	825	186	2.10
Flat-on-grade plus ridging-up later at 0.4%	2690	820	215	2.61

1. Total rainfall = 921 mm. Source: Pathak 1984.

runoff, soil loss, and yield over the flat-on-grade system. They also posed problems resulting from low stability and complications in accomodating certain crop combinations. In raised-land configurations, the expected benefits of high infiltration rates in the planting zone, and reduced velocity of overland flow, seemed to be counteracted by the extremely low surface-depression storage and by other problems resulting from turning the soil and exposure of the compact argillic horizon in the furrow zone. Thus, in Alfisols, unless furrow irrigation is required, the flat-on-grade configuration is probably the most effective.

Operational-scale research at ICRISAT, over a period of 6 years, has confirmed that clear benefits to soil and water conservation, and substantial increases in crop yield, can be obtained by using a number of improved management practices (Pathak 1984). Among these, the modified contour-bund system that includes gated outlets, involves land-smoothing and planting on grade instead of on contour, is the most promising (Table 9). In addition to a low annual runoff of 162 mm and soil loss of 1.38 t ha^{-1}, this system has been found to increase pearl millet yield by 19% and that of pigeonpea by 16%, compared with the BBF system (pearl millet yield, 1920 kg ha^{-1}; pigeonpea yield, 940 kg ha-').

Table 9. Effects of different systems of farming on runoff and soil loss on Alfisol watersheds, 1981.

Treatment	Runoff (mm)	Soil loss (t ha-')
Traditional system	248	4.68
Contour bund system	92	1.01
Modified contour bund system	162	1.38
Broadbed-and-furrow system	298	4.12

Total rainfall - 1094 mm. Source: Pathak 1984.

There is considerable evidence to show that the tillage operations (particularly primary tillage) selected should be appropriate if continuous cropping of SAT Alfisols is to be successful. This is in contrast to the humid tropics where considerable success has been reported with minimum tillage (Lal 1977 and 1980). Intensive primary tillage of SAT Alfisols was generally found necessary for creating a favorable zone for root proliferation, and for enhancing rainfall acceptance by the soil. Secondary tillage operations are necessary for seedbed preparation, and for weed control because herbicide use is still limited in the SAT. Since these soils generally undergo severe hardening during the dry season, cultivation is difficult before the rainy season. When powerful implements are utilized to permit plowing in dry conditions, the results are generally undesirable as large hard clods are created that necessitate further intensive tillage to produce a suitable seedbed (Rawitz et al. 1981). When cultivation must await the moistening of the topsoil, the effective length of the growing season is appreciably reduced and the farmer has to conduct all the required operations within a short period. Plowing at the end of the cropping season can, in some circumstances, be used to overcome these problems. Studies at Raichur (India) showed that Alfisols subjected to summer plowing had a higher rainfall-intake capacity than soils that were not (Hadimani and Perur 1971). Even shallow surface cultivation was found to be of advantage in helping the early rainwater to soak deeply into the soil. Hadimani et al. (1982) observed that rainwater penetrated to a depth of 30 cm in harrowed plots, but to only 15 cm in adjacent unharrowed plots.

The benefits of intensive tillage in terms of crop performance have been documented on many Alfisols. In Senegal, with shallow hoe cultivation the bulk density of the top few centimeters of soil decreased from 1.6 to 1.4 g cm^{-3}. With plowing by tractor the same benefits were effected to a depth of 10-30 cm (Charreau and Nicou 1971, Charreau 1972). In these soils, a decrease of 0.1 g cm^{-3} in bulk density significantly benefited root development and crop yields. Blondel (1967), Charreau and Nicou (1971), and Nicou and Chopart (1979) found very clear relationships between bulk densities—as reflected by porosity changes and various indices of root development (Fig. 4)—and final crop yields. Nicou and Chopart (1979) have shown that the proliferation of the root systems of sorghum, millet, and groundnut could be increased from 40% to more than 200% in soil depths down to 1 m or more through cultivation that need not even be deep. Nicou (1972) has made similar observations. These researchers hypothesized that even limited tillage was sufficient to enhance rapid and deep root establishment by the crop, thereby allowing it to escape the effects of detrimental dry spells early in the rainy season. Water losses through evaporation are considerable from deeply tilled Alfisols, and this may prove detrimental when rainfall is limited. Klaij (1983) demonstrates the need for ensuring good seed-soil contact by pressing the soil after sowing to allow adequate crop establishment on Alfisols. He also showed that an intensive form of tillage (split-strip plowing) can help increase crop yields.

Management of soil crusts for improving seedling emergence and crop stand on rainfed Alfisols is gaining increasing importance (Klaij 1983). Strong

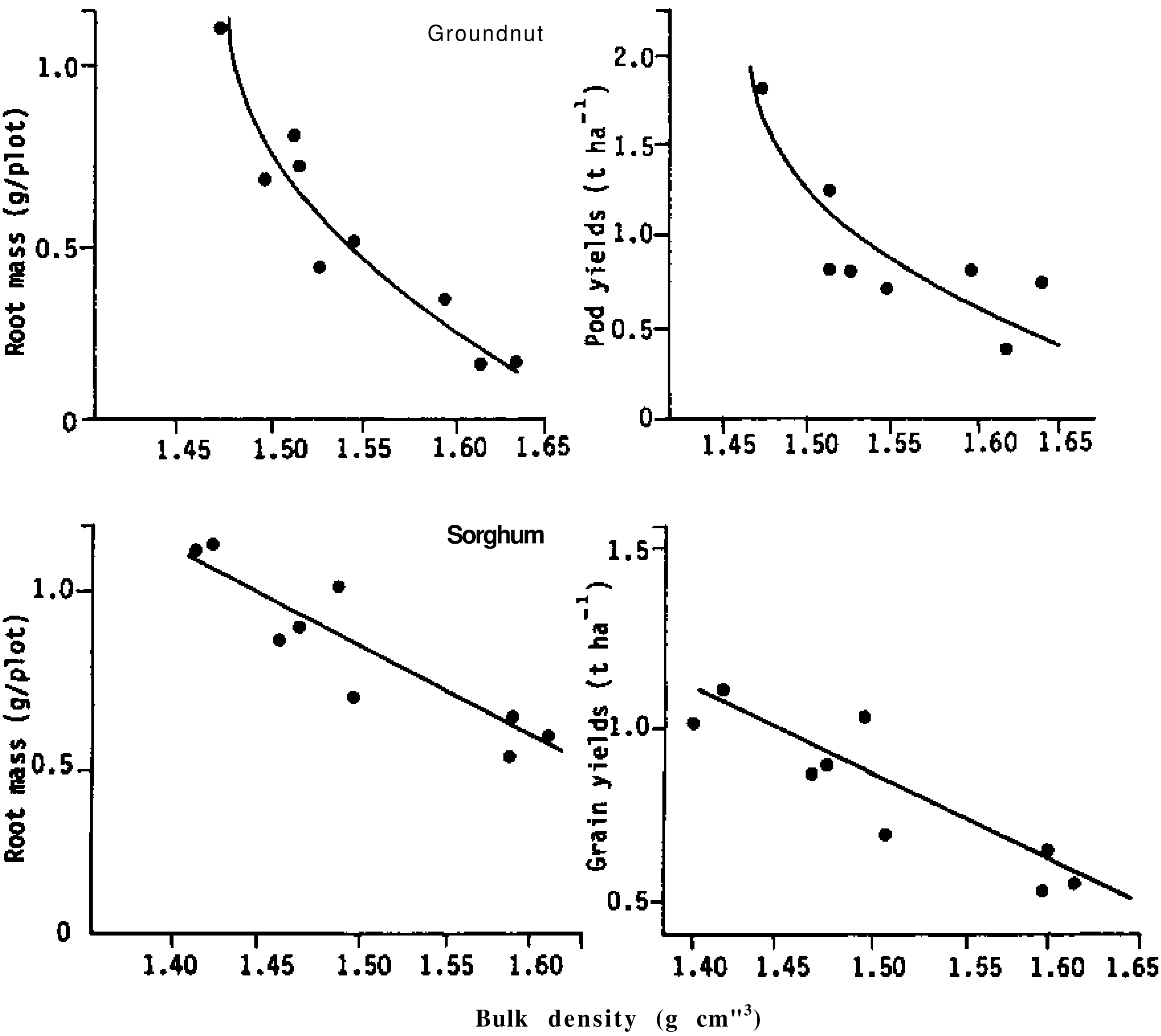


Figure 4. Relationships between bulk density, root development, and yields of groundnut and sorghum in sandy Alfisols at Bambey, Senegal.

surface crusts develop when seals created by rainstorms are subjected to rapid drying under direct sunlight. It has been found that a rolling crust-breaker with spokes mounted at precalculated positions can substantially improve seed emergence (in the case of susceptible seeds) when available soil moisture is not a limitation to growth (Awadhwal and Thierstein 1983). Soman et al. (1984) have developed a simple technique for field screening of genetic resistance of millet and sorghum to emergence through soil crusts. Little investigation to date has been done on the effects of chemical amendment on the strength of crusts formed on these soils. The benefits of increased shallow intercultivation—conducted frequently to break crusts subsequent to the normal practices—have been recently investigated. The practice was effective in increasing infiltration (Pathak 1984, Weststeyn 1983) and to some extent in reducing moisture losses through evaporation by producing a dust mulch. Breaking crusts reduced both runoff and soil loss (Table 10). During a high-rainfall year, no significant increase in crop yield was obtained from additional intercultivations. However, during normal and low rainfall years, crop yield increased significantly.

Addition of organic mulches on Alfisols was quite effective in reducing runoff and soil loss (Table 11). At ICRISAT, even in a high-rainfall year (1981), mulch applied at the rate of 10 t ha^{-1} reduced the seasonal runoff by 74% and soil loss by 80%, compared with the situation when no mulch was applied. In a normal rainfall year (1982), no significant runoff or soil loss was recorded from the mulch treatment (10 t ha^{-1}). During the same year a runoff of 205 mm and soil loss of 3.7 t ha^{-1} were recorded from the control treatment with no mulch added.

Table 10. Effects of shallow interrow tillage and landshaping on runoff and soil loss from an uncropped Alfisol, ICRISAT Center, 1981.

Tillage system		Runoff	Soil loss
Depth	Land shaping	(mm)	(t ha^{-1})
Shallow	Flat	138	3.2
	BBF	168	5.9
Nil	Flat	214	3.6
	BBF	289	8.9
SE		±8.2	±0.57

BBF = Broadbed-and-furrow system.

Table 11. Effect of different levels of organic mulch[1] on crop yield, runoff, and soil loss on Alfisols, 1981.

	Intercrop system			
Mulch rate (t ha^{-1})	Sorghum yield (kg ha^{-1})	Pigeonpea yield (kg ha^{-1})	Runoff (mm)	Soil loss (t ha^{-1})
No mulch	2790	1340	391	5.93
2.5	2800	1390	295	3.44
5.0	2980	1500	208	2.40
10.0	3040	1810	101	1.19
SE	±116	±99	±4.9	±0.221

1. Groundnut shells. Source: Pathak 1984.

Addition of organic mulch also increased crop yields in a sorghum/pigeonpea intercrop system. In a high-rainfall year, the mulch applied at the rate of 10 t ha^{-1} increased the sorghum yield by 9%, and that of pigeonpea by 35% over the no-mulch treatment. In normal- and low-rainfall years, more substantial increases in sorghum yield were recorded. When groundnut shells were used, a mulch rate of 5 t ha^{-1} appeared to be the minimum needed for increasing crop yields.

Harnessing runoff or development of other water sources for supplemental irrigation is important for optimizing the productivity of Alfisols since these soils are often shallow and have a low water-retention capacity (Fig. 5). The benefits from supplemental irrigation in terms of increased and stabilized crop production on Alfisols have been impressive, even in dependable rainfall areas. The potential for delivering excess water to surface water-storage structures (tanks) or groundwater reserves is good since even improved cropping systems use only 30-55% of the seasonal rainfall. The remainder, or 45-70%, runs off or drains to deeper layers. Both can potentially be tapped for supplemental irrigation. The high runoff on Alfisols during the early part of the rainy season (Pathak et al. 1985) provides a dependable surface-water source for most of the season. An analysis of 6 years* data collected from three tanks on Alfisol watersheds (Pathak 1980) showed that these tanks held sufficient water for supplemental irrigation during dry spells. Even in 1977, when runoff was the lowest in 9 years (1974-82), more than 35 mm of water was present in the tanks during periods when the probability of drought was high. In all years, a minimum of 50 mm of water was available in the tanks during 80% of the

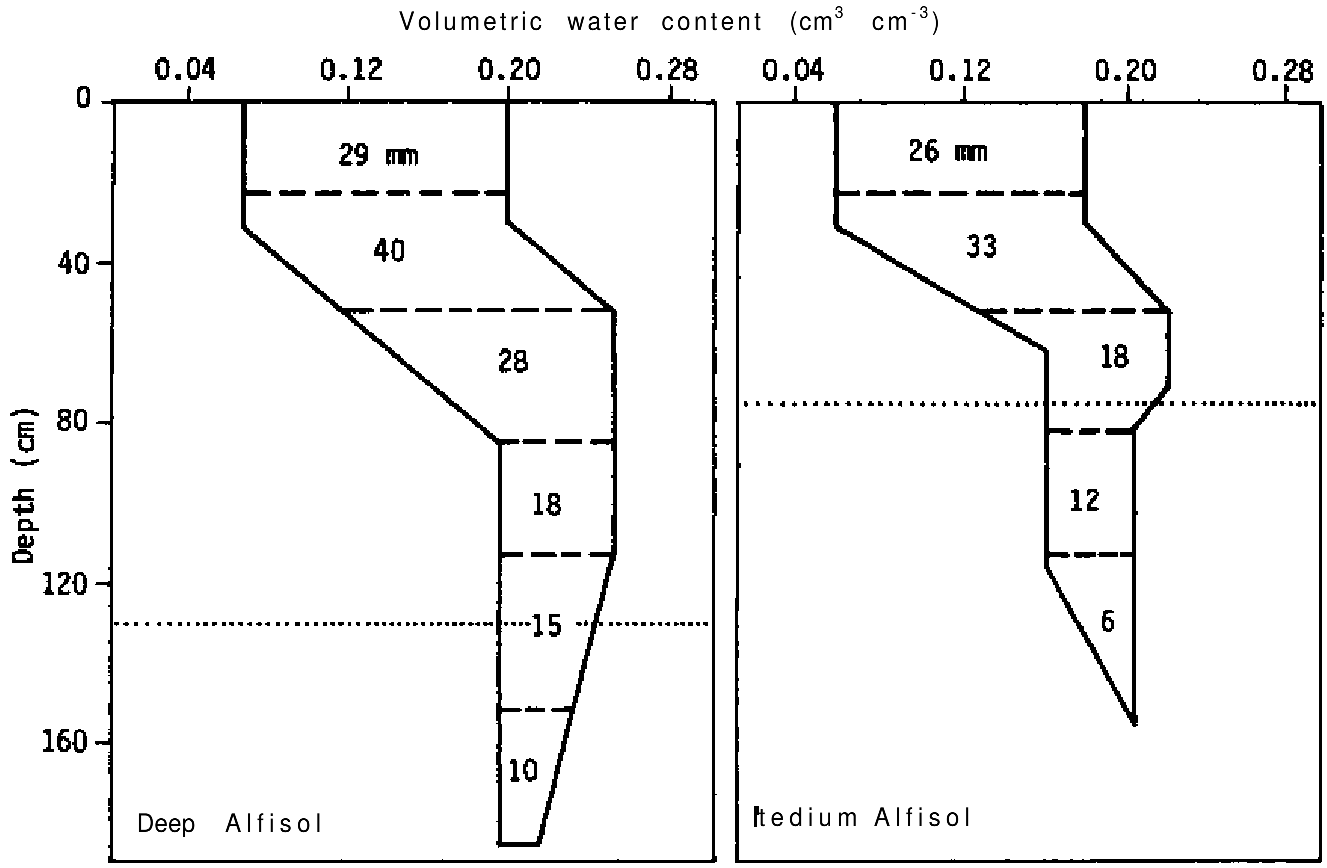


Figure 5. Available water profiles for deep (> 1 m) and medium (1.0-0.5 m) Alfisols at ICRISAT Center. The dotted lines represent the approximate lower end of the soil layer and the top of the murrum layer.

crop-growing period, and 75 mm during 30% of the period. However, tank storage can often be hampered by the high seepage rates in Alfisols.

Research is still in progress to determine the most feasible sealing materials and techniques (Maheshwari 1981). Analysis has shown that tanks can supply water needed for supplemental irrigation only when the average seepage rate is below 15 mm day^{-1}. A long-term analysis using runoff modeling (Pathak et al. 1984) showed that the probability of having 4 cm of water in July during periods of high drought probability is 70%, while in August, September, and October, the probability exceeds 92%. Ryan and Krishnagopal (1981) have determined that surface-water collection and storage potential for Alfisols at Hyderabad, India, was superior to that for Vertisols.

Data at ICRISAT indicate that supplemental irrigation increased yields in both the rainy and postrainy seasons (Pathak 1984). During the 1981 rainy season, good responses were obtained to supplemental irrigation of pearl millet, sorghum, and groundnut (Table 12). This table also shows that, as expected, the response to supplemental irrigation during 1982—a high-rainfall year—was quite low. In the postrainy season, the response to supplemental irrigation was significant in both years (Table 13). Deep-rooted crops, such as pigeonpea and castor, responded only to larger applications. Two irrigations, each of 4 cm, were therefore required.

It should be emphasized at this point that buildup of organic-matter levels is essential to impart favorable physical and chemical properties to these soils, and to improve productivity. The organic-matter contents of SAT Alfisols undergo a rapid decline when virgin lands are brought under cultivation. The decline of soil organic matter to a new equilibrium level is determined by the mode of land clearing, environmental conditions, and the farming system in use. As much as 40 t ha^{-1} of soil organic matter are reported to have been lost from the 0-20 cm horizon of Alfisols following clearing and 15 years of continuous cultivation (Charreau and Fauck 1970). The loss was maximum in the first 6 years and then it tapered off, reaching a relatively stable level which, under conventional cropping, is very low. This decline is primarily due to the fact that crop residues and farmyard manure are valued in

Table 12. Crop responses on Alfisols at ICRISAT Center to the application of 4 cm of supplemental irrigation[1] water during rainy-season droughts.

Year and irrigation date	Yield (kg ha^{-1})					
	Pearl millet		Sorghum		Groundnut	
	Control (no irrigation)	With supplemental irrigation (grain filling stage)	Control (no irrigation)	With supplemental irrigation (flowering stage)	Control (no irrigation)	With supplemental irrigation (pegging stage)
1981 (23 Aug)	2100	2710	2820	3218	690	1050
1982(20 Aug)	1630	1725	I	I	686	890

1. Sorghum was not grown in 1982. Source: Pathak 1984.

these regions for competitive uses other than return to the soil. However, both should be considered necessary components for enhancing organic-matter buildup and thereby contributing to enhanced productivity of Alfisols in the short term.

In the long term, strong clues for successful cropping and sustained productivity of Alfisols may be derived from experience gained in the humid tropics and temperate, semi-arid areas. In the humid tropics, these soils appear to be more amenable to management for sustained agricultural productivity than in the SAT. Considerable success has in fact been reported with minimum tillage, generous inputs of residues (e.g., mulching), and the application of herbicides within the cropping systems. The dependence on herbicides is necessarily heavy. The abundant water supply in these regions encourages some form of vegetative growth and overall biological activity throughout the year. Only certain types of vegetation are able to sustain themselves with significant viability despite the annual intense dry period in the SAT, particularly on Alfisols. Selected, fast-growing trees have this potential, and have been recommended for inclusion with conventional cropping systems in agroforestry schemes in the tropics. Cropping systems that capitalize on the attributes of such trees to the ultimate benefit of both the soil and the farmer are currently under increasing investigation in the SAT (Lundgren and Nair 1983).

Another strategy that has been favored for improving SAT Alfisols involves the combination of legume-ley farming and grazing animals (Jones and McCown 1983). Preliminary results indicate that this system, which has proved successful in the temperate regions of Australia, appears promising when the following features are included: (1) a self-

Table 13. Crop responses on Alfisols at ICRISAT Center, to the application of 4 cm of supplemental irrigation water during the postrainy season.

Year	Yield (kg ha-')											
	Pigeon pea			Castor			Cowpea			Tomato		
	Control	Once-irrigated (flowering stage)	Twice-irrigated (flowering & podding stages)	Control	Once-irrigated (flowering stage)	Twice-irrigated (flowering & podding stages)	Control	Once-irrigated (veg. stage: 30 days)	Twice-irrigated (veg. and flowering stages)	Control	Once-irrigated (veg. stage: 30 days)	Twice-irrigated (veg. and flowering stages)
1981-82	660	790	1120	715	920	1280	310	665	725	9600	14400	23200
1982-83	850	910	1185	795	870	1335	500	685	795	13100	17500	29300

Source: Pathak 1984.

generating legume-ley pasture for 1-3 years grown in rotation with a cereal; (2) allowing cattle to graze on native grass pastures during the wet season and leguminous pastures in the dry season; (3) planting crops directly into the pasture after it has been herbicide-killed; and (4) allowing volunteer pasture legume sward from hard seed to form an understory in the main crop. In contrast to conventional Alfisol cropping this system allows implementation of minimum tillage concepts.

Final Remarks

It must be emphasized that a balanced approach to soil and water conservation and optimization of productivity should be followed in future research strategies for Alfisols (El-Swaify 1983). In view of the specific nature of this workshop's objectives, our discussions were restricted to a review of management options. The need for base-line data that allow quantitative and integrated watershed-based planning also merits equal emphasis.

References

Awadhwal, N.K., and Thierstein, G.E. 1983. Development of rolling-type soil crust breaker. Agricultural Mechanization in Asia, Africa and Latin America 14(4);31-34.

Binswanger, H.P., Virmani, S.M., and Kampen, J. 1980. Farming systems components for selected areas in India: evidence from ICRISAT. Research Bulletin no. 2. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. 40 pp.

Blondel, D. 1967. Premiers elements sur rinfluence de la densite apparente du sol sur la croissance racinaire de 1'arachide et du sorgho—ses consequences sur les rendements. Pages 173-181 in Proceedings of the OAU/STRC Symposium on the Maintenance and Improvement of Soil Fertility, 8-12 Nov 1965, Khartoum, Sudan. Publication no. 98. London, UK: Organisation of African Unity, Scientific, Technical and Research Commission, Publications Bureau.

Charreau, C. 1972. Problemes poses par 1'utilisation agricole des sols tropicaux pardes cultures annuelles. Agronomic Tropicale 27(9):905-929.

Charreau, C, and Fauck, R. 1970. Mise au point sur 1'utilisation agricole des sols de la region de Sefa (Casamance). Agronomic Tropicale 25(2): 151-191.

Charreau, C, and Nicou, R. 1971. L'amelioration du profil cultural dans les sols sableux et sablo-argileux de la zone tropicale seche ouest-africaine et ses incidences agronomiques (d'apres les travaux des chercheurs de I'IRATen Afrique de l'Ouest). Agronomie Tropicale 26:209-255,565-631,903-978, 1183-1247.

Dagg, M.,and Macartney, J.C. 1968. The agronomic efficiency of the NIAE mechanized tied ridge system of cultivation. Experimental Agriculture 4:279-294.

El-Swaify, S.A. 1983. Conservation-effective farming systems for the semi-arid tropics. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. 48 pp. (Limited distribution.)

El-Swaify, S.A., and Dangler, E.W. 1977. Erodibilities of selected tropical soils in relation to structural and hydrologic parameters. Pages 105-114 in Soil erosion: prediction and control. SCSA Special Publication no. 21. Ankeney, Iowa, USA: Soil Conservation Society of America.

El-Swaify, S.A., and Dangler, E. W. 1982. Rainfall erosion in the tropics: a state-of-the-art. Pages 1-25 in Soil erosion and conservation in the tropics. ASA Special Publication no. 43. Madison, Wisconsin, USA: Soil Science Society of America.

El-Swaify, S.A., Dangler, E.W., and Armstrong, C.L. 1982. Soil erosion by water in the tropics. Research Extension Series no. 024. Honolulu, Hawaii, USA: University of Hawaii, Institute of Tropical Agriculture and Human Resources. 173 pp.

Hadimani, A.S., Hegde, B.R., and Satyanarayana, T. 1982. Management of red soils. Pages 689-700 in Review of soil research in India. Pt 2. New Delhi, India: Indian Society of Soil Science.

Hadimani, A.S., and Perur, N.G. 1971. Measurement of infiltration rate in some of the soils of the Tungabhadra Project Area. Journal of the Indian Society of Soil Science. 19:231-235.

Hudson, N.W. 1971. Soil conservation. Ithaca, New York, USA: Cornell University Press.

Jodha, N.S. 1980. Intercropping in traditional farming systems. Journal of Development Studies 16:427-442.

Jones, M.J. 1973. The organic matter content of the savanna soils of West Africa. Journal of Soil Science 24:42-53.

Jones, R.K., and McCown, R.L. 1983. Research on a no-till, tropical legume-ley farming strategy. Research Report S/10. Townsville, Australia: Commonwealth Scientific and Industrial Research Organization, Division of Tropical Crops and Pastures.

Kampen, J. 1980. Watershed management and technology transfer in the semi-arid tropics. Pages 111-120 in Proceedings of the International Symposium on Development and Transfer of Technology for Rainfed Agriculture and the SAT Farmer, 28 Aug-1 Sep 1979, ICRISAT Center, India. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics.

Kampen, J. 1982. An approach to improved productivity on deep Vertisols. Information Bulletin no. 11. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. 14 pp.

Kampen, J., and Burford, J.R. 1980. Production systems, soil-related constraints and potentials in the semi-arid tropics with special reference to India. Pages 141-165 in Priorities for alleviating soil-related constraints to food production in the tropics. Los Banos, Laguna, Philippines: International Rice Research Institute.

Kan war, J.S. 1983. Red soils of the semi-arid tropics: problems, potentials and management. Presented at the Symposium on Red Soils, 15-19 Nov 1983, Institute of Soil Science, Academia Sinica, Naning, China. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

Klaij, M.C. 1983. Analysis and evaluation of tillage on an Alfisol in a semi-arid tropical region of India. Ph.D. thesis, University of Wageningen, Wageningen, Netherlands.

Kowal, J. 1970. The hydrology of a small catchment basin at Samaru, Nigeria. III. Assessment of surface runoff under varied land management and vegetation cover. Nigerian Agricultural Journal 7:120-133.

Krantz, B.A., Kampen, J., and Virmani, S.M. 1978. Soil and water conservation and utilization for increased food production in the semi-arid tropics. Presented at the Eleventh International Congress of Soil Science, 19-27 June 1978, University of Alberta, Edmonton, Alberta, Canada. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. 22 pp. (Limited distribution.)

Lal, R. 1977. Soil management systems and erosion control. Pages 93-97 in Soil conservation and management in the humid tropics (Greenland, D. J., and Lal, R., eds.). New York, USA: John Wiley.

Lal, R. 1980. Physical and mechanical characteristics of Alfisol and Ultisols with particular reference to soils in the tropics. Pages 253-274 in Soils with variable charge (Theng, B. K. G., ed.). Lower Hutt, New Zealand: Department of Scientific and Industrial Research, Soil Bureau.

Lawes, D.A. 1961. Rainfall conservation and the yield of cotton in northern Nigeria. Empire Journal of Experimental Agriculture 29:307-318.

Lawes, D.A. 1963. A new cultivation technique in tropical Africa. Nature 198:1328.

Lawes, D.A. 1966. Rainfall conservation and yields of sorghum and groundnuts in northern Nigeria. Experimental Agriculture 2:139-146.

Lundgren, B., and Nair, P.K.R. 1983. Agroforestry for soil conservation. Presented at the International Conference on Soil Erosion and Conservation, 16-22 Jan 1983, Honolulu, Hawaii, USA.

Maheshwari, B.L. 1981. Evaluation of some low-cost tank sealing techniques for seepage control. M.S. thesis, Asian Institute of Technology, Bangkok, Thailand.

Nicou, R. 1972. Synthese des etudes de physique du sol realises par l'IRAT en Afrique tropicale seche. Seminar on Tropical Soils Research. Ibadan, Nigeria: International Institute of Tropical Agriculture. 19 pp.

Nicou, R., and Chopart, J.L. 1979. Root growth and development in sandy and sandy clay soils of Senegal. Pages 375-384 in Soil physical properties and crop production in the tropics (Greenland, D.J., and Lal, R.,eds.). New York, USA: John Wiley.

Pathak, P. 1980. Runoff collection, storage and groundwater recovery: research project report presented at the ICRISAT In-house Review. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

Pathak, P. 1981. Integrated operational-scale research on Alfisol watersheds: research report. Patancheru, A.P. 502 324 India: International Crops Research Institute for the Semi-Arid Tropics (Limited distribution.)

Pathak, P. 1984. Optimized land management system for Alfisols: research project report presented at the ICRISAT In-house Review. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

Pathak, P., Miranda, S.M., and El-Swaify, S.A. 1985. Improved rainfed farming for the semi-arid tropics: implications for soil and water conservation. Pages 338-354 in Soil erosion and conservation (El-Swaify, S.A., Moldenhouer, W.C., and Lo, A., eds). Iowa, USA: Soil Conservation Society of America.

Pathak, P., Murthy, V.V.N., El-Swaify, S.A., Singh, S., and Sudi, R. 1984. Runoff model for small semi-arid watersheds. Presented at the XXI Annual Convention of Indian Society of Agricultural Engineers, 5-7 Apr 1984, IARI, New Delhi, India. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics (Limited distribution.)

Randhawa, N.S., and Venkateswarlu, J. 1980. Indian experiences in the semi-arid tropics: prospect and retrospect. Pages 207-220 in Proceedings of the International Symposium on Development and Transfer of Technology for Rainfed Agriculture and the SAT Farmer, 28 Aug-1 Sep 1979, ICRISAT Center, India. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

Rastogi, B.K., Reddy, Y.V.R., and Annamalai, V. 1982. Economic dimensions of dryfarming technology. Pages 181-198 in A decade of dryland agricultural research in India 1971-80. Hyderabad, Andhra Pradesh, India: All India Coordinated Research Project for Dryland Agriculture.

Rawitz, E., Hoogmoed, W.B.,and Morin, Y. 1981. Development of criteria and methods for improving the efficiency of soil management and tillage operations with special reference to arid and semi-arid regions: final report. Rehovot, Israel: Hebrew University, Faculty of Agriculture. 260 pp.

Ryan, J.G., and Krishnagopal, C. 1981. Assessing the economics of water harvesting and supplementary irrigation: a simulation approach. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics. 31 pp. (Limited distribution.)

Sanchez, P.A. 1976. Properties and management of soils in the tropics. New York, USA: John Wiley.

Sanghi, N. K., and Rao, S.B.P. 1982. Operational research in dryland agriculture. Pages 212-231 in A decade of dryland agricultural research in India, 1971-80. Hyderabad, Andhra Pradesh, India: All India Coordinated Research Project for Dryland Agriculture.

Soman, P., Peacock, J.M., and Bidinger, F.R. 1984. A field technique for screening seedling emergence in pearl millet and sorghum. Experimental Agriculture 20(4):327-334.

Swindale, L.D. 1982. Distribution and use of arable soils in the semi-arid tropics. Pages 67-100 in Managing soil resources. Plenary session papers. Transactions of the 12th International Congress of Soil Science, 8-16 Feb 1982, New Delhi, India. New Delhi, India: Indian Agricultural Research Institute.

Theng, B.K.G. (ed.) 1980. Soils with variable charge. Lower Hutt, New Zealand: Department of Scientific and Industrial Research, Soil Bureau. 448 pp.

USDA (United States Department of Agriculture), Soil Conservation Service, Soil Survey Staff. 1975. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. Agriculture Handbook no. 436. Washington, D.C., USA: US Printing Office. 754 pp.

Weststeyn, S. 1983. A study on the surface structure of an Alfisol and its stability: a study report submitted to the Training Program at ICRISAT. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

Soil Properties and Management in Botswana

J. Sinclair[1]

Abstract

Agricultural cultivation in Botswana is concentrated in the east and north of the country in the 450-550 mm a^{-1} rainfall zones. Most farmers broadcast seed and then bury it, using an animal-drawn moldboard plow. The soils are mostly sand to sandy loam texture, with high bulk densities and hardness when dry. The important cations are calcium, magnesium, and potassium, and the Emerson Dispersion Index is about 8. Considerable runoff from the early rains prior to planting can occur on unplowed land, delaying land preparation and planting. Problems of emergence and establishment are experienced with the main crop, sorghum, because of high soil temperature, waterlogging, and crust formation. Root growth and plant vigor can be increased by plowing deeper than the 10 cm usually managed by animal-drawn plows and, on a loamy sand soil, considerable residual effects have been observed more than a year after deep plowing. Many of the problems would be reduced if water loss could be prevented at the start of the season, and a loose surface layer maintained to ensure rapid drainage of excess water. Plowing after harvest is best to produce a cloddy tilth, but tied ridges may also be satisfactory. If the soil is particularly susceptible to crusting, planting seeds in groups may be worthwhile.

Agriculture in Botswana

The isohyet map of Botswana is shown in Figure 1. Agricultural cultivation is concentrated in the north and east of the country, in zones receiving on average rainfall of more than 450 mm a^{-1}. This rainfall, however, occurs mostly between October and April; hence, monthly means are low and may vary considerably.

The system of agriculture practiced is extensive. The plowing in of broadcast seed using animal draft is the most common planting method. In many cases, plowing at the time of planting is the first and only tillage since the previous year. The dominant cereal—sorghum—is grown in mixed stands, usually with a legume, maize, and cucurbita. Cowpea is the main legume.

The mean area planted is 3-7 ha per family. With animal draft planting this area will take several days—if not several planting rains—to complete. As a consequence, the conditions at the time of planting vary considerably. The multiple dates of planting have been described as a risk-reducing strategy but many farmers (22% of households in 1981) are now hiring tractors, which enables planting to be completed in 1 day.

In theory, planting could be carried out from mid-November, but often the poor condition of the draft animals prevents planting until late December. Since the land may remain unplowed and weedy during this period, much water may be lost through runoff and transpiration.

Yields are very low: they may be restricted to a few hundred kg from varieties of sorghum that may yield several tonnes under good management.

The Soils

Most soils used for arable farming in Botswana are in the sandy loam to loamy sand, or sand textural range. The Kalahari sands have a concentration of particles in the fine-sand range, but in the other soils a wide range of sand sizes are found.

1. Soil Physicist, Dryland Farming Research Scheme, P.O. Bag 0033, Gaborone, Botswana.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983. ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

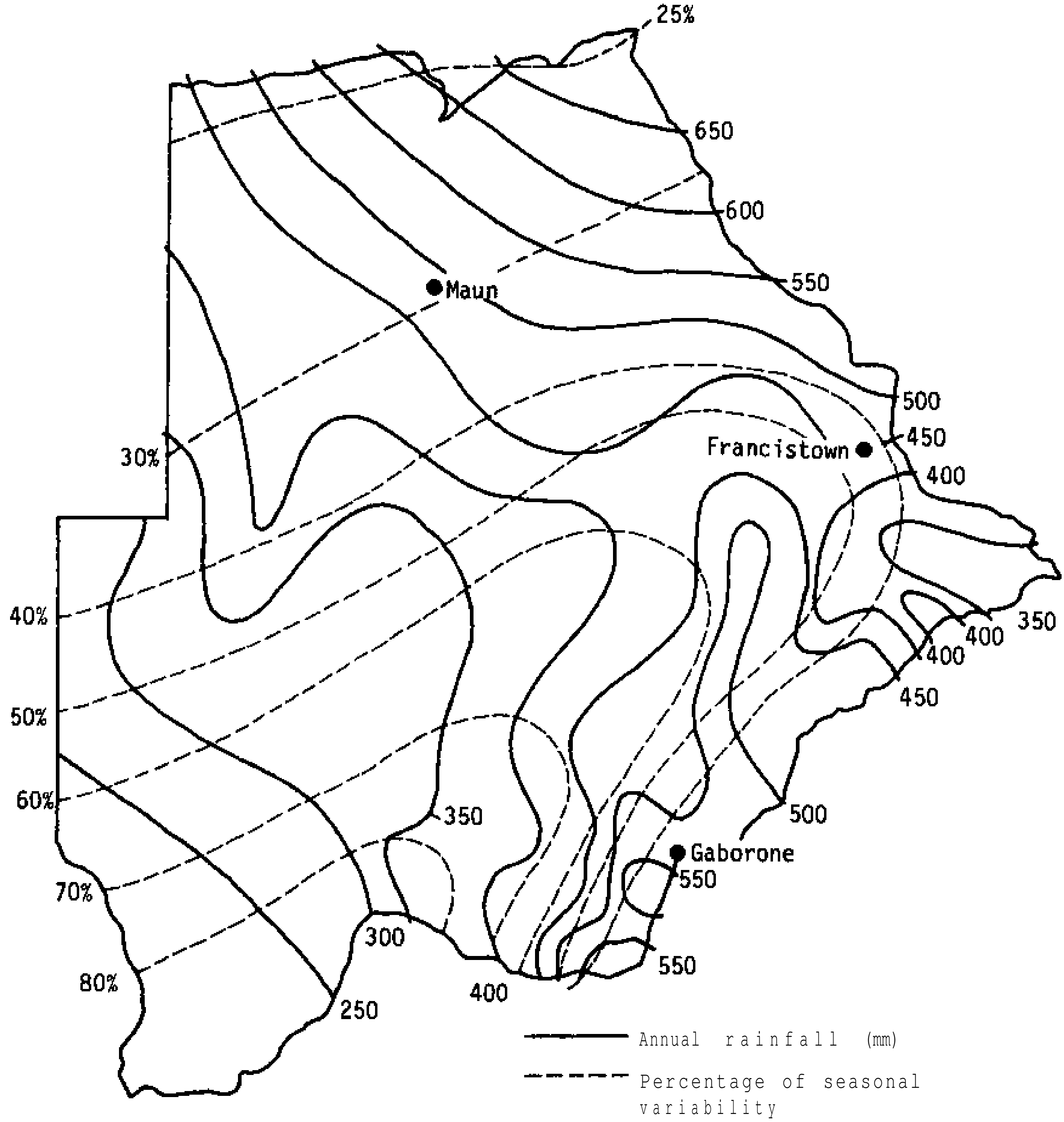


Figure 1. Mean annual rainfall and rainfall variability in Botswana (Source: Pike 1971.)

The soils arc characterized by their lack of structural stability: they set hard when dry but become very soft on wetting. This change is apparently completely reversible, suggesting thereby that there is no chemical cementation. They have relatively poor drainage and are liable to slump after heavy rain. The bulk densities in the undisturbed condition are about 1.65 Mg nr^3 for the sandy loams, and 1.7 Mg nr^3 for the loamy sands. Torsion vane measurements of shear strength of moist soil give values of 0.7-1.7 kg cm^{-2} for undisturbed soil. The properties of these soils can clearly present problems for the growth of plants.

About 30 soils from arable areas in Botswana were selected for a detailed study of their analytical and physical properties. Most of these soils fall in the Alfisol category, although a few are clay soils and Kalahari sands. Preliminary analytic results for the

Table 1. Properties of selected Alfisols from arable areas in Botswana						
	Soil group					
Sample size	Sand (4 soils)		Loamy sand (11 soils)		Sandy loam (8 soils)	
Particle size um	Mean	S.D.	Mean	S.D.	Mean	S.D.
2000-1000	10.6	3.3	10.0	3.6	9.2	4.8
1000-500	20.2	1.7	17.6	3.8	14.8	3.7
500-250	22.5	4.2	20.4	3.1	16.4	4.2
250-100	26.5	2.3	25.7	4.1	21.7	5.3
100-50	10.7	1.7	11.8	2.2	10.5	1.4
50-2	2.1	0.5	4.8	2.8	12.0	3.3
<2	6.5	0.9	8.2	1.0	11.9	3.2
Organic carbon %	0.17	0.04	0.27	0.10	0.46	0.17
pH(1:5 H_2O)	5.5	0.7	5.9	0.6	6.6	1.2
pH ($CaCl_2$)	4.3	0.6	4.6	0.6	5.5	1.3
C.E.C. meq 100 g^{-1} a.d.s.	1.7	0.2	2.4	0.7	6.5	2.9
Cations meq 100 g^{-1}	0.7	0.4	1.7	1.5	3.8	2.7
Ca	0.7	0.4	1.7	1.5	3.8	2.7
Mg	0.3	0.1	0.5	0.3	1.0	0.4
K	0.2	0.1	0.4	0.2	0.7	0.3
Emerson Dispersion Index	5.0	3.3	7.6	1.2	9.1	2.0
Bulk density (approx) Mg nr^3		1.7			1.6	
Water content (gravimetric) %						
0.033 MPa(l/3 bar)	4.5	1.0	6.1	1.2	10.6	1.6
0.1 MPa(l bar)	3.2	0.4	4.7	1.0	8.3	1.3
1.5 MPa(15 bar)	1.8	0.2	2.9	0.5	5.2	0.9

Alfisols and results from measurement of dispersion using the Emerson test are shown in Table 1. It should be noted that the sodium content of the soils is very low, and the only important cations are calcium, magnesium, and potassium. The sesquioxide content of the soils is not important. The results of the Emerson test are around 8, that is, the soils disperse completely when remolded after wetting at 100 cm H_20 tension. Emerson (1967) found that soils falling in this category contain significant amounts of hydrous mica (illite) in the clay fraction. The limited data available on the clays found in the soils of Botswana (Siderius 1973) showed hydrous mica and kaolin to be the important clays. Saturation of a group of soils with calcium or magnesium reduced dispersion of the clays, with the least dispersion shown by the calcium-saturated clay. This suggests that the percentage of potassium, or the acidity, may partially be responsible for clay dispersion in these soils. Investigations on the mechanical properties of these soils are still in progress.

Land Preparation and Runoff

Runoff up to 50% may occur on the <5% slope commonly found in Botswana. Simple measurements of depth of wetting of land, prepared in different ways, have been made on a few occasions, and some results are shown in Table 2. These results emphasize the importance of keeping the land open to receive rainfall. Prior to the growing season, it would seem that a cloddy tilth—if it can be

Table 2. Depth of moist soil (m) on sandy loam after a 34-mm shower.

Experiment A		Experiment B	
Plowed	0.35	Tied ridge furrow	0.24
Unplowed	0.10	Untied ridge furrow	0.17
		Flat unplowed	0.11

prepared—is as effective as tied ridges for allowing water to penetrate the soil. A major problem in preparing the land for planting can be the slow rate at which unplowed plots become wet to adequate depth.

Emergence

Emergence is the major problem with the sorghum crop. Once a reasonable plant population has been established, it appears that the crop can cope with other problems such as pests, diseases, and drought, to eventually produce a grain yield. The soil at the time of planting may be either too wet, too dry, too hot, too hard, or a combination of these. In Botswana, around planting time (November to mid-January), rainfall may be inadequate, or may occur in concentrated spells. If the surface of the field is uneven and runoff occurs, the low spots of the field may easily become too wet for seeds or seedlings to survive. The infiltration in these low spots is such that there may be standing water on them for several days after a heavy rain.

During periods of rain, the temperature usually drops to a reasonable level, but if hot weather returns after planting, the soil temperatures may rise quickly. Figure 2 shows soil temperature at 10 cm under bare soil over 3 years at the research station in Sebele. The period 1980/81 was generally cool, the temperature dropping to about 25°C during a period when there were good rains. The other 2 years had periods of high and low temperatures. While the temperature at 10-cm depth at 1400 will not be the same as the temperature at seed depth in a seedbed, it may reflect the sort of variability that can occur around the seed.

Experiments on germination and growth in moist soil at constant temperatures have shown the optimum temperature for germination to be 40° C, and the lethal temperature to be 45°C; then 37-55°C for subsequent growth. The lethal temperature for the germinating seed can clearly occur in the soil at seed depth; the higher temperature, which kills the shoot, can be found close to the soil surface. In a relatively open, rough seedbed, the soil will have much lower thermal conductivity than in a fine, slumped seedbed. The germinating seed in an open seedbed will not experience the same extremes of temperature as are apparent from the meteorological record.

In the 1982/83 season, heavy rains in November caused seedbeds to slump. Poor establishment of the crop was attributed to the soil being too wet and hot. In January, crop establishment on loose seedbeds was good despite similar temperatures. A loose seedbed will help emergence by enabling the seedling to avoid too close contact with the hot soil as it approaches the surface. The hardening of the surface soil as it dries after planting is frequently observed to contribute to poor or delayed emergence.

Pot experiments using a recording penetrometer have given a log-log relationship between water content and penetration resistance. The sandy loam and loamy sand soils can both attain a strength that prevents the emergence of seedlings after a few days of wetting. Other experiments have shown that, as might be expected, disturbance of a wet soil followed by rewetting can lead to greatly increased crust strength, even when the disturbance is at a wetness close to the wilting point. Table 3 shows the force on an upward-moving 1.5-mm diameter probe as the crust dries and thickens on an undisturbed soil, and on soil gently stirred when wet. The maximum values shown by direct measurement of the force exerted by a sorghum seedling were between 0.5 and 1.0 N, which are much less than crust strengths measured with a 1.5-mm diameter probe. Measurements of the shoot and root growth of a number of crop plants, and the penetration resistance of the soil at a range of bulk densities and water contents, show that growth is stopped when the penetration pressure of the probe reaches about 2 MPa. Placing a number of seeds together in the soil is a straightforward solution to the problem of crusting.

One experiment was carried out in the field using the 'Masdar' rotary jab planter. A number of seeds were planted in each hole. The results from two sorghum plantings, each on two different soils, are shown in Figure 3. Similar results were found for

Table 3. The maximum force (N) on a 1.5-mm diameter flat-ended probe going up through a soil crust.

		Time after wetting (days)			
Soil	Treatment	1	5	6	8
s L, Sebele	Disturbed	2	18	16	26
	Control	1	10	8	6
s L, Mahalapye	Disturbed	1	8	9	32
	Control	1	5	7	8
1 S, Sebele	Disturbed	5	2	8	22
	Control	2	2	7	5
1 S, Sebele	Disturbed	2	9	9	26
	Control	5	8	8	12

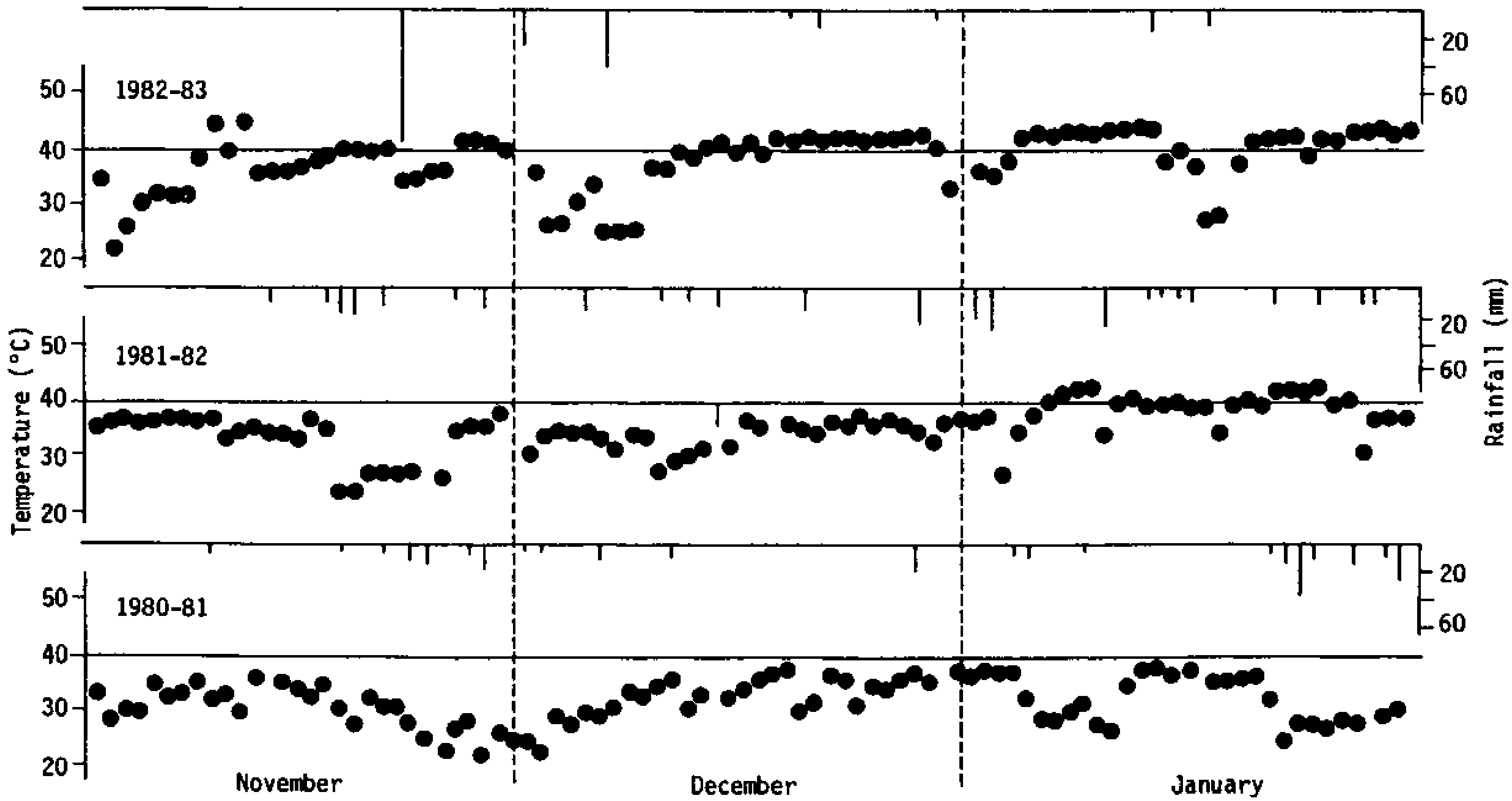


Figure 2. Daily rainfall and the temperature of bare soil at 10-cm depth at 1400 hours, Sabele Research Station, Botswana.

sunflower. The seeds were soaked for 12 h before planting or planted dry (as is normally done). The second planting developed excellent crusting conditions because 44 mm of rain fell on the planting day, and good drying conditions followed. The analysis of the results showed that establishment of 'hills' was

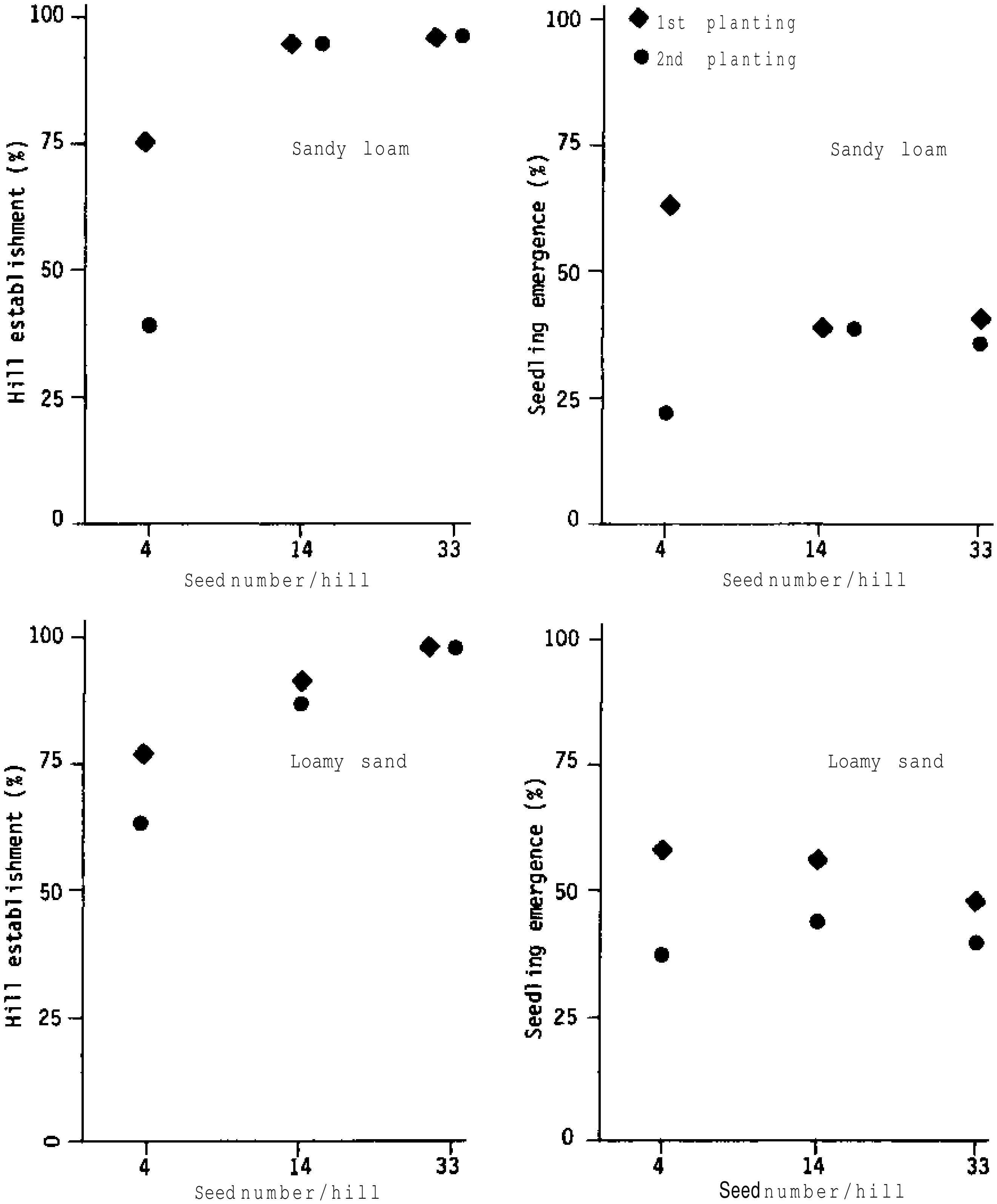


Figure 3. Seedling emergence and hill establishment for various seed rates for two sorghum plantings on two soils, Botswana.

significantly reduced in both the soils for the second planting at the lowest seed rate. The total seedling emergence significantly decreased at the lowest seed rate on the sandy loam soil. Soaking seed produced no significant differences in establishment, although soaked seed generally gave lower values than unsoaked. On the 4th day after the second planting, however, emergence of soaked seed improved significantly. The data for soaked seed agreed with those from experiments carried out in the previous 2 years.

From these results it appears that planting more than 10 seeds together could help crop establishment under capping conditions in the sandy loam soil, and produce an even stand in loamy sand soil.

Roots

Roots are essential to support the plant, and to supply water and nutrients. It has been observed that if a dry spell follows planting, the primary adventitious roots may not be able to penetrate the soil, and the plants may even be pushed out of the soil, breaking existing roots. The supply of water by roots was studied using the neutron probe to give information on the uptake of water by the plant. The roots were directly sampled in experiments where the soil had been tilled to different depths: zero tillage, shallow tillage (10-15 cm), and deep tillage (20-30 cm).

Experiments were conducted with deep tillage in one year, followed by zero or shallow tillage the next, to discover whether there was any residual effect of deep tillage. Results from both the neutron probe and from root sampling showed that deep tillage had a residual effect.

Table 4 shows results from root sampling of two experiments over 2 years. The sandy loam data for 1980/81 showed a greater length of root in the surface 10 cm of the soil in previously shallow-tilled plots, while in the 10-20 cm depth range, the mass of the root was greater in deep and previously deep-tilled plots. These results are explicable if tillage treatments C and D caused the primary adventitious roots to be shorter, and root proliferation to be shallower and closer to the plant than treatments A and B. Some of the samples from A were almost entirely composed of primary roots. The greater length of roots at 0-10 cm in C implies that the roots were closer to the plant, indicating that they had greater difficulty growing away from the plant than in other treatments. It should be noted that discing and sweeping at about 10 cm depth in previous years are presumed to have had some compacting effect on

Table 4. Roots sampling on two tillage trials.

Root measurements, 1981, day 60 sandy loam						Loamy sand 1981/82, about 120 days after planting			
							Depth of planting (cm)		
Tillage 81 depth (cm)	Tillage Pre-81 depth (cm)	Sample depth (cm)	Root length, cm cm^{-3} soil	Root weight, mg cm^{-3} soil	Specific length, m g^{-1} root	Soil depth (cm)	25 Deep Root length (cm cm^{-3})	10 Shallow Root length (cm cm^{-3})	Zero Root length (cm cm^{-3})
20*	20*	0.10	1.04 } **	0.28	26.5 } ***	0-20	.52	.38	.72
10*	20'		1.96 }	0.31	62.8 }	20-40	.20	.06	.05
10*	10+		2.93 } **	0.24	72.7 } **	40-60	.24	.05	.22
10*	10∘		2.18 }	0.23	93.2 }	60-80	.28	.07	.08
						80-100	.08	.05	.07
Implement/treatment 10-20			0.75	0.08	92.2 } ***				
* moldboard (A)			0.83	0.07	128.2 }				
' chisel (B)			0.72	0.05 ***	165.8 ***				
+ disc (C) ∘ sweep (D)			0.67	0.03	158.0				

the soil. Hence, the residual effect of the shallow mold board plowing after the deep chiseling may appear anomalously great.

The second set of results in Table 4 is from a loamy sand where the field was brought into use after some 5 years of grass-growing. The results clearly showed the effect of deep plowing on subsequent root growth: an effect manifest in the form of greatly increased root length in the deep-plowed plots. The results from moisture measurements agreed with the results from root-sampling, with greater depletion of water in the deep-plowed plots.

In the 2nd year of the tillage experiment, shallow or zero tillage was introduced on previously deep-plowed plots to study the residual effect of deep plowing. Root sampling was carried out soon after planting. The results in this case were less clear than in the previous year.

On sandy loam, root length was greater in the deep-plowed plots of the current year, but no residual effects were found in the root lengths. Measurements of plant height and soil strength revealed a similar pattern.

In the loamy sand trial, roots in plots that had not been deep-plowed were less developed than in plots that had been deep-plowed in the 1st or 2nd year.

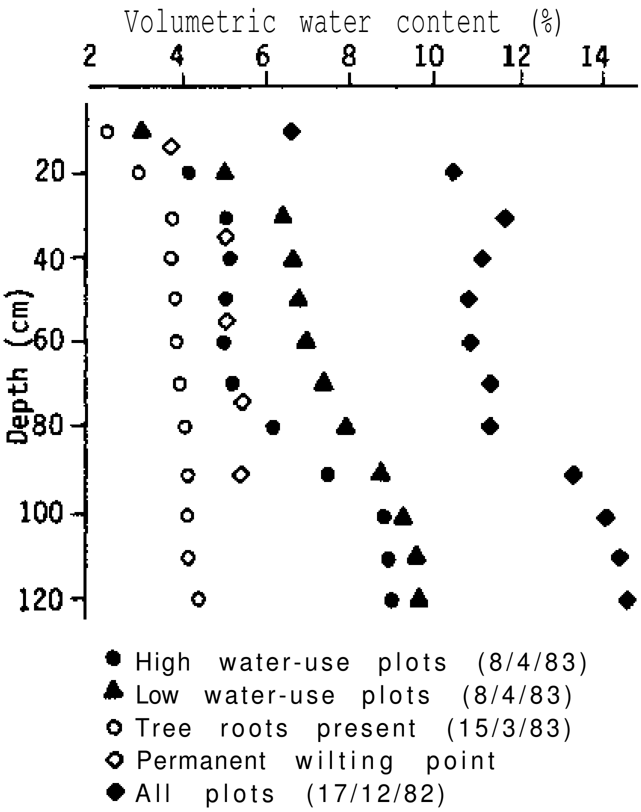


Figure 4. Soil/water profiles from the loamy sand tillage trial, Botswana.

Profile moisture clearly shows the effect of tillage on water use by the crop. The cropped plots separated into distinct low and high water-use plots (Fig. 4). Both plots with no treatment in either year and one with shallow treatments both years comprised the low-use group, while the remaining nine belonged to the high-use group. The two groups differed even at shallow depths, suggesting that the root systems of the low-use group were poorer across almost the entire depth range.

Laboratory-determined values of the wilting point (-15 MPa) and end-of-season values from high water-use plots correlated up to 80 cm depth. But below that depth, it seems, the sorghum variety used in the experiment, Segaolane, is unable to root efficiently. A similar result was obtained the previous year. The nearly uniform values of water content to depth in the 'acacia' plots showed that the inability of sorghum to extract water from below 80 cm is not determined solely by soil factors.

Measurements of plant height, numbers of flowering heads, and grain yield followed the same pattern, with little difference between the plots which had at one time been deep-plowed. However, in a very harsh year, the only significant difference in grain yield was between the (zero, zero) plots and the others.

The differences observed in the crop were presumably produced by the differences in soil strength and, possibly, water infiltration. The shear strength in the (deep, shallow) and (deep, zero) plots at 15 cm was significantly less than in the (shallow, shallow) and (zero, zero) plots, with mean values of 7 and 13 t m^{-2} respectively.

The treatment differences were expressed least in the grain yields. This suggests that the better early growth and greater water use may not have conferred a great advantage on the plants in the deep-plowed plots. In fact, they may have used water somewhat profligately prior to grain-fill, thereby exhausting the water supply, while in other plots very slow soil water-use was maintained throughout grain-fill.

Management Choices

It is evident that maintaining a loose soil surface that permits (1) the rapid infiltration of rainfall to greater depth, (2) easy emergence of seedlings, and (3) adequate root growth, is of great importance in these soils.

Plowing immediately after harvest in some years may be practical, although, if the rains end early, this is possible only on the sandiest soils. This pre winter plowing is definitely possible only on summer-fallowed land—a practice not popular among traditional farmers. An intermediate position is to plant a short-season crop, such as cowpea, which can be cleared from the land much earlier than sorghum. Besides permitting or giving a better chance of earlier plowing, bare fallowing or the use of a short-season crop also allows water storage in the soil profile over winter, although water storage would be of greater benefit only in the event of minimal planting rains in the spring (Botswana: Ministry of Agriculture 1982a). Obviously, a coarse tilth is desirable for early plowing. Arndt (1964) has shown that clods display maximum resistance to breakdown by rain at a diameter of about 8 cm; resistance increases very little beyond this size. Unfortunately, a farmer using ox-drawn equipment has almost no choice in his preparation of land; the moldboard plow will give a tilth that is determined by the soil and its water content. All that the farmer may be able to do is to increase the number of days that the soil is in the right condition for plowing, and to ensure even wetting of the land. Early plowing prior to the rainy season will help do both these things, even if the plowing has to be repeated after an early rain to create the desired tilth.

Ridges, with or without ties, are another alternative for preventing water loss from land. In many cases, the topography in Botswana does not suit untied ridges as undulations running across the main slope of the land may prevent any meaningful plowing on the contour. Another general problem with ridging may be the level of compaction in the furrows or basins. This is difficult to avoid when animal draft is used. However, the agricultural engineer with the Evaluation of Farming Systems and Implements Project (EFSAIP), Botswana, has found tied ridges a practical system with animal-drawn implements (Botswana: Ministry of Agriculture 1982b). In this system, the ridges are remade each year with no overall primary tillage operation. Measurements indicate that the soil in the ridges remains loose throughout the season, presumably because of rapid drainage of excess water to the basins. Experience with wide beds has not been very productive largely because crop residues block implements. The practice of remaking ridges without primary tillage must, of course, be followed for a number of years so that long-term effects on rooting may be studied.

The land preparation for planting should leave as coarse a tilth as possible, and be compatible with the planting procedure used. A planter unit hung from the side of a plow (Botswana: Ministry of Agriculture, 1981b) can create a very coarse seedbed with adequate emergence if the correct seed rate is used. The potential problem with the more open seedbed is that it may dry more quickly. This would not seem to be a major problem with timely planting, but, if planting is done over a number of days after rainfall, it may become necessary to plant deeper and perhaps to press the seed more firmly into the soil. Arndt (1964) shows that the split-rim press wheel compacts the soil at a depth below the surface, the depth determined, apparently, by the angle of the rims. Thus, the use of this wheel offers the possibility of compacting the soil just below the seed, while leaving uncompacted the friable soil just above it. This type of wheel is used on planters in Botswana where dangers of compaction at the surface exist.

Drying ridges at and after planting may be a problem. However, it appears that the planters used are sufficiently heavy to knock the top off the ridge and plant well into the moist soil underneath. The choice among the various methods of land preparation will depend on the soil and topography. A sandy loam soil can be expected to yield reasonably coherent clods which, if not broken down mechanically, should be able to resist rainfall impact. Planting on the flat may be perfectly satisfactory if the land can be plowed early. If it cannot be plowed early, considerable water may be wasted before the soil is wet to an adequate depth. In this case, ridging with ties, if necessary, should be considered. Runoff can be substantial on loamy sand soil, and the clods not so resistant to rainfall impact. Tied ridges may again be desirable.

When planting on the flat, deep-plowing frequently improves yields. On the research farm, this was clearly an effect of improved water use; on the farm, it may improve weed control as well. The problem is the practical one of how farmers who use animal draft power can plow deep. Plowing by tractor, usually hired, is an alternative now frequently resorted to in Botswana. It is certainly not an economic practice, and that is why the possible residual effects of deep-plowing have been studied. Residual effects are clearly and strongly found on the loamy sand soil, and are nearly absent on the sandy loam soil. At present, there is no reason to suppose that these soils are not typical of their class. Data so far suggest that deep-plowing every 3 years may really benefit plant growth on the loamy sand soils. Greater benefits could be expected if a deep-rooting variety of sorghum, excellent in other respects as well, were available. Deep-plowing should be considered with some caution if there is any impediment to rooting within 1 m of the soil profile.

Planting seeds in groups, or 'hills', is practiced widely in other parts of Africa but not in Botswana. It seems to be a worthwhile practice in soils that are particularly prone to crusting. Soaking seed prior to planting has not been found beneficial

Further details of experimental work discussed here will be found in past and forthcoming Annual Reports of the Dryland Farming Research Scheme, Botswana, Phase III.

Acknowledgment

I am grateful to the Natural Resources Division of the UK Overseas Development Administration for financial support, to the Government of Botswana for the generous provision of research facilities, and to my colleagues at the agricultural research station who carried out some of the work discussed in this paper.

References

Arndt, W. 1964. Investigations of some physical problems of Katherine soils. Page 73 in Technical memorandum 64/3. Canberra, Australia: Commonwealth Scientific and Industrial Research Organization, Division of Land Research and Regional Survey.

Botswana: Ministry of Agriculture. 1981 a. Botswana agricultural statistics. Gaborone, Botswana: Ministry of Agriculture, Agricultural Research Station, Sebele.

Botswana: Ministry of Agriculture. 1981b. Evaluation of the Farming Systems and Agricultural Implements Project (EFSAIP), Botswana, 1980-81. Report no. 5. Gaborone, Botswana: Ministry of Agriculture, Agricultural Research Station, Sebele.

Botswana: Ministry of Agriculture. 1982a. Dryland Farming Research Scheme (DLFRS), Botswana, phase 3: third annual report, December 1982. Gaborone, Botswana: Ministry of Agriculture, Agricultural Research Station, Sebele.

Botswana: Ministry of Agriculture. 1982b. Evaluation of the Farming Systems and Agricultural Implements Project (EFSAIP), Botswana, 1981-82. Report no. 6. Gaborone, Ministry of Agriculture, Agricultural Research Station, Sebele.

Emerson, W.W. 1967. A classification of soil aggregates based on their coherence in water. Australian Journal of Soil Research 5:47-67.

Pike, J.G. 1971. Rainfall and evaporation in Botswana. Technical Document no. 1. Gaborone, Botswana: UNDP.

Siderius, W. 1973. Soil transitions in central east Botswana (Africa). Ph.D. thesis, Rijksuniversiteit te Utrecht, Belgium.

An Evaluation of Soil-Water Management on an Alfisol in the Semi-Arid Tropics of Burkina Faso

Eugene R. Perrier[1]

Abstract

Experiments were undertaken at Kamboinse Experiment Station in Burkina Faso to compare the yield advantages of flat and ridged soil-surface treatments, with and without mulching and with open and tied ridges, to obtain data on cultivation practices that conserve water and increase infiltration. Data on grain and dry-matter yields and the growth characteristics of two varieties of sorghum and three of pearl millet used in the experiments over 2 years are presented. It was found that mulch can significantly increase yields regardless of the method chosen for water conservation: flat, open ridges, or tied ridges. The best system was the use of tied ridges with mulch. The traditional method of flat sowing restricts crop yield. This was found to be particularly true for the improved varieties, for which plowing was found to be necessary for increasing their yields. Plowing before sowing increased the sorghum (E 35-1) yield by 236%.

The Semi-Arid Tropical Environment of Burkina Faso

The semi-arid tropics (SAT) of Burkina Faso in West Africa are characterized by two seasons: a dry season that lasts roughly from October to May, followed by 4-6 months of rainfall. The rainy-season rainfall is highly erratic and varies from 400 mm in the north to 1500 mm in the south. The storms are convectional in nature, and seasonally balanced by the high-pressure ridges of the Sahara desert and the low-pressure systems off the Bight of Benin. Air temperatures tend to be moderate, averaging nearly 30°C, with the maximum reaching 44°C during April, and the minimum 3°C (with no frosts) during the winter month of January.

The West African region is made up of ancient crystalline rocks that have been above sea level long enough to be worn to plateau surfaces of highly-indurated sediments of Precambrian age that form the substrate (FAO-UNESCO 1977). West Africa has no true mountains like the Alps in Europe.

The Alfisols south of the Sahara desert consist mainly of Ustalfs. On the upper parts of the slopes, these soils have a loamy sand to sandy loam surface and below a clayey horizon that contains a few iron nodules (Ferric Luvisols). Further down the slopes, the surface soils grade to loams with restricted internal drainage. These soils have rather poor structural properties because of lower clay and organic-matter content in the surface layers. However, iron concretions greatly increase with depth and progressively impede the internal drainage (Sanchez 1976).

The Alfisols at Kamboinse Experiment Station in Burkina Faso used for sorghum and millet production are described as ferralitic soils with reddish colors, low base saturation, and poor internal drainage. These soils are subject to considerable microvariations, often linked to the position in the toposequence (ICRISAT 1980). The topsoils are usually shallow and their surface, if not properly managed, will crust readily under the impact of raindrops, resulting in considerable runoff. These soils show nitrogen and phosphorus deficiencies.

1. The International Center for Agricultural Research in the Dry Areas, P.O. Box 5466, Aleppo, Syria.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987, Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Rainfall

Kamboinse Experiment Station is situated 14 km north of Ouagadougou. The climates at Kamboinse and Ouagadougou are similar. The 60-year mean annual rainfall for Ouagadougou is 860 mm, whereas it is 762 mm from 11 years of records at Kamboins6. The annual rainfall for 1981 was 700 mm, and for 1982, 717 mm.

Table Ib. The moisture relationships for loam and sandy loam soils at Kamboinse Experiment Station.

Soil	Saturation (%)	Field capacity (%)	Wilting point (%)	Infiltration rate (cm ha-')
Loam	39	15	7	1.8
Sandy loam	30	8	4	2.2

Soil characteristics

The general characteristics of Alfisols that were experimented on throughout the reported study period, are presented in Tables la and Ib. Additional information on these types of Alfisols has been presented by Roose (1981).

The bulk density of the soil increases with depth. This is caused either by compaction or by the ferralitic gravelly materials that are formed at lower soil depths. Further, the clay content of these Alfisols on the upper portions of the colluvium increases with depth. Two factors may govern this effect: (I) the downward movement of the finer particles with water percolation; and (2) the upward movement of clay particles caused by the action of termites, and the eventual loss of these fine particles due to erosion. Thus, as the clay content and the bulk density increase with depth, the rate of percolation becomes restricted. This relationship can be put in perspective by the in-situ lysimetric data of Charreau (1972) for an Alfisol in Burkina Faso. These show a runoff level at 32% of the annual rainfall for cultivated soil, and as high as 60% for bare soil.

The Use of Tied Ridges

The concept of zero runoff implies that all of the precipitation remains on the soil surface until it infiltrates into the soil or is collected for future use. One of the techniques used throughout Africa for retaining rainfall in the soil is the construction of tied ridges. An alternative, with a slight modification, is the creation of microcatchment basins. In Burkina Faso, ridges may be formed by tractor or by oxen with ridgers (listers). But ridges and ties are usually manually constructed with the aid of a "daba", a short-handled hoe. Hudson (1971) suggests that the ridges should be constructed on a gradient, with the ties lower than the ridges so that any sudden release of runoff, caused by the nonabsorption of rainwater, will occur along each contoured ridge and not down the slope.

Tied ridges (10-20 cm deep) can be constructed as microcatchment basins, that is, the ridges can be deep (30-40 cm) so that all of the water that falls or runs into them is captured. In general, the differences between the two systems reflect soil type and slope as well as maintenance, and the amount of

Table 1a. Some selected characteristics of loam and sandy loam soils„ at Kamboinse' Experiment Station.

Soil depth (cm)	Particle size distribution(%) Sand	Silt	Clay	Bulk density (g cm"3)	Hydraulic conductivity (cm h^{-1})	PH	Base saturation	Cation exchange capacity (meq 100 g^{-1})
Loam								
0-10	52.3	32.1	15.6	1.25	4.8	6.2	61	4.82
10-20	61.4	17.4	21.2	1.43	3.2	6.0	54	5.74
20-30	49.7	21.6	28.7	1.69	3.5	5.7	69	5.34
50-100	50.1	20.4	29.5	1.84	3.0	5.4	74	4.46
Sandy loam								
0-10	68.6	12.2	19.1	1.33	8.7	6.8	52	3.37
10-20	62.2	15.1	22.7	1.52	4.5	5.9	76	4.41
20-50	54.1	17,8	28.1	1.68	3.1	5.6	73	4.04
50-100	48.4	22.1	29.5	1.78	2.3	5.9	74	3.96

manual labor required to maintain the ties and dams after storms.

Using ridges can be very effective. But they help increase yields only when surface runoff occurs at a greater rate than infiltration; that is, when water needed to refill the soil profile in the root zone is lost. If the infiltration rate is adequate to replenish the soil moisture in the root zone during rainfall, or within a day after rainfall, it becomes immaterial whether the surface water is captured or permitted to flow away as runoff. When the soil profile down to the root zone has been refilled to field capacity, further infiltration can result only in a saturated soil profile, imbalance of soil-air-water, and the eventual loss of plant nutrients by leaching. Also, when ponding occurs for an extended period of time, say 2-3 days, tied ridges may prove detrimental to plant growth by limiting soil aeration and creating anaerobic conditions in the upper layers of the soil surface. It is quite common to see algal blooms when ponding occurs for more than 1 day. In other words, puddling and crusting of the surface soil can limit infiltration.

Sorghum Production on Alfisols

In 1981, sorghum research fields at Kamboinse were designed to evaluate the effects of soil surface treatments, both with and without plowing, on the yield and growth characteristics of two sorghum varieties: E 35-1 and local Kamboinse. Both were replicated three times. The treatments were: (1) flat sowing; (2) flat sowing with rice straw mulch (6 t ha^{-1}); (3) flat sowing with surface cultivation after each rainfall; (4) open ridges (no ties); (5) open ridges with rice straw mulch; (6) tied ridges; and, (7) tied ridges with rice straw mulch.

Soon after the start of the rains, the fields were sown with the two sorghum varieties when the soil was at or near field capacity. The fertilizer (14-23-15) was applied at the rate of 100 kg ha^{-1} just prior to seeding, and a side dressing of 65 kg ha^{-1} of urea was applied later. The plots measured 5 * 10 m, and each variety was sown in rows 80 cm apart. The E 35-1 was seeded in pockets 30 cm apart within the row, with two seeds per pocket at a rate of 90 000 steeds ha^{-1}. The local Kamboinse variety was sown in pockets 45 cm apart within the row, with two seeds per pocket at a rate of 60 000 seeds ha^{-1}.

The ridges were tied or dammed immediately after germination. This was followed by the addition of rice straw mulch. The ties in the tied ridges required maintenance twice during the growing season. Severe storms tend to wash and erode the ties, which eventually begin to leak. Hence, maintenance is essential for their proper functioning.

Table 2 shows the effect of tillage and soil surface treatments on sorghum yield. E 35-1 more than doubled in yield over the traditional flat treatment when mulch was applied. This was also the case with the local Kamboinse varieties on the plowed treatment. Similar trends in yield were observed for the unplowed treatment, except that yields tended to be lower. There were no significant differences in yield between the open and tied ridges for the same treatment level, that is, mulch versus no mulch. The interaction between plowing treatment and variety showed that E 35-1 yielded far less without mulch when compared with the local Kamboinse variety. Flat sowing with cultivation after each rain resulted in a slight but not significant increase in yield compared with flat sowing without cultivation.

The 1982 experiments were conducted on the main plots, and the sorghum varieties used were the same as in 1981. The rice straw mulch applications were at the rates of 0, 10, 15, and 20 t ha^{-1} of dry material, and the row spacings of the ridges were 0.5, 0.75, 1.0, 1.25, and 1.5 m, with all ties at 1.0-m

Table 2. Effect of tillage, crop variety, and soil surface treatment on grain yield at Kamboinse Experiment Station (t ha^{-1}).

Soil surface treatment	Plow treatment				
	Plowed		Not plowed		
	E35-1	Local	E 35-1	Local	Means
Flat	1.57	1.10	0.67	0.91	1.06
Flat with mulch	3.6	2.60	2.59	2.80	2.91
Flat cultivation	2.06	1.39	1.45	1.46	1.58
Ridges open	2.41	1.63	0.50	1.00	1.39
Ridges open/ mulch	3.10	2.32	2.20	2.18	2.45
Ridges tied	2.20	2.32	1.86	1.50	2.00
Ridges tied/ mulch	3.29	2.83	2.93	2.30	2.84
Plow vs variety	2.60	2.03	1.76	1.73	

The analysis of variance showed:

1. Replication: nonsignificant.
2. Plowing treatments: significant (F = 26.3, df = 1/56).
3. Varieties: significant (F = 6.88, df =1/56).
4. Soil surface treatment: significant (F = 24.1, df = 6/56).
5. Interaction between plowing treatment and variety: significant (F = 5.89,df = 1/56).
6. Comparison between mulched and nonmulched plots: significant (F = 128, df = 1/23).

spacing and about 15 cm deep. These plots were randomized into complete blocks of six replications.

During this season, the two sorghum varieties were planted at a spacing of 0.22 m between pockets and thinned to one plant per pocket. The sowing rate varied according to the spacing of the ridges; that is, at a spacing of 0.5 m the sowing rate was 105000 seeds ha^{-1}, at 0.75 m it was 66 000 seeds ha^{-1}, at 1.0 m it was 40 000 seeds ha^{-1}, and at both 1.25 m and 1.5 m spacings it was 27000 seeds ha^{-1}.

Table 3 presents the mean grain yield of each crop variety in relation to the tied ridge compartment area. Since rice straw mulch was added late in the growing season, the effect of mulching was statistically nonsignificant in all the collected data sets and, therefore, these data are not presented.

The yield at 0.5 m row spacing was nearly double that at the 1.5 m row spacing. E 35-1 variety responded to the tied ridge compartment area at a greater rate than the local Kamboinse' variety. The relatively low yield of the local variety can partly be attributed to the late sowing date. Further, the relationship between yield response and size of tied ridge compartment is complicated because of the variable stand density, which ranged from 105 000 plants ha^{-1} at 0.5 m spacing to 27000 plants ha^{-1} at 1.25 and 1.5 m spacings. These data suggest that the smallest tied ridge compartment significantly increased the yield of both varieties.

The mean of total dry matter per plant as related to the tied ridge compartment area and variety is shown in Table 4. The significant replication effect was attributed to wind damage from a severe rainstorm late in the season that caused lodging in some plots. Although the sorghum heads were saved, it was difficult to keep the plant stalks intact, and this led to termite damage. Nonetheless, the increase in the quantity of dry matter with reduction in the tied ridge compartment area was seen for both varieties. While E 35-1 produced more grain than local Kamboinse, the dry matter production was the same for both.

The plant index of E 35-1 was 38.5% and that of local Kamboinse 20.8%. This shows that E 35-1 is a more efficient grain producer than local Kamboinse. And, since the plant index is also a rating of comparative efficiency, it indicates that E 35-1 is more energy-efficient than local Kamboinse.

Table 3. Effect of the size of the tied ridge compartment and crop variety on grain yield at Kamboinse Experiment Station (t ha^{-1}).

Ticd-ridge compartment area (m^2)	Sorghum variety E35-1	Sorghum variety Local	Means
0.50	5.17	3.00	4.08
0.75	4.33	2.76	3.55
1.00	4.11	2.45	3.28
1.25	3.56	2.24	2.90
1.50	2.72	1.90	2.35
Variety means	4.02	2.49	

The analysis of variance for the split-split plot showed:
1. Replication: nonsignificant (F = 4.16, df = 5/23).
2. Varieties: significant (F = £67. df = 1/23).
3. Size of catchment area: significant (F - 70 5, df = 4/99).
4. Interaction of variety with size of area: significant (F - 8.2, df = 4/99).

Table 4. Effect of the size of tied ridge compartment and crop variety on the total plant dry matter, at Kamboinse Experiment Station (t ha^{-1}).

Tied-ridge compartment (m^2)	Sorghum variety E 35-1	Sorghum variety Local	Means
0.50	14.3	14.8	14.5
0.75	10.3	11.8	11.2
1.00	9.6	10.7	10.2
1.25	7.8	10.0	8.9
1.50	6.6	7.8	7.3
Variety means	9.7	11.0	

The analysis of variance for the split-split plot showed:
1. Replication: significant (F = 11, df = 5/23).
2. Varieties: significant (F = 25, df = 1/23).
3. Size of catchment area: significant (F = 33, df = 4/99).

Pearl Millet Production on Alfisols

The effect of soil treatments for water conservation on the subsequent production of two varieties of millet (Ex-Bornu and local Kamboinse) were compared with the following treatments: (1) flat sowing; (2) open ridges; (3) tied ridges; and (4) tied ridges with rice straw mulch (6 t ha^{-1}).

The field was seeded 2 days after a rainstorm. The rows were spaced 80 cm apart. The Ex-Bornu variety was sown with one seed per pocket spaced every 30 cm and at a rate of 45000 seeds ha^{-1}. The local Kamboinse variety was grown with one seed per pocket spaced every 45 cm and at a rate of 30 000 seeds ha^{-1}.

The millet yields for different crop variety and soil surface treatments are shown in Table 5. The significant interaction of soil surface treatment as a function of variety is a result of the effect of pollen wash on the Ex-Bornu variety, in the case of the treatment that used tied ridges with mulch.

The 1982 millet study tested the effect of the tied ridge compartment area in relation to the quantity of mulch on three varieties of millet (Ex-Bornu, Souna 3, and local Kamboinse') which were arranged in randomized complete blocks with five replications. There were four levels of rice straw mulching (0,10, 15, and 20 t ha^{-1}) and five levels of tied ridges, with rows spaced at 0.5,0.75,1.0,1.25, and 1.5 m. The ties were all of 1 m length.

All three varieties were planted at a spacing of 0.22 m between pockets and thinned to 1 seed per pocket at a rate of 105000 seeds ha^{-1} at the 0.5 m row spacing; 66000 seeds ha^{-1} at the 0.75 m row spacing; 40000 seeds ha^{1} at the 1.0 m row spacing; and, 27000 seeds ha^{-1} at both 1.25 m and 1.5 m row spacings.

Table 5. Effect of the crop variety and soil surface treatment on grain yield at Kamboinse Experiment Station (t ha^{-1}).

Soil surface	Millet variety		
treatment	Ex-Bornu	Local	Means
Flat	0.24	0.14	0.19
Ridge open	0.30	0.12	0.21
Ridge tied	1.15	0.36	0.75
Ridge tied with mulch	0.62	0.65	0.63

The analysis of variance showed.

1. Varieties were significantly different (F = 18.42, df = 1/16).
2. Soil surface treatments were significantly different (F = 23.77, df = 3/16).
3. Interaction between soil surface treatments and variety was significantly different (F = 12.72, df = 3/12).

The mean grain yields are presented in Table 6 for crop variety in relation to the tied ridge compartment area. As mentioned earlier, the effect of mulching was not significant and, therefore, these data are not presented.

Table 6. Effect of the size of tied-ridge compartment and plant variety on grain yield1 at Kamboinase Experiment Station (t ha^{-1}).

Tied-ridgc compartment area (m^2)	Millet variety			
	Local	Ex-Bornu	Souna 3	Means
0.50	1.00	2.11	2.23	1.79
0.75	1.12	2.33	2.18	1.88
1.00	1.14	2.41	2.59	2.08
1.25	1.02	1.97	2.39	1.79
1.50	1.07	2.14	2.33	1.84
Variety means	1.07	2.19	2.35	

The analysis of variance for the split-split:

1. Replication: nonsignificant (F = 2.21, df = 4/18).
2. Varieties: significant (F = 165, df = 2/18).
3. Size of catchment area: significant (F = 7.12, df = 4/162).
4. Interaction between varieties and catchment area size: significant (F = 2.19, df = 8/162).

The millet yield was affected by downy mildew, especially in the 0.50 and 0.75 m row spacings, the local Kamboinse* variety being the most severely affected throughout all treatments. The yields ranged from 3.22 t ha^{-1} for the Souna 3 to 0.81 t ha^{-1} for the local Kamboinse variety. These data suggest that the 1-m spacing is the most satisfactory for millet production. In addition, Souna 3 produced significantly more grain than Ex-Bornu, and both these varieties produced significantly more grain than the local Kamboinse'. As distinct from the sorghum data, there appears to be little, if any, evidence of plant density affecting the relationship between grain yield and the catchment area.

Table 7 shows how plant dry matter is related to the tied ridge compartment catchment area and the plant variety. The local Kamboinse variety produced maximum dry matter at 5.26 t ha^{-1}, followed by Ex-Bornu at 4.25 t ha^{-1}, and Souna 3 at 3.61 t ha^{-1}. Also, the closer row spacings produced significantly more dry matter in the Ex-Bornu and Souna 3 varieties when compared with the 1.25 or 1.5 m row spacings.

Souna 3 had the highest plant index at 62.5% and was the most efficient grain producer, that is, less energy was used in the production of dry matter. Ex-Bornu's plant index was 50% and that of the local Kamboinse 16.2%. However, at harvest, the stalks of Souna 3 were the highest in moisture content, 68.7%, followed by Ex-Bornu, 61.3%, and the local Kamboinse, 61.0%.

Table 7. Effect of the size of tied ridge compartment and plant variety on total plant dry matter at Kamboinse Experiment Station (t ha^{-1})).

Tied-ridge compartment area (m^2)	Millet variety Local	Ex-Bornu	Souna 3	Means
0.50	5.82	4.31	4.01	4.71
0.75	5.23	4.46	3.33	4.34
1.00	7.24	4.95	4.08	4.76
1.25	4.86	3.75	3.31	3.97
1.50	5.14	3.77	3.35	4.09
Variety means	5.26	4.25	3.61	

The analysts of variance for the split-split plot showed:

1. Replication: nonsignificant ($F = 2.0$, df = 4/18).
2. Varieties: significant ($F = 20.9$, df = 2/18).
3. Size of catchment area: significant ($F = 12.8$, df = 4/162).
4. Interaction between area size and variety: significant ($F = 14.5$, df = 4/162).

Discussion and Conclusions

The soil surface management studies on these Alfisols were designed to investigate the relative size of the catchment area using tied ridges, and the effectiveness of different quantities of crop residues as mulch for several varieties of sorghum and millet crops. The data on yield were used as the major statistic for evaluation. Plant characteristics such as height, number of heads, number of good heads, total dry matter, etc., were also measured and analyzed.

During rainfall, it was observed that mulch improved infiltration on these Alfisols by two distinct methods: reducing raindrop impact and increasing termite and biological activity. The straw absorbed the impact of the raindrops, and no puddling or muddy water was observed at the soil surface. Without mulch, the energy of the rain drops is absorbed by the bare soil surface and, as expected, these falling raindrops break down and disperse soil aggregates. When the bare soil surface is covered by a thin film of water, the force of the raindrops striking the surface causes the water film to become puddled or muddy. As surface water infiltrates into the soil, the puddled soil particles are filtered out in the surface layer. This process rapidly impedes water flow into and through the soil pores. This thin, dense layer has a much lower infiltration rate than that which the soil had before the rainfall. When this process is permitted to continue it causes surface-sealing and compaction, leading to reduced infiltration and a possible increase in runoff. However, tied ridges or microcatchment basins store water and, if puddling and surface-sealing is severe, this stored water is essentially lost through evaporation.

The mulch encouraged termite and biological activity at the soil surface. Termites started to consume the plant material immediately after it was placed on the field. Thus, surface water collected from the rainfall entered the soil through microholes or pores made by the termites. The termites consumed the mulch material at a rather slow rate, but by the end of August only a small amount of the debris remained. Also, the termites consumed only the rice, sorghum, and millet dry mulch material, and did not attack the growing plants. During the termite activity, large amounts of clay materials were transported from the deeper horizons to the surface. This should, in time, benefit the upper layers of these sandy-surfaced Alfisols.

Biological decomposition started immediately after the first rainfall. As these materials are decomposed and digested by soil organisms, their byproducts become a part of the underlying soil horizons through infiltration. Biological activity increases the number of micropores in the soil profile, thereby providing another pathway for the entry of water into the root zone.

During heavy rainfall, water puddled on all the plots without mulch. Standing water remained in the tied ridge plots without mulch for up to 3 days after the cessation of rainfall, and algae formed at the bottom of the tied ridges. No standing water was found to remain shortly after rainfall in the tied ridge plots with straw mulch. Nearly all of the straw mulch decomposed by harvest time, and postharvest operations were not affected.

Application of mulch will significantly increase yields regardless of the method chosen for water conservation: flat, open ridges, or tied ridges. The best treatment is the use of tied ridges with mulch. During midseason droughts, on all treatments where mulch was used plants showed less stress—as observed by the color and curling of leaves—compared with those in the other treatments. When no plowing was done, E 35-1 was severely affected by loss of seedlings, and this resulted in significant yield reductions. Nevertheless, a great deal of this seedling loss was circumvented when mulch was applied.

The traditional method of sowing on flat, bare surfaces restricts yield. This was particularly noticeable in the sorghum variety E 35-1. Plowing before sowing increased the yield of E 35-1 by 236%; tied ridges and mulch by 493%. Although the pearl millet yield (Ex-Bornu) was depressed by pollen wash, mulch greatly improved the other growth characteristics.

Local varieties are well adapted to environmental conditions and the usually low level of Alfisols management found in most parts of Burkina Faso. The exotic varieties will provide a much greater yield response with increased work effort, but this may not necessarily be true of the local varieties.

The use of tied ridges on Alfisols reduces weeding. Water may pond in the tied ridge plots for 2-3 days after rainfall, making the environment extremely poor for seedling growth and development. When mulch is used, the work of weeding is further reduced. Mulching shades the soil surface of the catchment area, which in turn creates a poor environment for weed growth.

References

Charreau, C. 1972. Problemes poses par l'utilisation agricole des sols tropicaux par des cultures annuelles. Agronomic Tropicale 27(9):905-929.

FAO/UNESCO. 1977. Soil map of the world. Vol. 6. Africa. Paris, France: UNESCO.

Hudson, N. 1971. Soil conservation. London, UK: Batsford.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1980. Annual report, Republic of Burkina Faso, Kamboinse Experiment Station. Ouagadougou, Burkina Faso: ICRISAT.

Roose, E. 1981. Dynamique actuellc de sols ferrallitiques et ferrugineux tropicaux. Bondy, France: ORSTOM (Office de la Recherche Scientifique et Technique Outre-Mer).

Sanchez, P.A. 1976. Properties and management of soils in the tropics. New York, USA: John Wiley.

Water Harvesting for Collecting and Conserving Water Supplies

G. W. Frasier[1]

Abstract

Water-harvesting / runoff-farming techniques are technically feasible methods of supplying water for animals, households, and growing plants. Some water-harvesting systems have been outstanding successes, others total failures. Despite use of proper materials and design, many systems have failed because social and economic factors were not adequately integrated into the systems. There will be a higher probability of system failure when funds are available for construction at no obligation to the user unless there is a clear understanding of who is responsible for maintenance. A successful water-harvesting system must be: (a) technically sound, properly designed, and maintained; (b) socially acceptable to the water user and his method of operation; and (c) economically feasible in both initial cost and maintenance at the user level.

Introduction

Water harvesting is the term used to describe the process of collecting and storing water from an area that has been modified or treated to increase precipitation runoff. A water-harvesting system is a complete facility for collecting and storing runoff. The system consists of a catchment or water-collecting area, a water storage facility, and various auxiliary components such as sediment or trash traps, fencing, and evaporation control. Runoff farming is a water-harvesting system specifically designed to provide water for growing plants. Water harvesting can be an expensive method of water supply; but it can provide water in most areas where other methods are not feasible.

Water harvesting is an ancient method of water supply dating back to over 5000 years (Hardan 1975). During the past 30 years, increased awareness of the importance of water conservation has generated a renewed interest in water harvesting. There is a considerable amount of technical literature which describes or presents information concerning the various techniques of water harvesting and runoff farming. Unfortunately, much of this information is scattered in scientific or technical journals and proceedings of various meetings, and is written in a manner that is difficult to interpret for direct field application by farmers and technicians (Frasier 1975, Cooley et al. 1975, Hollick 1982). This paper summarizes some of the methods and materials used to collect and store precipitation runoff for growing crops and for providing drinking water for man and animals. Some effective concepts and methods are outlined here.

System Design

Irrespective of the intended use for the collected water, the basic criteria for designing a water-harvesting/runoff-farming system are the same. There is no system that is universally "best", since each site has its own unique characteristics. The designer, installer, and the ultimate user should become as familiar as possible with the available techniques and adapt one that is best suited to the local environmental, social, and economic condi-

1. Southwest Rangeland Watershed Research Center, Tucson, Arizona, USA.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils. 1-3 December 1983. ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

tions. There are many separate elements that must be considered: precipitation patterns, water-requirement patterns, land topography, alternative water sources, availability of materials, equipment, labor, and acceptability of water-harvesting concepts by the water user. Many of these factors are interrelated, and must be considered simultaneously.

Precipitation

The quantity and timing of precipitation is one of the most difficult parameters to lay down accurately. Monthly averages, obtained from long-term precipitation records, are the most common data base. To minimize the effect of short-term random fluctuations, it is desirable to use records dating back a minimum of 10 years. If there are extreme variations in precipitation quantities, data from the two wettest years should be deleted. When sufficient years of precipitation data are available, expected rainfall amounts can be determined by probability analysis techniques. Usually it is not economically feasible to design a water-harvesting system to meet the least expected precipitation. The user must decide the amount of risa that can be accepted should there be insufficient precipitation during some periods.

Water Requirements

Table 1 lists the total consumptive water use for a few common crops. Table 2 gives estimates of daily domestic household use and daily drinking water requirements for various animals. For runoff-farming applications, the crop-growing season is the time of water need, and the water supply system must be able to supply the weekly or other short-term consumptive use demands (Erie et al. 1982). Seepage and evaporative losses of water from storage must be included as part of the water requirement.

Alternative Water Sources

The various alternative methods of water supply should be considered prior to installation of a water-harvesting system. There have been instances where the local people were aware of other potential water sources, such as undeveloped springs or shallow groundwater; but technicians not familiar with the area made the decision to use water harvesting as the method of water supply without thoroughly investigating other potential sources. Utilizing temporary or intermittent water sources with the total water supply system can, in some places, justify the installation of smaller water-harvesting systems.

Table 1. Total water consumptive use for selected crops.

Crop	Period of growth	Total seasonal use (mm)
Cash or oil crops		
Castor bean	Apr-Nov	1130
Cotton	Apr-Nov	1050
Flax	Nov-Jun	795
Safflower	Jan-Jul	1150
Soybean	Jun-Oct	560
Sugar beet	Oct-Jul	1090
Lawn or hay crops		
Alfalfa	Feb-Nov	2030
Bermuda grass	Apr-Oct	1100
Blue panic grass	Apr-Nov	1330
Small grain crops		
Barley	Nov-May	635
Sorghum	Jul-Oct	645
Wheat	Nov-May	655
Fruit		
Grapefruit	Jan-Dec	1215
Grape (early-maturing)	Mar-Jun	380
Grape (late-maturing)	Mar-Jul	500
Orange (navel)	Jan-Dec	990
Vegetables		
Broccoli	Sep-Feb	500
Cabbage (early)	Sep-Jan	435
Cabbage (late)	Sep-Mar	620
Cantaloup (early)	Apr-Jul	520
Cantaloup (late)	Aug-Nov	430
Carrot	Sep-Mar	420
Cauliflower	Sep-Jan	470
Lettuce	Sep-Dec	215
Onion (dry)	Nov-May	590
Onion (green)	Sep-Jan	445
Potato	Feb-Jun	620
Maize (sweet)	Mar-Jun	500
Green manure crops		
Guar	Jul-Oct	590
Pea (papago)	Jan-May	495
Sesbania	Jul-Sep	330

Source: Erie et al. 1982.

Table 2. Estimates of daily water requirement for domestic use and drinking water for various animals.

Use	Daily water requirement (L d^{-1})
Domestic	
Per person cooking, drinking, and washing	40
Additional for flush toilets and shower	75-150
Animal drinking	
Beef cattle	
Mature animals	30-45
Cows with calves	40-85
Calves	20-30
Dairy cattle	
Mature animals	40-55
Cows with calves	45-70
Sheep	
Mature animals	4-8
Ewes with lambs	6-10
Horses	40-45
Wildlife	
Mule deer	4-8
Antelope	1-2
Elk	20-30
Swine	15
Chicken (per 100 head)	15
Turkeys (per 100 head)	25

Source: Frasier and Hyers 1983.

Availability of Materials and Labor

The cost of alternative water sources, and the importance of the water supply, determine the cost of a system. One must balance the cost of materials with the cost of labor. Usually, water-harvesting systems for supplying drinking water are constructed from materials that are more costly than can be economically justified for runoff-farming applications.

In many installations there will be several combinations of catchment and storage size that will provide the required quantities of water. The system with the lowest total cost is often the desired unit, but maintenance costs must also be included in the selection process. To insure that there are no critical periods when there will be insufficient water, the final size of the catchment and storage tank should be determined by computing an incremental water budget of collected water versus water needs (Frasier and Myers 1983).

Acceptance and Needs as Viewed by the User

The acceptance of water-harvesting concepts by the water user is an important factor in the performance of a water-harvesting system. Some materials and/or system designs require more maintenance than others. If the user does not believe that the system is the best for his purpose or situation and fails to provide the required maintenance, the system will fail. In areas where the concepts of water-harvesting/runoff-farming are not fully accepted because of various social or economic factors, the first system installed must be constructed from materials that have minimum maintenance requirements and maximum effectiveness. Materials and techniques that cost less may be used on subsequent units once the user has been shown that the ideas are valid.

Catchment Area Treatments

There are many ways that a catchment area can be modified to increase the quantity of precipitation runoff. These can be separated into three general categories: (1) topography modifications, (2) soil modifications, and (3) impermeable coverings or membranes. Table 3 presents a list of some of the common catchment treatments.

Topography modifications

The earliest catchment treatments are believed to have involved some form of topography modifications, and were simply areas cleared of brush and rocks, with small collection or diversion ditches to direct the runoff water to the storage. An example of this technique is the placement of water collection channels at the lower edge of rock outcroppings. With a minimum of materials or skilled labor, relatively large quantities of water can be obtained at low costs. Some of the most extensive uses of topography modification for catchment treatments are the "roaded" catchments in western Australia. These

Table 3. Potential water-harvesting catchment treatments.

Treatment	Runoff efficiency (%)	Estimated life (years)	Materials initial cost[1] (U.S. $ m^{-2})
Topography modifications			
Land smoothing and clearing	20-35	5-10	0.05- 0.20
Soil modifications			
Sodium salts	50-80	5-10	0.20- 0.50
Water repellents, paraffin wax	60-95	5-8	0.50- 1.00
Bitumen	50-80	2-5	1.00- 2.00
Impermeable coverings			
Gravel-covered sheeting	75-95	10-20	1.00- 1.75
Asphalt-fabric membrane	85-95	10-20	1.75- 2.50
Concrete, sheet metal, and artifical rubber	60-95	10-20	5.00-20.00

1. Adjusted to 1983 material costs.
Source: Frasier 1981.

are large areas of bare land shaped and compacted into parallel ridges and furrows (Laing 1981, Frith 1975).

Catchments utilizing topography-modification techniques are usually characterized by low initial costs, but they may have relatively low runoff efficiencies. These treatments are effective if properly matched to suitable soil types and topographic features. Slope angles and overland flow distances must be properly designed to avoid serious damage to the catchment surface through water erosion (Hollick 1982).

Soil modifications

Soil modification treatments involve chemicals applied to the soil surface by spraying or mixing to reduce or stop water infiltration. These treatments can potentially provide large quantities of water at low cost. Unfortunately, most soil modification treatments have been unsuccessful because of the necessity to match specific soil and climatic characteristics. Bitumen or asphalt have been widely tested as a soil modification treatment. This treatment is best suited for use on fine sandy soils and has a projected effective life of 2-5 years (Myers et al. 1967).

Salt treatment (sodium-dispersed clay) is potentially the cheapest soil modification technique. This treatment consists of mixing a water-soluble sodium-based salt (NaCl) at a rate of about 11t ha^{-1} into the top 2 cm of soil. After mixing the salt with the soil, the area is wetted and compacted to a firm, smooth surface. For this treatment to be effective, the soil should be made up with 20% or more of kaolinite- or illite-type clay. The sodium salt disperses the clay, plugs the soil pores, and reduces the hydraulic conductivity (Dutt 1981).

Water-repellent treatments can potentially be a low-cost soil modification technique. A chemical that is applied to the catchment surface causes the soil to become hydrophobic (water-repellent) by changing the surface tension characteristics between the water and soil particles. Many chemicals can create a water-repellent surface, but only a few compounds have been shown to be effective for water-harvesting applications (Myers and Frasier 1969). One of the simplest water-repellent chemicals to apply is a water-based sodium silanolate. The treatment does not provide any soil stabilization and is not suited for soils containing over 15% clay. It does have high potential for increasing runoff from rock outcroppings where soil erosion is not a problem. It has an effective life of 3-5 years.

Another water-repellent treatment is formed by spraying molten, refined wax on the prepared soil surface. The wax is deposited as a thin layer on the surface, and as the sun warms the soil, the wax remelts and moves into the soil, coating the soil particles with a thin coat of wax and rendering them water-repellent (Fink et al. 1973). This treatment is best suited to soils containing less than 20% clay and catchment sites where the surface soil temperature exceeds the melting point of the wax during some part of the year (Frasier 1980). The paraffin wax does not provide significant soil stabilization, and the treatment can be damaged by water erosion.

Impermeable coverings or membranes

Any impermeable or waterproof sheeting or membrane can be used as catchment covering. Many conventional construction materials such as concrete, sheet metal, and artificial rubber sheetings have been used (Cooley et al. 1975). These materials are relatively expensive, but when properly installed and maintained are durable, and may be the best treatment for some locations. Large expanses of concrete will crack. All cracks and expansion joints must be periodically filled with some type of sealer. Roofs of sheet metal have long been used to collect rainwater. Costs can be reduced by placing the sheet metal on the ground (Lauritzen 1967). In the 1950s, many catchments were covered with sheets of artificial rubber. Improper placement and susceptibility to damage by wind and animals destroyed most of these units.

Several types of plastic and other thin sheetings have been investigated as potential soil coverings for water-harvesting catchments. Unfortunately, most of these thin film coverings were found to be susceptible to mechanical damage and sunlight deterioration. Wind damage potential can be reduced by placing a shallow layer of clean gravel on the sheeting after it has been positioned on the catchment surface. The sheeting is the waterproof membrane, and the gravel protects the sheeting from mechanical damage. This treatment requires periodic maintenance to ensure that the sheeting remains covered with the gravel. Wind-blown dust trapped in the gravel layer provides a seedbed for plants and has been a minor problem. This treatment is relatively inexpensive if clean gravel is readily available (Cluff 1975).

One treatment being widely used to supply drinking water for wildlife and livestock in the United States is a membrane of asphalt-saturated fabric. The fabric is either a random-weave fiberglass matting or a synthetic polyester filter fabric matting. The matting is unrolled on the prepared catchment surface and saturated with the asphalt emulsion. Three to 10 days later, a second coating of asphalt is brushed on the membrane. These membranes are relatively resistant to damage by wind, animals, and weathering processes (Myers and Frasier 1974).

Water Storage

Water-storage techniques for holding the water collected from a catchment area can be separated into two general groups: (1) the soil profile or monolith, and (2) tanks or ponds. The type of storage selected will depend on many factors, such as the ultimate use of the water, availability of construction materials, availability and skills of labor, and site topography.

Soil monolith storages

In many runoff-farming applications, the soil profile within the crop-growing area is the water storage container. The primary factors that must be considered in designing soil monolith storages are: (1) the depth of the soil profile, (2) water-holding capacity of the soil, and (3) the infiltration rate of the soil surface.

Tank and pond storage

Any container capable of holding water is a potential water-storage facility. External water storage is a necessary component for drinking water supply systems, and may also be a part of a runoff-farming system where the water is applied to the cropped area by some form of irrigation system. In many water-harvesting systems, the storage facility is the most expensive single item, and may represent up to 50% of the total cost.

Unlined earthen pits, or ponds, are usually not satisfactory methods of storing water for water-harvesting systems unless seepage losses are naturally low, the soil is sealed with chemicals, or the losses are controlled by liners of plastic or artificial rubber. Exposed liners are susceptible to damage from sun, wind, animals, and plants. Chemical soil sealants have limited applications, and should be used only as recommended and guaranteed by the manufacturer.

There are many types, shapes, and sizes of wooden, metal and reinforced plastic storage containers. Costs and availability are primary factors for determining the potential suitability of these containers. One common type of storage is a tank constructed with steel walls, with a concrete bottom or other type of impermeable liner or bottom. Containers constructed from concrete and plaster are relatively inexpensive, but their construction requires a significant amount of hand labor (Frasier and Myers 1983).

Since water harvesting is generally an expensive method of supplying water, controlling evaporation losses is an important factor, and should be an integral part of all water-storage facilities. Although relatively expensive, roofs over the storage are commonly used. Floating covers of low-density synthetic foam rubber are effective means of controlling evaporation from vertical-walled, open-topped containers (Dedrick et al. 1973). Evaporation control on sloping-side pits or ponds is difficult because the water-surface area varies with the depth.

Runoff-farming Systems

There are two basic runoff-farming systems. One is the direct water application system by which the runoff water is stored in the soil profile of the crop-growing area. The other is the supplemental water system by which runoff water is stored off-site and applied to the crop as needed. Some runoff-farming installations are a combination of the two types.

Direct water systems

In a direct water system the collected runoff water is diverted or directed onto the cropped area during precipitation. With this system, both runoff water and precipitation infiltrate into the soil. Except during low-intensity storms, the combined quantity of runoff and precipitation will exceed the infiltration rate of the soil. Dikes or ridges must be placed around the runon (cropped) area to retain the water and allow it to infiltrate into the soil. The runoff water for these systems may be obtained from channels using water-spreading techniques.

One common direct water runoff-farming system used for growing shrubs or trees comprises small catchments prepared directly upslope of the growing area. Typical catchment areas vary from irregular shapes with minimal site preparation and soil treatment to graded, compacted areas that are sealed to maximize the runoff efficiency. Runoff to runon area ratios vary from 1:1 to 20:1, depending on the expected quantity of water needed.

Systems utilizing water-spreading techniques, by which the water is diverted from channels or upland areas, may encompass relatively large areas (Fig. 1). They have been used for growing grain crops and forage grasses. Some of these systems may have

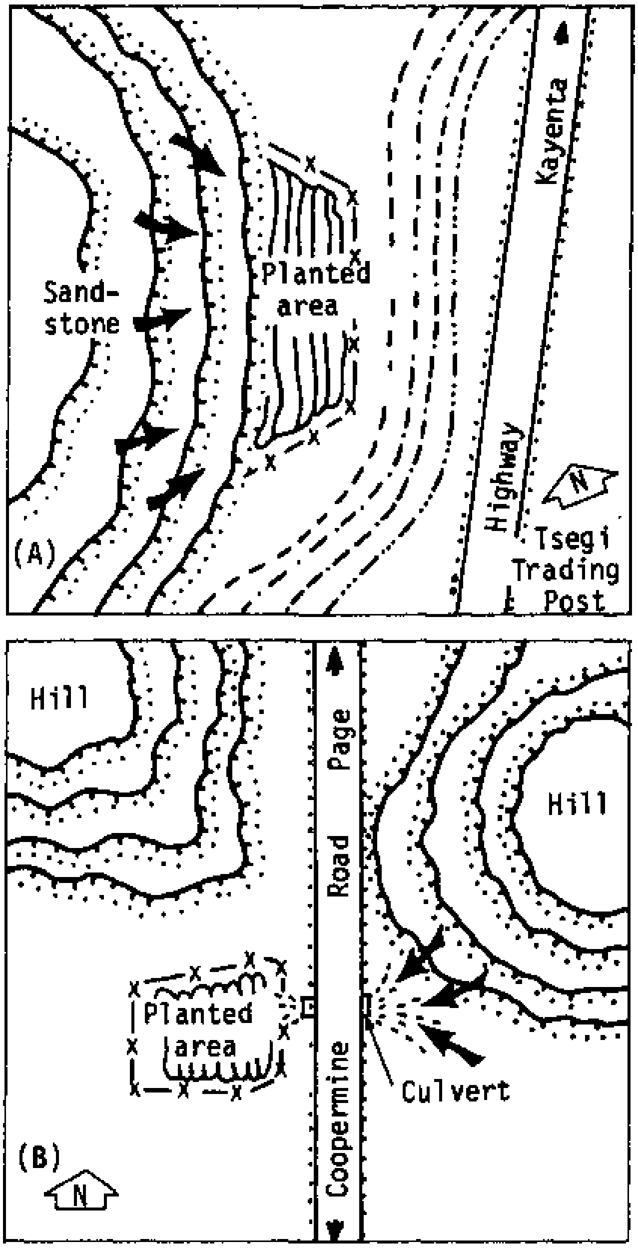


Figure 1. Water-spreading runoff-farming systems. A: John Boyd floodwater farming area near Copermine, Arizona, USA. B: Tsegi Canyon floodwater farming area near Kagenta, Arizona. (Source: Billy 1981.)

extensive ditching systems within the cropped area to permit better control of the water. Most of these systems in use today have evolved, over many years, by trial and error.

Supplemental water systems

A supplemental water system is one by which runoff water is collected and stored in a tank or pond away from the growing area, permitting its later application to the crop through some form of irrigation system. These systems have the advantage of being able to supply water to the crop when needed, but the disadvantage of extra costs and problems of providing the required water storage and irrigation facilities. If the catchment and storage facilities are located above or upslope of the cropped area, flood irrigation systems are an effective means of water application.

In the past decade, drip or trickle irrigation systems have come into use. These systems facilitate uniform water application, but are expensive to install. If the catchment and storage facilities are upslope, gravity provides the required water pressure. Otherwise, the water pressure is obtained by pumping.

Excess water that does not infiltrate into the soil profile drains into a storage tank or pond for later use. A typical system is composed of land graded into large ridges and furrows (roaded catchments) which have a gradient leading to the storage pond. Crops, such as grapes or fruit trees, are planted in the bottom of the furrows. An irrigation pump-back system is used to water the plants between runoff flows.

Case Histories

Village water

Shungopovi, Hopi Indian Reservation. The village of Shungopovi is located in Second Mesa, on the Hopi Indian Reservation in northeastern Arizona, USA. The village, built on top of sandstone rock mesas, had no source of water except that carried up from the valley, initially on foot, and later on the backs of burros. In the early 1930s a small water-harvesting system was installed to partially relieve the water shortage in the village. An area of approximately 0.3 ha was cleared of vegetation and the loose soil removed to expose the sandstone bedrock. A deep cistern was dug into the rock and covered with a concrete roof. This system was a functional part of the village water supply for about 30 years (Chiarella and Beck 1975).

Techo Cueneca, Mexico. The Techo Cueneca water-harvesting system provides part of the domestic water supply for 30 families (approximately 180 people) for the village of Lagunita y Ranchos Nuevos, in north-central Mexico. This system consists of an inverted galvanized metal roof (269 m^2) supported on a steel framework above a steel tank of 80 m^3. Labor for constructing the unit represented 36% of the total cost, and was provided by the village. The system provides drinking water to the entire village for an average of 4.5 months each year. The villagers are allotted 20 Ld^{-1} per family. Water produced from the system is about one-third the cost incurred by hauling (1981 data; Carmona and Velasco 1981).

Pan Tak, Papago Indian Reservation. This is a multifamily water supply system. The Pan Tak village has three families (approximately 15 people) located approximately 100 km west of Tucson, Arizona. The water supply was a shallow well, a steel, closed-top storage tank of 39 m^3 and a gravity distribution system. The well, when pumped slowly, provided an adequate supply for existing domestic requirements.

In 1966, a large petroleum company, interested in water-harvesting, constructed a water-harvesting system adjacent to the village. This system consisted of a 1-ha catchment coated with sprayed asphalt, and a 300-m^3 steel rimmed, concrete-bottommed tank (uncovered). The design allowed the water to seep from the tank to the groundwater where it could be pumped as needed to maintain the level of the well. The catchment area was reasonably effective in producing runoff for a few years, but there are no data or reports as to the success of recharging the groundwater and its recovery by the well. There was no scheduled maintenance program, and the system was abandoned.

In 1981 a grant was obtained by the Papago Indian Tribe to rejuvenate the system to increase the village's water supply. The lower half of the catchment area was cleared of vegetation, smoothed, and a membrane treatment of gravel-covered polyethylene installed. The large storage tank was cleaned and fitted with a pump, chlorinator, and filter unit and connected to the domestic supply tank. Two years later, this system was not being used because of the lack of local interest.

Runoff farming

Page Ranch, University of Arizona. The Page Ranch runoff-farming facility is located at the University of Arizona Page-Trowbridge Experimental Range north of Tucson, Arizona. This facility is used as an experimental and demonstration facility, and has several types of runoff-farming systems. The largest unit is a combination system for growing grapes. The catchment area was shaped into large ridges and furrows, and the sides of the ridges treated with sodium chloride mixed into the top 2.5 cm of soil. Grapes are planted at the bottom of the furrows. Excess water from the furrows drained into a pond sealed with sodium salts. The water collected in the pond is pumped back onto the grape-growing area and applied through a trickle irrigation system (Dutt and McCreary 1975).

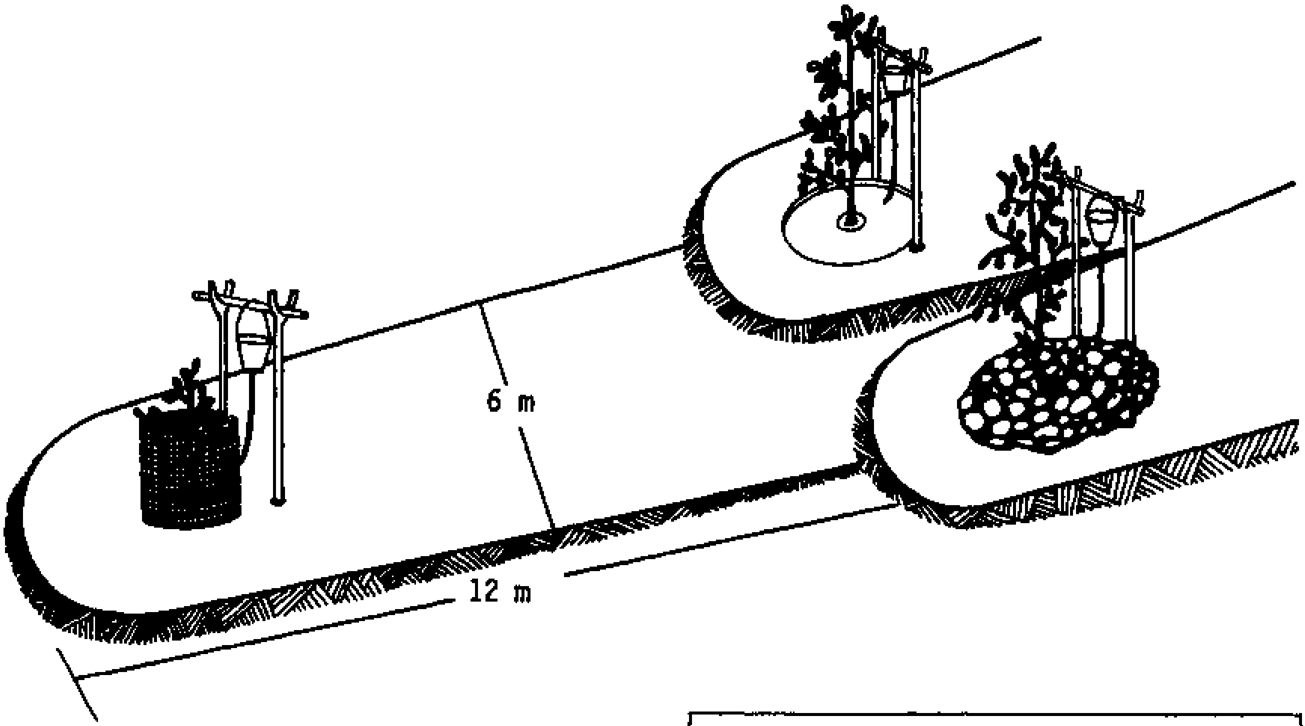
Black Mesa, University of Arizona. The Black Mesa water-harvesting system, a demonstration facility located in northeastern Arizona on displaced overburden from a strip coal mine, is one of the largest combination systems in the United States. It consists of (1) three water storage ponds with a total capacity of slightly over 3000 m^3, (2) two leveled agricultural terraces of 1 ha each, (3) a "roaded" catchment for a 0.5-ha orchard, and (4) a fiberglass-asphalt gravel catchment of 3.2 ha, and a 2.9-ha salt-treated catchment. A pump system is used to transfer the collected water between ponds and to lift the water to irrigate the crop areas initially by flood irrigation, then later by means of a sprinkler system.

Annual crops grown and evaluated were beet, onion, turnip, potato, chard, lettuce, cabbage, tomato, squash, bean, pumpkin, melon, mango, and maize. All crops, except tomato, did well, with some producing at levels above the national average. The economic value of the maize produced was the lowest of all crops. This was not unexpected because maize is a traditional food in the area, and was planted for social reasons. Fruit trees had never been grown in the area before. All trees were growing well after 3 years, but it was too soon to determine the potential production of the varieties planted. Income from the water-harvesting project was about $1700 net per cultivated ha in 1981. Agricultural yields are expected to increase when the orchards reach maturity (Thames and Guff 1982).

Mexico. One of the many runoff-farming systems being evaluated in Mexico is located in the state of Nuevo Leon. This system is composed of a set of 248 direct-runoff units for growing pistachio trees. Each tree has a separate contributing runoff area of 70 m^2 (Fig. 2). Runoff area treatments under evaluation are: (1) compacted soil, (2) soda ash (Na_2CO_3), (3) road oil, (4) gravel-covered polyethylene, (5) gravel-covered asphalt, and (6) control (smoothed soil). Soil moisture is monitored under each tree at depths of 15,35, and 55 cm. Also included were various soil coverings immediately around the tree to limit water loss by evaporation (Velasco and Carmona 1980). Because of the growth rates of the trees, this is a relatively long-term study. One preliminary observation was that on some of the salt-treated units, the treated soil eroded from the catchment surface, and was deposited around the trees. This significantly reduced the infiltration rate.

U.S. Water Conservation Laboratory. The U.S. Water Conservation Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Phoenix, Arizona, has several water-harvesting, runoff-farming research sites. One runoff farming site in south-central Arizona was used to determine if the marginal plant growth and seed yields of native stands of jojoba (Simmondsia chinensis) could be improved with additional water using water-harvesting techniques. Small (20-m^2) direct-runoff systems were constructed around individual bushes in native stands. Three runoff area treatments were evaluated: (1) control (undisturbed), (2) compacted and later treated with clay and sodium salts, and (3) paraffin wax water repellents. Water use of each plant was determined by neutron soil moisture measurements. Because of severe frost encountered at three separate times during the 7-year study (1974-80), it was concluded that commercial farming of jojoba, under the climatic conditions at the test site, would not be practical (Fink and Ehrler 1981).

Southwest Rangeland Watershed Research Center. Limited studies have been conducted near Tombstone, Arizona, by the Southwest Rangeland Watershed Research Center, Agricultural Research Service, U.S. Department of Agriculture, on the effects of additional water provided by a direct-application runoff-farming system on the forage production of blue panic grass (Panicum antidotale). Runoff to crop-growing area ratios of 0:1, 1:1, 2:1, and 3:1 were evaluated. Runoff area treatments were (1) bare soil, (2) seeded with grass, and (3) waterproofed with paraffin wax. During a 3-year study, forage yields, using waxed runoff areas of 2:1, were 16 times the control (0:1). Adjusting yields to account for the land removed from potential production with the catchment area showed an average yield 5 times greater from the treated runoff area, as compared with an uninterrupted planting of grass (Schreiber and Frasier 1978). The increased forage production obtained from the waterproofed runoff area is probably not economically feasible for most areas where forage is the only product.



Socioeconomic Considerations

Water-harvesting/ runoff-farming techniques are practical methods of water supply for most parts of the world. It is a relatively expensive method of water supply. During the past few decades there have been several water-harvesting/runoff-farming systems constructed and evaluated worldwide. While many of these systems have been outstanding successes, some were failures. Some systems failed despite extensive efforts because of material and/or design deficiencies. Some others failed because of personnel changes, communication failures, or because the water was not needed. Word-of-mouth publicity of one failure will often spread more widely than all of the publicity from 10 successful units.

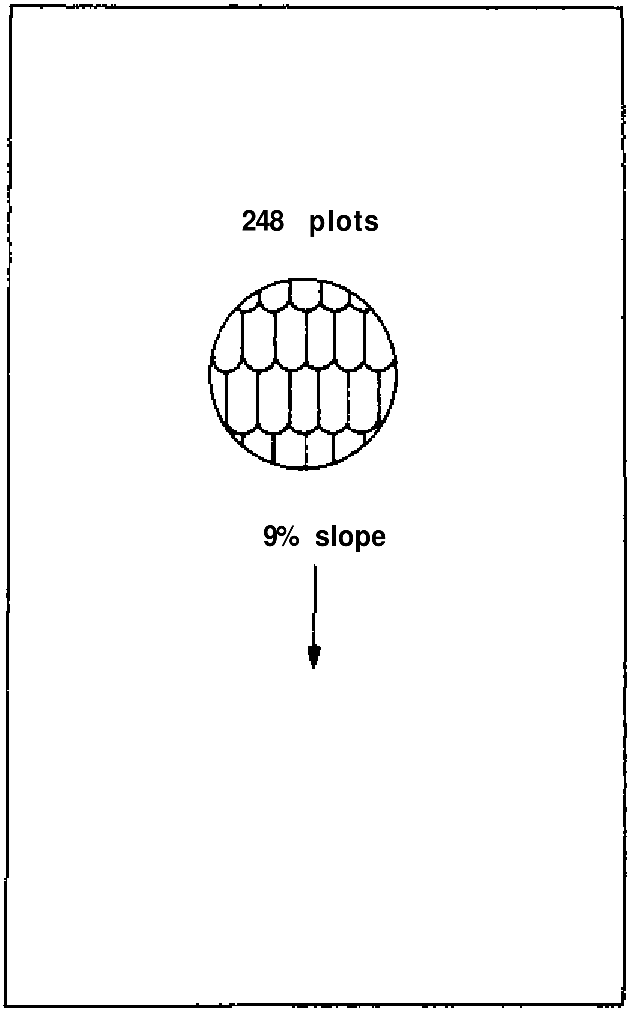


Figure 2. An experimental runoff-farming system for growing pistachio nuts. (Source: Velasco and Carmona 1980.)

References

Billy, B. 1981. Water harvesting for dryland and flood-water fanning on the Navajo Indian Reservation. Pages 3-7 in Rainfall collection for agriculture in arid and semiarid regions: proceedings of a workshop, 10-12 Sept 1980, Tucson, Arizona, USA (Dutt, G.R., Hutchinson, C.F., and Anaya Garduno, M., eds.). Farnham Royal, Slough, UK: Commonwealth Agricultural Bureaux.

Carmona-Riuz, G., and Velaseo-Molina, H.A. 1981. Rain harvesting for human livestock consumption in the semidesert high plains of Mexico. Pages 77-81 in Rainfall collection for agriculture in arid and semiarid regions: proceedings of a workshop, 10-12 Sept 1980, Tucson, Arizona, USA (Dutt, G.R., Hutchinson, C.F., and Anaya Garduno, M., eds.). Farnham Royal, Slough, UK: Commonwealth Agricultural Bureaux.

Chiarella, J.V., and Beck, W.H. 1975. Water harvesting catchments on Indian lands in the Southwest. Pages 104-114 in Proceedings of the Water Harvesting Symposium, 26-28 Mar 1974, Phoenix, Arizona, USA(Frasier, G.W., ed.). Washington, D.C., USA: U.S. Department of Agriculture, Agricultural Research Service.

Guff, C.B. 1975. Engineering aspects of water harvesting research at the University of Arizona. Pages 27-39 in Proceedings of the Water Harvesting Symposium, 26-28 Mar 1974, Phoenix, Arizona, USA (Frasier, G.W., ed.). Washington, D.C. USA: U.S. Department of Agriculture, Agricultural Research Service.

Cooley, K.R., Dedrick, A.R., and Frasier, G.W. 1975. Water harvesting: state of the art. Pages 1-20 in Watershed management: proceedings of a symposium, 11-13 Aug 1975, Logan, Utah, USA. New York, USA: American Society of Civil Engineers.

Dedrick, A.R., Hanson, T.D., and Williamson, W.R. 1973. Floating sheets of foam rubber for reducing stock tank evaporation. Journal of Range Management 26(6):404-406.

Dutt, G.R. 1981. Establishment of Nad-treated catchments. Pages 17-21 in Rainfall collection for agriculture in arid and semiarid regions: proceedings of a workshop, 10-12 Sept 1980, Tucson, Arizona, USA (Dutt, G.R., Hutchinson, C.F., and Anaya Garduno, M., eds.). Farnham Royal, Slough, UK: Commonwealth Agricultural Bureaux.

Dutt, G.R., and McCreary, T.W. 1975. Multipurpose salt treated water harvesting system. Pages 310-314 in Proceedings of the Water Harvesting Symposium, 26-28 Mar 1974, Phoenix, Arizona, USA (Frasier, G.W., ed.). Washington, D.C, USA: U.S. Department of Agriculture, Agricultural Research Service.

Erie, L.J., French, O.F., Bucks, D.A., and Harris, K. 1982. Consumptive use of water by major crops in the southwestern United States. Conservation Research Report no. 29. Washington, D.C, USA: U.S. Department of Agriculture, Agricultural Research Service. 40 pp.

Fink, D.H., Cooky, K.R., and Frasier, G.W. 1973. Wax-treated soils for harvesting water. Journal of Range Management 26(6):396-398.

Fink, D.H.,and Ehrler, W.L. 1981. Evaluation of materials for inducing runoff and use of these materials in runoff farming. Pages 9-16 in Rainfall collection for agriculture in arid and semiarid regions: proceedings of a workshop, 10-12 Sept 1980, Tucson, Arizona, USA (Dutt, G.R., Hutchinson, C.F., and Anaya Garduno, M., eds.). Farnham Royal, Slough, UK: Commonwealth Agricultural Bureaux.

Frasier, G.W. (ed.) 1975. Proceedings of the Water Harvesting Symposium, 26-28 Mar 1974, Phoenix, Arizona, USA. Washington, D.C, USA: U.S. Department of Agriculture, Agricultural Research Service. 329 pp.

Frasier, G.W. 1980. Harvesting water for agriculture, wildlife and domestic uses. Journal of Soil and Water Conservation 35(3): 125-128.

Frasier, G.W. 1981. Water for animals, man, and agriculture by water harvesting. Pages 83-86 in Rainfall collection for agriculture in arid and semiarid regions: proceedings of a workshop, 10-12 Sept 1980, Tucson, Arizona, USA (Dutt, G.R., Hutchinson, C.F., and Anaya Garduno, M., eds.). Farnham Royal, Slough, UK: Commonwealth Agricultural Bureaux.

Frasier, G.W., and Myers, L.E. 1983. Handbook of water harvesting. Agriculture Handbook no. 600. Washington, D.C, USA: U.S. Department of Agriculture, Agricultural Research Service.

Frith, J.L. 1975. Design and construction of roaded catchments. Pages 122-127 in Proceedings of the Water Harvesting Symposium, 26-28 Mar 1974, Phoenix, Arizona, USA (Frasier, G.W., ed.). Washington, D.C., USA: U.S. Department of Agriculture, Agricultural Research Service.

Hardan, A. 1975. Discussion: Session I. Page 60 in Proceedings of the Water Harvesting Symposium, 26-28 Mar 1974, Phoenix, Arizona, USA (Frasier, G.W., ed.). Washington, D.C, USA: U.S. Department of Agriculture, Agricultural Research Service.

Hollick, M. 1982. Water harvesting in the arid lands. Pages 173-247 in Scientific reviews on arid zone research (Mann, H.S., ed.). Vol.1. Jodhpur, Rajasthan, India: Scientific Publishers.

Laing, I. A.F. 1981. Evaluation of small catchment surface treatments. Australian Water Resources Council Technical Paper no.61. Canberra, Australia: Australian Government Publishing Service. 123 pp.

Lauritzen, C.W. 1967. Rain traps of steel. Utah Science (Sep):79-8I.

Myers, L.E., and Frasier, G.W. 1969. Creating hydrophobic soil for water harvesting. Journal of the Irrigation and Drainage Division, American Society of Civil Engineers 95 (IRI):43-54.

Mym, L.E., Frailer, G.W., and Griggs, J.R. 1967. Sprayed asphalt pavements for water harvesting. Journal of the Irrigation and Drainage Division, American Society of Civil Engineers 93(IR3):79-97.

Mym, L.E., and Frailer, G.W. 1974. Asphalt-fiberglass for precipitation catchments. Journal of Range Management 27(1): 12-15.

Schreiber, H.A.,and Frailer, G.W. 1978. Increasing range land forage production by water-harvesting. Journal of Range Management 31(l):37-40.

Thames, J.L., and Cluff, C.B. 1982. Water harvesting on surface mine spoils. Presented at the Wisconsin Mined-Land Rehabilitation Research Workshop, 1-11 June 1982, Fort Collins, Colorado, USA. 4 pp.

Vetaco-Molina, H.A., and Carmona-Ruiz, M.C.G. 1980. Cosecha de agua de lluvia para consumo humano. Consumo Pecuario y Agncultura de Secano. Primer Reporte de Evaluacion, Comision National de las Zonas Aridas. Monterrey, Nuevo Leon, Mexico: Instituto Technologico y de Estudios Superiores des Monterrey. 33 pp.

Water Supply Optimization with Discrete Stochastic Linear Programming

T. Engelhardt[1]

Abstract

A concept of improving irrigation management on Alfisols in hard-rock regions of the semi-arid tropics is presented. A discrete stochastic linear programming model was developed which permits the user to quantify the optimum water supply for composite watershed management for traditional agricultural production in south India. The model is flexible enough to be applicable to different site-specific conditions. Results show the beneficial impact of artificial groundwater recharging on agricultural production, employment, and income. Open dug wells, together with surface reservoirs for groundwater recharge, form an economically sound system of water management for increasing productivity on a sustained basis.

Composite watershed management will substantially increase productivity of the watershed; it is likely to increase mainly paddy production, but also oilseeds and wheat. It will also increase employment in rural areas. Further research, however, is needed to better understand the water flow from surface to aquifer and vice versa. Also, improved systems of water management on farmers' fields are required, especially for the irrigation of postrainy-season crops.

An Alternative Concept of Water Management

Despite years of research at ICRISAT and other institutions, little progress has been made in improving traditional rainfed agriculture on Alfisols in the SAT. The water-retention capacity of Alfisols is too limited to permit effective management of monsoon rainfall within the soil profile. The need to find new ways of retaining rainfall, either on the surface or under the ground, for supplemental irrigation is now recognized. One traditional method of runoff management is to collect and store it in irrigation tanks. But a traditional tank (which occupies a large area with low efficiency) is difficult to maintain when population density increases and land becomes more valuable (von Oppenand Subba Rao 1980). Another method is well irrigation. But this type of irrigation often depletes groundwater. Alarming depletion of groundwater is reported from Tamil Nadu (Sivanappan and Aiyasamy 1978) and other parts of the world. The negative effects of systems using groundwater on ecological balance, and the difficulties in managing surface-water irrigation projects (Botrail 1981), call for exploring alternative approaches to irrigation management.

Hard-rock regions, especially granitic regions with single-layered aquifers in the SAT, seem suitable locations for trying out a different concept of irrigation management. This concept may be called composite watershed management (CWM). The concept is based on responsibilities shared by farmers and government: farmers manage their water sources efficiently and government authorities provide water sources and manage aquifers. Farmers do not generally even conceive of the problem of aquifer management (Stoner 1978). Geophysical conditions in these areas are such that lineaments (fractures and fissures) in the hard rock permit water distribution from the source to the fields. Advanced technologies make it possible to find these lineaments and put them to effective use

1. University of Hohenheim, Inititut 490, Postfach 700562, D-7000 Stuttgart 70, West Germany.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants* Workshop on the Sute of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

for locating wells and reservoirs (Todd 1980). Some of the villagers* practices, such as storing water in small reservoirs or canals, have benefited aquifer yields (Engelhardt 1983). Farmers in southern India close the sluice of tanks towards the end of the rainy season for sustained groundwater recharge. Some of these have been described by Baden-Powell (1892) for southern India, and by Dhavan (1981) for Sri Lanka. A policy for extending water-distribution systems over a large area to enhance artificial groundwater recharge has been suggested.

If focus of efforts to improve agriculture in the Alfisol regions of the SAT is shifted to composite watershed management, two questions will arise.

1. What is the impact of artificial recharging structures on water availability, agricultural production, employment, and income?
2. What is the optimum size of reservoir for artificial recharging?

Both questions are related and call for simultaneous solution in order to arrive at an optimum investment strategy and optimum production organization. The most suitable tool for providing a solution to such a complex problem is a computerized mathematical model. Based on a field survey in a watershed near Hyderabad, a discrete stochastic linear programming model was designed. The results from different model runs are reported below. Only the agronomic and hydrological parameters obtained from field surveys and from literature were entered into the programming matrix. The infrastructural, economic, and natural conditions of a watershed, as well as the hydrologic properties of the aquifer, were not included as variables in the model. Because of site specificity there is no single answer to the problem of how to optimize water supply and allocation. Hence the solutions reported below relate to site-specific situations.

Model Description

Discrete stochastic linear programming model

Linear programming (LP) is a standard tool in economic planning. The disadvantage with ordinary LP models is that parameters and activities are assumed to be certain. Results of farm surveys, however, indicate the stochastic nature of agricultural production.

In the SAT the uncertainty of input and output levels is mainly due to unreliable rainfall. Consequently the model had to take into account the stochastic nature of rainfall and, hence, agricultural production. The discrete stochastic linear programming model developed for this research is shown diagrammatically in Figure 1.

The discrete stochastic linear programming (DSLP) technique was first developed and applied by Rae (1971a and b) and used with simulation by Trebeck and Hardaker (1972). DSLP differentiates between various states of nature. These states occur with probabilities. The probability of occurrence of one state of nature is based on past experience. All such activities as crop production, irrigation, marketing, etc., are formulated separately for every state. Parameters chosen are based on past experience.

In the study region rainfall in the rainy season is either high (>500 mm) or low (<400 mm). Since crop production takes place in two seasons (rainy season: Jun-Nov; and postrainy season: Dec-May), input-output relationships vary according to the amount and distribution of rainfall between the earlier (Jun-Sep) and the later part of the rainy season (Oct-Nov). (Note that the terminology for seasons used in this paper differs from more widely accepted definitions of rainy, postrainy, and dry seasons.)

Following are the five different states for which input-output relationships had to be averaged.

For rainy-season cropping activities:

State 1 High rainfall years (probability of occurrence 0.5)

State 2 Low rainfall years (probability of occurrence 0.5)

For postrainy-season cropping activities:

State 3 High rainfall in early part and also high rainfall in later part ("wet after wet"; probability of occurrence 0.375)

State 4 High rainfall early and low rainfall late ("dry after wet"; probability of occurrence 0.125)

State 5 Low rainfall early and low rainfall late ("dry after dry"; probability of occurrence 0.5)

(The state "wet after dry" does not occur.)

The different states are assumed not to compete for resources which are available in all states. But because rainfall determines the total water availability in a state, the activity levels in each state are

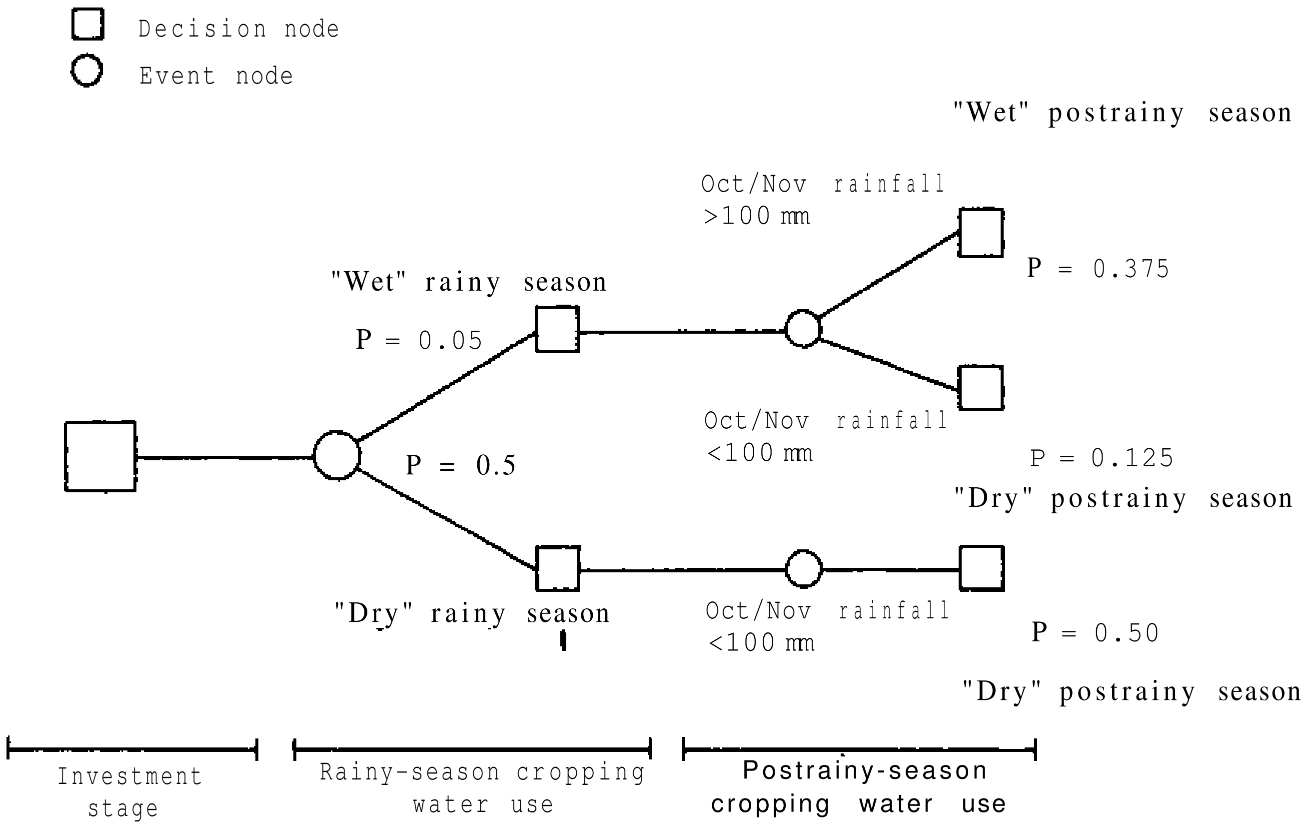


Figure 1. Diagrammatic representation of the discrete stochastic linear programming model.

determined by water. The postrainy and the rainy seasons, however, compete for water resources: water can be used in the rainy season for irrigation or it can be transferred to the next season by storage. The objective function maximizes expected income from the different activities (i.e., income multiplied by probability of occurrence of a state). As a result, the optimum composition of activities related to the expected state will be obtained. The objective value is the weighted average of all activity levels that enter into the the optimal solution.

There are several stages in the model. The first is the investment stage. During this stage, the decision whether to invest in reservoirs and wells is made based on expectations of occurrence of the various states. The extent of investment made in the first stage determines the resources available in the following stages and their respective states. Investment cost enters the objective function as annualized capital cost.

Water balance

The model described above is combined with a water-balance model (Fig. 2). In this model the rainfall is divided into runoff and effective rainfall (the portion which infiltrates into the soil). Runoff can be stored in reservoirs that recharge groundwater. A certain percentage of effective rainfall recharges the aquifer directly by deep percolation. The remaining portion will be available to meet the evapotranspiration requirements of the crops. Because of the different agronomic characteristics, as far as water requirement is concerned, crops are differentiated into wet crops (e.g., paddy), and rainfed crops that can be provided with supplementary irrigation in times of drought stress.

Model runs and strategies

The model was used to optimize agricultural production and investment on percolation reservoirs for various economic settings. As shown in Figure 3, mode] runs were performed at two levels: (a) on an idealized 2000-ha region, and (b) on a 5-ha farm. The runs optimizing production in the two regions were divided into: runoff less than 20% of rainfall; and runoff more than 20% of rainfall.

The latter represents a situation where only cropping and water-storage activities take place in the

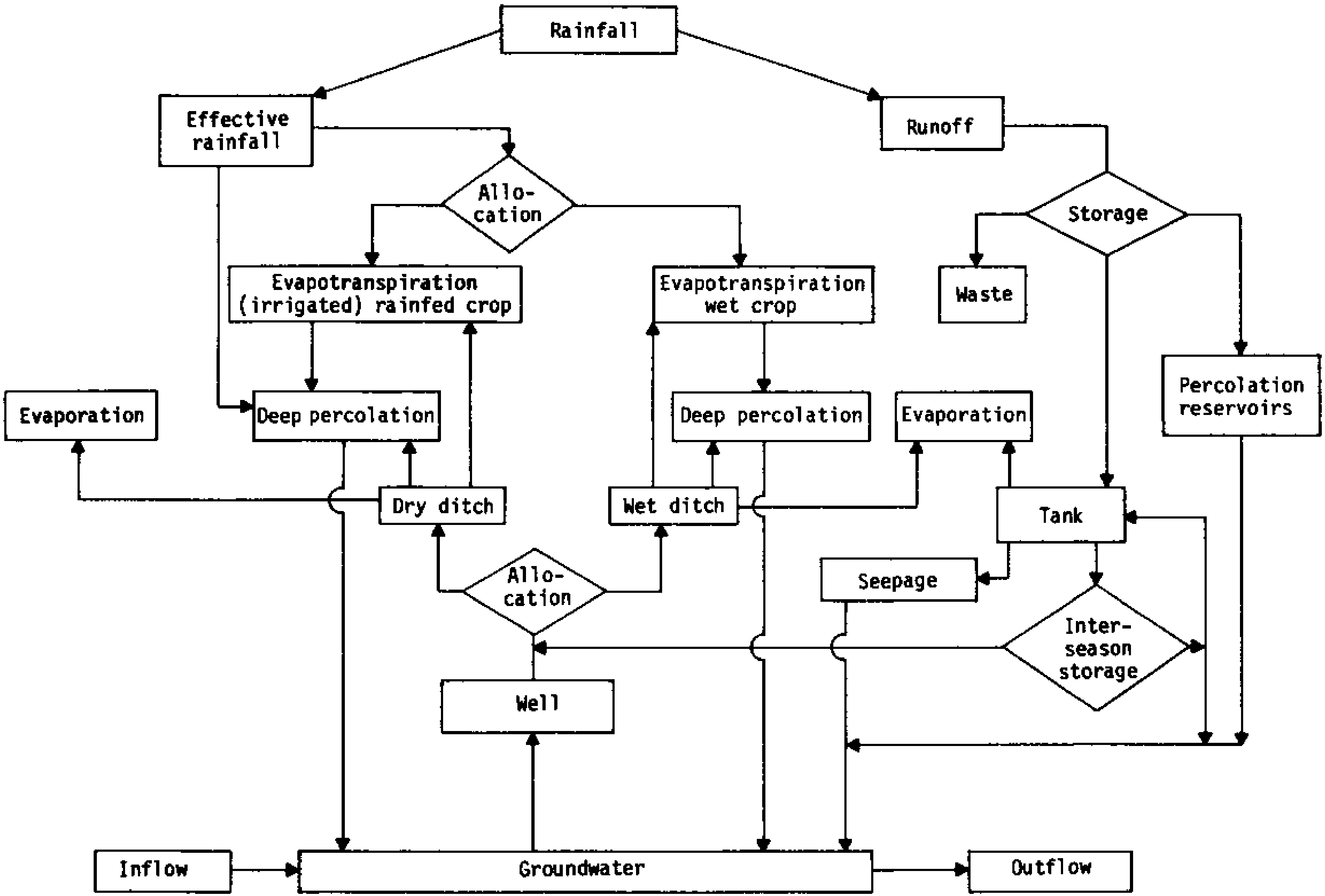


Figure 2. Water balance of the model on composite watershed development and management.

2000-ha watershed, but runoff water is also brought in from outside in addition to runoff from within the region. Under this setting, land submerged by water competes with land for arable production, whereas total runoff is assumed to be unlimited.

Further model runs were made by varying the ratio of the submerged to the irrigated area. A possible strategy for implementing a percolation tank construction project could be to request every farmer who owns a well to sponsor one recharge reservoir of specific size. Runs in group 1 reflect such a strategy. Group 2 describes a situation where a maximum of 3.72% of the total watershed can be submerged.

In all groups of runs, two further sequences of runs were made, one describing a situation with old wells only (5, 10, and 15 wells per 100 ha) and in the other, investment was provided for new wells. The purpose of regional model runs was to define the optimum investment strategy for percolation reservoirs and wells. Depending on the cost of such reservoirs, and on the water demand in a region (i.e., where there are old wells, new ones can be constructed that have additional water requirements), various optimal compositions of hydrological infrastructures (wells, tanks) have been derived.

As the regional model is a "group-farm model", unlimited mobility of resources is assumed. This is not so in reality. Therefore results are not directly comparable with reality, which is more complex.

One run was made to assess a situation where a minimum paddy requirement had to be fulfilled. For the single farm, our interest concentrated on the impact of electricity cost on production and income, and on the profitability of well construction.

The Impact of Composite Watershed Management

Regional model

As the main concern is the impact of reservoir construction on production, labor, water use, and income, these parameters are reported for major runs (Table 1). The results are given as expected means, i.e., activity levels of the optimum solution are multiplied by the probabilities of occurrence of the states in which they are performed. It can be seen from Table 1 that pursuing a strategy of one reservoir per well will have little impact on production, employment, or water availability. If well density is

Model	a. Region	a1. Coolected runoff <20% of rainfall	0.1862 ha submerged/well	5 10 Wells/ 15 100 ha
			3.72% of total watershed submerged	5 10 Wells/ 15 100 ha
		a2. Collected runoff >20% of rainfall	Optimum area submerged	5 10 Wells/ 15 100 ha
	b. Farm	Well capacity: 5 ha nr^{3} a^{-1}	Electricity price	0 : Rs kWh^{-1} 0.95
			Well investment cost	0 I Rs/well 50 000

Figure 3. Model runs.

Table 1. Selected model results: 2000-ha watershed.

Run	Well density (wells/100 ha)	Area submerged (%)	Expected net income (Rs ha⁻¹)	Cropping pattern (%): Rainy season, Rainfed	Rainy season, Irrigated, Wet	Rainy season, Irrigated, Dry	Postrainy season, Irrigated, Wet	Postrainy season, Irrigated, Dry	Human labor (m-d ha⁻¹): Rainy	Human labor: Post-rainy	Water pumped ('000 m³/season): Rainy	Water pumped: Post-rainy	Production (t): Coarse grain	Oil-seed	Fine paddy	Grain wheat
0	-	-	192.64	100	-	-	-	-	29	-	-	-	872	-	-	-
1.1	5	0	436.87	81.6	0	18.4	0.8	8.6	45	10	490	1160	706	301	52	158
1.2	10	0	574.02	69.1	0	30.9	0.8	9.1	56	11	680	1220	587	506	55	166
1.3	15	0	711.17	56.6	0	43.4	0.9	9.6	67	11	880	1290	467	711	58	175
2.1	5	0.9	476.61	76.1	0	23.0	1.0	9.4	49	11	690	1310	662	377	64	173
2.2	10	1.9	667.76	58.3	0	39.8	1.2	13.1	64	15	1100	1760	455	653	79	239
2.3	15	2.8	851.78	40.5	0	56.7	1.4	15.5	79	18	1520	2090	337	931	94	284
3.1	5	3.7	515.81	71.3	0.1	24.9	1.4	12.3	51	15	830	1770	621	408	103	282
3.2	10	3.7	761.50	47.6	0	48.7	1.6	17.0	72	20	1530	2290	414	799	103	415
3.3	15	3.7	898.65	35.0	0	61.2	1.6	17.4	82	20	1730	2360	294	1004	106	428
4.1	5	13.7	593.55	61.3	3.1	21.9	1.2	23.8	50	26	1700	2800	534	360	279	437
4.2	10	28.7	988.79	21.3	6.1	43.9	2.3	47.7	71	52	3400	5610	186	720	558	874
4.3	15	25.0	1262.16	0.0	0.0	75.0	11.1	36.8	89	53	2390	7850	0	1230	711	675

low (5 wells/100 ha), the increase in net income per ha due to increase in storage volume is negligible. To submerge a larger area for the sole purpose of groundwater recharge is not profitable (at well density of 5 wells/100 ha and 13.7% arable area submerged), because groundwater availability is then no longer limiting production. However, as well density increases (e.g., 10 wells/100 ha) it becomes worthwhile to extend the area submerged.

Percolation reservoirs with wells could transform an unirrigated agricultural system into an irrigated system with a better submerged area to irrigated area ratio than that of traditional tank irrigation systems. It has been shown by von Oppen and Subba Rao (1980) that the ratio of command area to submerged area is 0.9 in traditional irrigation tank systems. In a model run of 5 wells/100 ha, this ratio is 1.8. For well density of 10 wells/100 ha, the ratio would be 1.7.

In the case of 5 wells/100 ha, composite watershed management increases paddy production by 436%, supplementary irrigated oil seeds (e.g., groundnut) by 20%, and supplementary irrigated postrainy-season crops (e.g., wheat) by 176%. Supply of sufficient water from percolation reservoirs would increase employment opportunities by 38%. The effect would be mainly on employment in the post-rainy season, which is traditionally a slack season. In this season, employment opportunities increase by 160%. But it is likely that construction of percolation reservoirs will lead to construction of more wells. Theoretically 33% of the arable land used should be submerged for maximum groundwater recharge. Wells may have to be licenced and discharge restricted by a quota system, or by imposing progressive water rates. It should also be clear that percolation reservoirs should be only part of a package of activities that include bunding, afforestation, and other practices.

The results reported above are based on runs with reservoir construction costs at zero. This was done assuming that costs and secondary benefits break even. The secondary benefits of percolation reservoirs on employment, silting of downstream reservoirs, water balance of the region, etc., are difficult to assess on purely economic grounds. Because benefits from one reservoir cannot be enjoyed exclusively by a single farmer, percolation tank construction can be pursued only by the community (e.g., government). Therefore construction costs are of secondary importance so long as benefits from the system outweigh the costs.

However, parametric changes in construction costs of percolation reservoirs can test the stability of the optimum solution. Table 2 shows the optimum area submerged, depending on reservoir cost. This analysis shows that at zero cost of construction (to the farmer), a maximum area of 13.7% is brought under percolation tanks for 5 wells/100 ha, and 28.7% for 10 wells. As investment costs to the farmer increase, less and less area is submerged by percolation tanks. At present costs of about Rs 1 m^{-3} only 5-8% of the area would be submerged.

The main result from this analysis is that percolation reservoirs are profitable if such benefits as employment generation, additional production, and production stability are utilized in the analysis. It also shows that the cost of percolation tank construction cannot be borne by the farmers.

The model does not consider agronomic aspects of crop production. Therefore, results should be carefully interpreted as far as the cropping pattern is concerned. For instance, groundnut and wheat are two examples of irrigated dry crop production vs wet crops (e.g., paddy).

Interestingly, paddy production in the postrainy season enters optimum solutions in almost every run. In addition, instead of groundnut, wheat is produced in the postrainy season. Groundnut is mainly produced in the rainy season. Because agronomic constraints were not taken into account in the model, this result should not be overstressed.

Table 1 shows expected average cropping patterns, mean input quantities, and average production. These are based upon individual activities given by the model for every state. Because water constrains agricultural production in a dry postrainy season following a dry rainy season, no production activities are performed. Instead, water is used in the rainy season. If water availability increases, production of hybrid paddy on a small area begins in the postrainy season, and the limited amount of water is not spread over a larger area to irrigate dry crops.

Table 2. Optimum •ret submerged and cost of reservoir.

Investment cost (Rs m^{-3})	5 wells/100 ha (% submerged)	10 wells/100 ha (% submerged)
0	13.7	28.7
0.28	11.9	25.0
0.87	10.5	25.0
0.96	8.5	18.1
1.01	5.2	8.2
1.18	1.5	5.6
4.13	1.0	4.0
5.51	0.0	0.0

This is because paddy yields are high in a dry postrainy season that follows a dry rainy season. Only further agronomic research can establish reasons for the differences in yield levels of irrigated crops during the postrainy season. This example shows that input/output parameters of the same cropping activity vary according to different states of nature.

Tests were conducted with minimum paddy area per well. The minimum requirement was set at 1.4 ha for the rainy season and 0.9 ha for the postrainy. These are average areas under paddy in the well command area. Results indicate that natural recharge from the catchment can sustain only 6 wells/100 ha under such requirements. With percolation reservoirs submerging 3.7% of the catchment, artificial and natural recharge sustains 24 wells/100 ha.

This result shows that, if a policy for increased paddy production in a small-holder irrigation system is to be pursued, percolation reservoirs are essential for safeguarding groundwater recharge. Natural recharge will normally be insufficient to recharge the aquifer if an increasing number of well owners irrigate paddy.

Farm model (5 ha)

The same model can be used at the regional or farm level. In the latter case provision has to be made for unlimited water supply because, for the individual farmer, the quantity of water that he can draw is limited only by the capacity of the well. The capacity of the well is defined by the properties of the geological formation of the strata into which it is sunk. Average well capacity in the region is about 30000 m^3 per season.

The model was used to optimize the cropping pattern for a model farm with or without a well; to determine the maximum cost of a well so that investing in it is profitable; and to compute the elasticities of water demand, depending on electricity rates. By comparing cropping results from a farm with well irrigation, and results from a farm without, the impact of irrigation on farm income, cropping pattern, employment, and factor-use has been assessed.

The expected net income (minus annual capital cost of the well) would be Rs 1117 ha^{-1}. The cropping pattern would provide employment for 1868 man-hours ha'[1] at a current wage rate of Rs 0.3 h^{-1}.

Without irrigation, all 5 ha of the farm could be planted with rainfed sorghum. This would provide 235 man-hours of employment per ha. The annual expected net income from such dryland farming is Rs 192 ha^{-1}. A comparison of the two optimum solutions show that irrigation farming gives 5-6 times the expected net income per ha from pure rainfed farming.

The farm with irrigation facility would draw 45000 m^3 groundwater at an electricity tariff of Rs 0.16 kWh^{-1}. The cropping pattern is fairly stable regardless of electrical rate changes up to a certain level. It is when the electricity price exceeds Rs 0.6 kWh^1 that changes in cropping activity may occur. This means that, for agricultural use, electrical rates could be increased to the rate charged for industry (Rs 0.6 kWh^1) without affecting production. A price increase in electrical rates would, however, reduce income per ha. Table 3 shows the effect of electricity price (i.e., water price) on farm income and water consumption. It is likely that increased water rates will lead to more judicious water management, thereby counteracting the effect of red uced income.

It is possible to compute the average submerged area necessary to sustain the quantity of water consumed by the farm: 2.89 ha under a percolation reservoir is necessary to supply a 5-ha farm with sufficient water for optimal production. The ratio 1.73 of irrigated area to submerged area is much higher than that in traditional tank irrigation systems.

In the regional model, our interest focused on the impact of percolation reservoir costs on their feasibility. It was found that farmers may not voluntarily come forward to construct percolation reservoirs. Another constraining factor may be the cost of digging wells. Therefore, a run was done to compute the maximum amount a farmer will be able to invest in digging a well. As well costs increase solutions remain stable up to an investment of Rs 47000 per well with characteristics as assumed in the model (capacity 30000 m^3 per season). This indicates that farmers are likely to build their own wells because of the tremendous profitability of well irrigation as compared with unimproved rainfed farming.

Table 3. Electricity rates and farm income of a model farm (5 ha, 1 well).

Rate Rs kWh^{-1}	Annual net income (Rs ha-')	Water pumped (m^3)
0.0	1442	64050
0.16	1117	45093
0.35	746	45093
0.50	450	45093
0.60	270	32816
0.95	192	0

Further Reseach Requirements

The results discussed above do not necessarily reflect reality because, besides water availability, other constraints such as labor capacity, crop rotations, and subsistence requirements were not considered. This exclusion was intentional, in order to ensure that water-resource constraints are not masked by other constraints.

There is need for further research to determine more precisely the dynamic nature of groundwater flow. Little progress has been made in research on this aspect in the past.

Research on agronomic aspects should cover water management at the farm level. More accurate measurements of water application at the field level should be made. This is mainly to understand better why farmers prefer to irrigate wet crops instead of providing supplemental irrigation for rainfed crops. From our point of view the tremendous impact on yield of small but strategic irrigation at critical growth stages should result in the wider adoption of supplemental irrigation. In field surveys farmers listed several factors (Engelhardt 1983), such as (a) excessive water, (b) subsistence requirements, (c) pest- and disease-control problems, and (d) marketing constraints. However, these factors do not appear to be plausible explanations considering the results from irrigation trials under research conditions.

As mentioned earlier, aquifer management is not new; it has been practiced for centuries and farmers take to it intuitively. Numerous aquifer irrigation projects have been implemented in India in the past, especially in the states of Andhra Pradesh, Tamil Nadu, and Maharashtra. There has, however, been no systematic monitoring of aquifer performance, farmers' response to this method of irrigation, and the impact on production. While there is a surprisingly large amount of knowledge on artificial groundwater recharge with various government departments, it is not readily available to those who need it. ICRISAT could play an important part in collecting and disseminating this knowledge. Transfer of the concept of percolation tanks and dug wells to large areas in Africa with similar geological and climatic conditions seems feasible (Thomas 1982). More in-depth research, however, is required on this aspect. Here again ICRISAT can play a key role in the transfer of a technology that not only could halt the dangerous lowering of the groundwater table, but holds out promises for improving agricultural production on SAT Alfisols.

Acknowledgment

The author would like to thank M. von Oppen for his assistance during research at ICRISAT, and for his comments on this paper.

References

Baden-Powell, B.H. 1892. The land-system of British India. 3 vols. Oxford, UK: Clarendon Press.

Bottral, A.F. 1981. Comparative study of the management and organization of irrigation projects. World Bank Staff Working Paper no. 458. Washington, D.C., USA: World Bank.

Dhavan, B.D. 1981. Development of dugwell irrigation in Maharashtra. New Delhi, India: Institute of Economic Growth.

Engelhardt, T. 1983. Economics of traditional small holder irrigation management in South India. Ph.D. thesis, Universitat Hohenheim, Stuttgart, Federal Republic of Germany.

Rae, A.N. 1971a. Stochastic programming, utility, and sequential decision problems in farm management. American Journal of Agricultural Economics 53(3):448-450.

Rae, A.N. 1971 b. An empirical application and evaluation of discrete stochastic programming in farm management. American Journal of Agricultural Economics 53(4): 625-638.

Sivanappan, R.K.,and Aiyasamy, P.K. 1978. Cost of well water in Coimbatore region. Irrigation and Power 35(4):509-514.

Stoner, R.F. 1978. Conjunctive use of surface and ground water supplies. International Commission on Irrigation and Drainage Bulletin 27(2):65-67, 80.

Thomas, R.G. 1982. Harvesting water in the hard-rock zones. Ceres 89(15):5-6.

Todd, D.K. 1980. Ground water hydrology. 2nd edn. New York, USA: John Wiley.

Trebeck, D.B., and Hardaker, J.B. 1972. The integrated use of simulation and stochastic programming for whole-farm planning under risk. Australian Journal of Agricultural Economics 16(2): 115-120.

von Oppen, M., and Subba Rao, K.V. 1980. Tank irrigation in semi-arid tropical India. Economics Program Progress Report no. 9. Patancheru, A.P. 502324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

Tank Irrigation in Southern India: Adapting a Traditional Technology to Modern Socioeconomic Conditions[1]

M. von Oppen[2]

Abstract

Tank irrigation is a long-established technology to manage runoff water for irrigation. In India the area under tank irrigation is decreasing. This paper presents two concepts to adapt or transform the traditional water management system to suit modern socioeconomic conditions: (a) improved tank management with water control; and (b) an alternative land-management system to control runoff and erosion to recharge groundwater and sustain irrigation wells. Model calculations for the first concept show that improved tank management with a water control system of closing sluices on rainy days would save enough water to irrigate an additional 20% of the command area at a 17% lower risk of crop failure. Investment in an organization to employ and supervise tank water controllers can be justified by the expected returns from the increased area under irrigation. The second concept can be expected to generate substantial increases in net returns and employment. Further research is required to verify these findings.

Introduction

Water management holds the key to improved productivity of agricultural land in the semi-arid tropics (SAT). Tanks and open wells are traditional sources for small-scale irrigation in Indian agriculture. With increasing population pressures, however, difficulties arise: tanks degenerate because of inefficient maintenance and water control; and, with well irrigation becoming increasingly more attractive, construction of wells increases while tanks disappear. Groundwater levels fall because of overexploitation and reduced recharge from tanks. As costs and availability of conventional energy sources (diesel, electricity) become more restrictive, well irrigation meets with problems.

Improvement of Water Control in Existing Tanks

Research on irrigation tanks in southern India has shown that tank irrigation can be profitable (von Oppen and Subba Rao 1980b). But the performance of a majority of irrigation tanks has been poor, and this is reflected in the overall decline of tank-irrigated areas and growing instability.

Even in the case of tanks that may have some rudimentary management form of water distribution, e.g., a set date for opening of the sluice, the water is generally let out continuously once the sluice has been opened. Water controllers in charge of operating the sluice in the past have now almost disappeared. Better water management could be achieved through such simple measures as the following. (1) Reducing the outflow at night, since crop water requirements are less at that time. (2) Keeping the sluice closed on rainy days, assuming that rainfall will be sufficient to supply the requirement on those days. And (3) a combination of these two.

None of these measures will require any physical changes to be made to the tank as such. The water outlet structures will remain as they are because the outlets are traditionally fitted with a round hole that can be closed with a conical wooden plug from the top of the sluice. There will be no need for improved

1. Abridged version of an earlier paper: von Oppen et al. 1983.
2. Economics Program (now Resource Management Program), ICRISAT, Patancheru, A.P. 502 324, India.

ICRISAT (International Crops Research Institute for the Semi-iArid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center. India. Patancheru, A.P. 502 324, India: ICRISAT.

distribution channels for new cropping systems; paddy irrigation and field-to-field flow will continue.

A simulation model was built to compute the amount of water that can be saved, for instance, if the sluice remains closed on rainy days. Based on daily rainfall data the model computes the effects of various water-control rules. It calculates: (1) the chances of successfully growing a crop in the rainy season (there is still water in the tank during the 43rd week), and (2) the amount of water available for growing a second crop (at the end of the 43rd week). The 43rd week is assumed to be the end of the first season for a rice crop that takes about 120 days to mature.

The results are presented in Table 1. They show that, in a 10-ha command area, water control by closing the sluices on rainy days will reduce the number of years during which the tank runs dry before harvest from 50 years to 40, i.e., the probability of crop failure in the command area of this particular tank will drop from 0.69 to 0.56. Assuming an increase in the command area of 20%, water control would bring down the risk of crop failure from 0.73 to 0.59. These probabilities of crop failure are relatively high because of the small tank size assumed. Larger tanks have relatively lower evaporation and seepage losses, and therefore would benefit even more from water control involving water storage over longer periods.

In summary, water control of the kind described will permit irrigation of a command area that is 20% larger and at a 17% lower risk of crop failure. The water left in the tank at the end of the rainy season will be 24% above the amount under no water-control conditions in the existing tank.

Water control will, of course, not be cost-free. An organization to employ and supervise tank controllers will have to be established. This organization has to be planned for individual states in India and in such a way to make it fit into the existing structure of the respective department responsible for tank irrigation.

For assessing the costs of such a water-control system, a study was carried out by an ICRISAT consultant (Venkatram 1980). Conditions prevailing in the states of Maharashtra, Andhra Pradesh, Karnataka, and Tamil Nadu were studied, and the most feasible organization was projected. The costs of the water-control systems projected for each state were compared with the expected returns from a 20% larger tank-irrigated area. These comparisons are presented in Table 2. For each of the states included in the study it shows the expected total returns from a water-control system to farmers and to the state governments. The returns to farmers, of course, exceed those to the state governments by a multiple of over 15, as the farmers' average net returns from tank-irrigated agriculture exceed the present water rates by the same multiple.

The alternatives for financing the schemes in the different states and the likely expenditures are also presented in Table 2. It was assumed that for water regulators, 20% of the salary could be borne by the

Table 1. Tank simulation model results (with irrigation on Alfisols) using 70 years of daily rainfall data (Hyderabad, 1901-1970).

	10-ha command area 1000 m^3 outlet		12-ha command area 1200 m^3 outlet	
Details	Daily outlet without water controller	Nonrainy day outlet with water controller	Daily outlet without water controller	Nonrainy day outlet with water controller
Number of years the tank runs dry at the end of 43 rd week (27 October)	48/70 (0.69)'	39/70 (0.56)	51/70 (0.73)	41/70 (0.59)
Average water stored in the tank (in m^3) at the end of 43rd week	23800 (100)2	33000 (139)	22200 (100)	29600 (133)

1. Probability of tank being dry.
2. Percentage figure.

Table 2. Expected returns and expenditures (in million rupees) from improved water-management alternatives in tank-irrigated areas of selected states in India.

			Alternative expected expenditures				
					Supervision and water regulation		
						Government[6]	
	Expected returns		Grant for water regulator				
State	Farmers[1]	Govt[2]	Farmers[3]	Govt.[4]	Farmers[5]	Inspectors & supervisors	Supervisors
Andhra Pradesh	140.0	6.8	24.0	6.0	30.0	6.24	4.80
Karnataka	65.6	5.2	19.2	4.8	24.0	3.12	2.40
Maharashtra	19.3	6.2	NA[7]	NA	NA	NA	NA
Tamil Nadu	129.7	9.4	9.9	6.6	16.5	4.78	3.67

1. From 20% additional irrigated area at average farmers' net returns.
2. From 20% additional irrigated area at present water rates.
3. Farmers pay 80% of salary (Rs 100/month) for water regulators.
4. Government pays 20% of salary (Rs 25/month) for water regulators.
5. Farmers pay full salary (Rs 125/month) of water regulator.
6. Government pays for special supervisory staff, either (a) inspectors (1 per 50 tanks) and supervisors (1 per 20 inspectors), or (b) supervisors (1 per 100 tanks).
7. NA = not available.

Source. Venkatram 1980.

state government and the remaining 80% by the farmers who supervise; or, the farmers could pay the full water controllers' salary and the governments could provide supervision by inspectors and supervisors, or supervisors only. The expenditure for farmers would in all cases be only a fraction of the returns from a 20% additional command area. The expenditures for the governments would in no case exceed their returns from increased income as derived from existing water rates from 20% additional irrigated areas.

This exercise is indicative of the feasibility of the scheme at the aggregate level. The scheme is feasible and economically highly profitable to farmers while at the time being moderately remunerative to state governments.

The implementation of the scheme at the village level may initially pose some problems. Those who now have access to water may be apprehensive about its availability when the command area is extended. But, their experience with more stable water supplies during the first season and 24% more water during the second season (which has not been accounted for in terms of additional irrigated area) should convince those reluctant to collaborate.

Further study, including experimental research in villages, is required to decide how best and where to implement this concept. There may be cases where the concept described below is more applicable.

A Composite Water Management System for Alfisol Watersheds

Historically, one can observe a nonlinear relationship between population density and tank irrigation in large parts of India. Tanks tend to be established at population densities of 50-60 persons km^{-2}; higher population densities lead to creation of more tanks up to a maximum of about 220 persons km^{-2}. But beyond this point, an increase in population leads to a decreased number of tanks (von Oppen and Subba Rao 1980a). This observation is based on the simple truth that, with increased population pressure, the value of the land that a tank occupies rises. Consequently, the rationale for use and maintenance of a tank as an object of common property is increasingly being questioned by farmers and landless people. Private claims on the fertile tank land are followed by encroachments, which in turn lead to lower water levels and decreased irrigation efficiencies.

At the same time, irrigation wells around the tank provide water for irrigation. If tapped and recharged

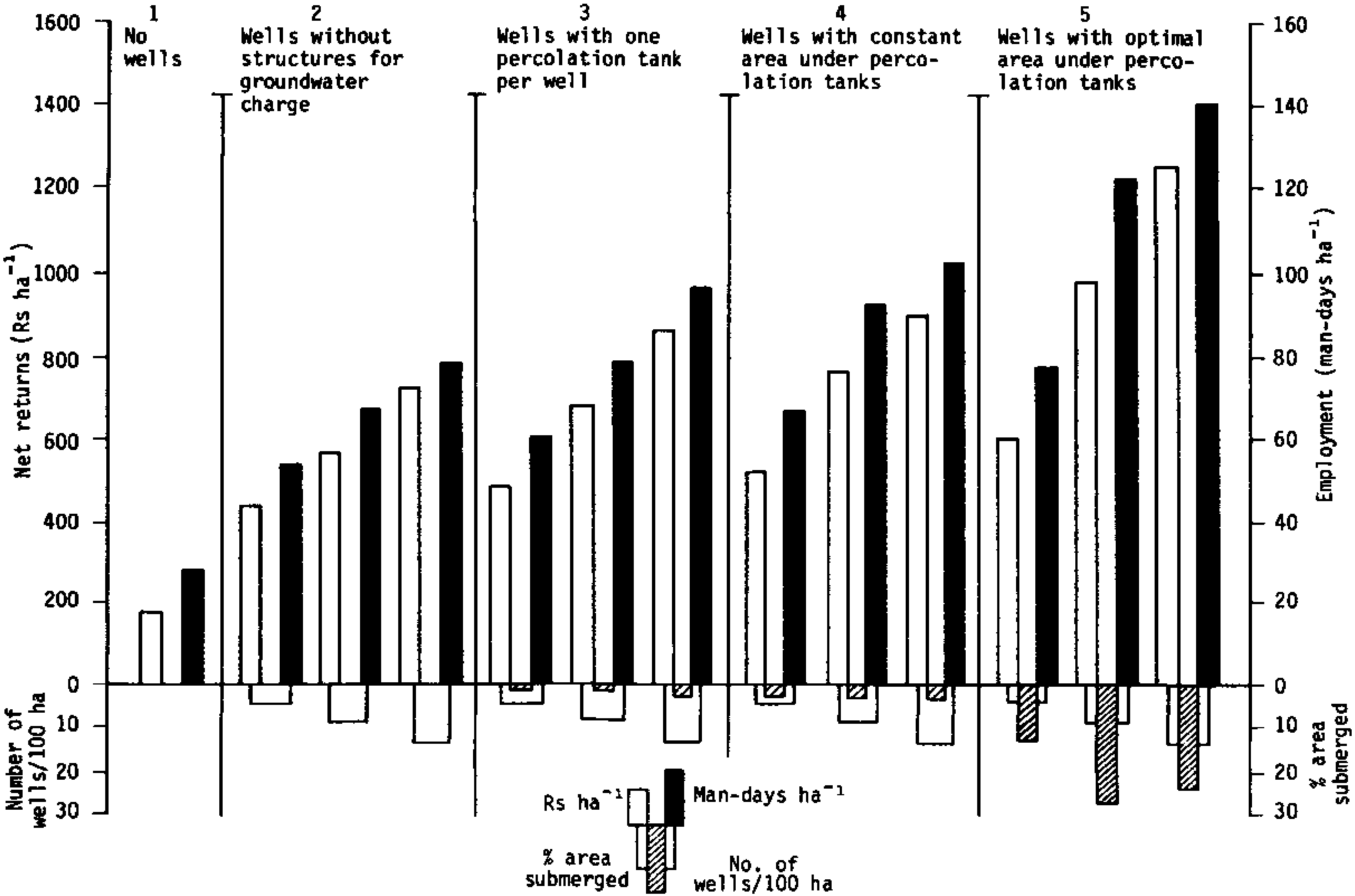


Figure 1. Net returns and employment on an Alfisol watershed under alternative water-management systems (results based on a model).

efficiently, this groundwater can irrigate all or most of the land formerly served by the tank, assuming favorable hydrogeologic characteristics.

Research at ICRISAT was initiated in 1981 to assess the potential of this concept, keeping in view the cost factors listed above and comparing these with the expected advantages in an optimization framework (Engelhardt 1983). This research was based on field surveys and a discrete stochastic linear model. The model allows the user to assess the impact of composite watershed management on SAT agriculture, which is constrained by the stochastic nature of its water supply. Parametric changes and sensitivity analysis of critical and unknown technical and economical parameters such as well density, factor cost, and product prices enable identification of the natural and socioeconomic environment for implementing the new concept.

Results from the model are summarized in Figure 1, which shows the benefits from water management were calculated in net returns (Rs ha^{-1}) and employment (man-days ha^{-1}). For comparison, the benefits of five alternative systems were calculated, ranging from rainfed agriculture with no wells to systems with wells (at different levels of well densities), but with no or only limited groundwater recharge.

While rainfed agriculture without wells produces net returns of Rs 200 ha^{-1} and provides employment for about 30 man-days ha^{-1}, well irrigation drastically increases benefits to double (at 5 wells/100 ha) or more than triple (at 15 wells/ 100 ha) the levels of rainfed agriculture. But at higher densities well water is restricted by limited groundwater. Substantial increases in net returns can be generated at high well densities through groundwater recharge. At optimum levels of groundwater recharge, about 15-25% of the cultivated area would be submerged by percolation tanks and the increase in productivity would be about 30% at low well densities of 5 wells/100 ha, but 70% at densities of 15 wells/100 ha.

Conclusions

The two concepts proposed for improved watershed management on Alfisols are: (1) improved tank management with water control, and (2) an alternative system of runoff- and erosion-controlling land management for groundwater recharge and sustained well irrigation. These two concepts were analyzed at ICRISAT in an exante framework and found to have considerable potential. Therefore, applied experimental work is justified to confirm these results and specify the changes required for introducing the new concepts. Research proposals are being considered by funding agencies for follow-up experimental work.

References

Engelhardt, T. 1983. Economics of traditional smallholder irrigation management in South India. Ph.D. thesis, Universitat Hohenheim, Stuttgart, Federal Republic of Germany.

Venkatram, B.R. 1980. Administrative feasibility of a Tank Irrigation Authority. Economics Program Consultancy Report. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

von Oppen, M., and Subba Rao, K.V. 1980a. Tank irrigation in semi-arid tropical India. Part 1. Historical development and spatial distribution. Economics Program Progress Report no. 5. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

von Oppen, M. ,and Subba Rao, K.V. 1980b. Tank irrigation in semi-arid tropical India. Part 2. Technical features and economic performance. Economics Program Progress Report no. 8. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

von Oppen, M., Subba Rao, K.V., and Engelhardt, T. 1983. Alternatives for improving small-scale irrigation systems in Alfisols watersheds in India. Paper presented at the Workshop on Water Management and Policy, 13-15 Sep 1983, Khon Kaen, Thailand. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

Production Constraints and Management Requirements

B: Tillage, General Management, and Fertility

Implement Development for SAT Alfisols

R.K. Bansal, N.K. Awadhwal, and V.M. Mayande[1]

Abstract

Field operations in Alfisols and related soils require timeliness and precision for the early establishment of a crop in the rainy season. Animal-drawn, multipurpose wheeled tool carriers (WTCs) have been found to be the most appropriate machinery for this purpose. Three designs discussed in this paper covered I ha in 3-4 hours for different tillage operations, and could be drawn by a pair of oxen of average size. A WTC fitted with a planter-and-fertilizer applicator, consisting of an inclined plate for seed metering and oscillating mechanisms for fertilizer metering and a double-shoe furrow opener, gave excellent results in sowing various crops, and covered 1 ha in 4-5 hours with an average draft of 1530 N (156 kg/) for four rows. A rolling crust breaker, developed to enhance seedling emergence through the surface crust, gave good results. Intensive primary tillage of Alfisols showed advantages in the early stages of crop growth, but they tended to disappear late in the season. Results of tillage studies conducted for 4 years indicate a need for further research to find out the comparative advantages of different intensities of primary tillage during the cropping season and off-season.

Introduction

As discussed elsewhere in this volume, Alfisols and related soils in the semi-arid tropics have certain inherent characteristics, such as low water-holding capacity, high erodibility, and a potential for excessive runoff, that are constraints in crop production under rainfed conditions. Alfisols are often very shallow and possess a subsurface layer of compacted soil that inhibits root development and water percolation. The loamy sand texture of the topsoil and predominance of kaolinite among the clay minerals make these soils structurally "inert" (Charreau 1977). Thus the noncracking topsoil becomes very hard when dry, making primary tillage possible only after good showers before the rainy season. Structural instability of these soils often causes crusting of the surface when rain alternates with dry periods. The formation of a crust subsequent to sowing can be a serious problem for the establishment of a crop with required plant density.

Alfisols therefore offer a considerable challenge regarding the development of farm machinery required for: tillage and seedbed preparation operations that make possible the early sowing of crops; the improvement of metering and placement of seed and fertilizer; the enhancement of seedling emergence in the event of crust formation; and the effective control of interrow weeds. The need to evaluate alternative tillage practice and to study the reaction of the soil to tillage tools, plant and soil interaction during plant establishment and early growth, and seedbed requirements were also recognized. This paper summarizes farm machinery development, and the results of selected experiments conducted on Alfisols, at ICRISAT Center.

Machinery Development

Multipurpose wheeled tool carriers (WTCs)

In the SAT, farmers mostly depend on human labor and draft animals (usually oxen) in their farm operations. In India a range of ox-drawn implements,

i. Farming Systems Research Program (now Resource Management Program), ICRISAT. Patancheru, A.P. 502 324, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

such as a country plow, a blade harrow, a seeder with hand metering for two or three rows, and an inter-row weeding hoe are common everywhere. These implements are attractive to farmers because of their low purchase and maintenance costs, easy availability from local artisans, and minimal repair requirements. But they are slow in operation, are tiring to use, and often fail to give the precision required for intensive cropping.

After initial experience with traditional ox-drawn implements in farming systems research at ICRISAT Center, efforts were directed towards the development of multipurpose wheeled tool carriers. As the name implies, such a tool carrier, drawn by oxen, asses, or mules, is capable of performing various field operations by the attachment of appropriate implements. The frame and linkages on the WTC have provisions for making vertical and lateral adjustments in the position of the implement with respect to the soil surface or the crop. An implement mounted on the WTC can be raised into a transport position, or lowered to operate in the soil, with a lever. A WTC provides stability in operation, comfort for the operator, and is designed to maintain the correct direction of travel in the field.

The first design of a WTC found to be promising

Figure 1. A Tropicultor with spring tines in use for seedbed preparation.

Figure 2. An Agribar being used for plowing on broadbeds with a set of left- and right-hand moldboard plows.

was the Tropicultor, already in use in some parts of West Africa. The Tropicultor was evaluated at ICRISAT Center and modified. Later, more work was done on matching implements to meet the operational requirements without undue stress on the oxen. The Tropicultor (Fig. 1) has a set of pneumatic wheels supporting a tubular frame, with a beam at the front and a square toolbar 1.7 m long at the rear. The toolbar is attached to the lifting linkages with removable pins such that its height from the ground can be varied. All implements are mounted on the toolbar with simple U-clamps. The Tropicultor can also be converted into a two-wheeled cart by mounting a cart attachment over the frame.

The Tropicultor was found to be very effective and useful for field operations in watershed areas at ICRISAT Center and in farmers' fields. However, its high purchase price has been a major constraint in its acceptance by Indian farmers. Subsequently, development of relatively low-cost tool carriers with comparable versatility and utility was initiated. The first low-cost design, the Akola Cart, was derived from an ox-drawn small cart popular in the Akola region of Maharashtra State in India. Its frame and wheels are made of wood, and a hollow, rectangular steel toolbar is attached to the frame. A lifting mechanism operated by a lever placed in the center raises or lowers the implement mounted on the toolbar. The arrangement for mounting implements on the toolbar is similar to that for the Tropicultor.

The second low-cost design is the Agribar (Fig. 2). It is made of steel and has a 1.7-m long square toolbar to which a beam is attached at right angles. The toolbar is supported on two wheels of 30 cm diameter. Implements mounted on the toolbar can be raised or lowered by operating a lever at each end of the toolbar one by one. Implements for the Agribar are the same as those used with the Tropicultor, and the manner of mounting is identical.

To compare the performance of these three WTCs, we measured the actual field capacity (the area covered in 1 hour), and the draft requirements for different operations. To enlarge the scope of the experiment, a 20.9 kW (28 hp) TE-type Bouyer tractor was also included in the study. Plot sizes varied from 271 to 688 m^2, because of the shape of the field.

For all field operations, the Tropicultor had greatest reliability (ICRISAT 1982). With the Akola Cart there were problems of frequent breakdowns because of failure of the wooden components. Similarly, the Agribar, at that stage in its development, was not strong enough to withstand the load of two normal-sized 225-mm wide moldboard plows or ridgers. Accordingly, smaller plows and ridgers were used on the Cart and the Agribar. Results obtained for the time required per ha for different operations (Table 1) showed that the Tropicultor was the most efficient. Because of the smaller plows used with the Akola Cart and the Agribar, plowing was done twice in the respective plots. For other operations the difference between the treatment in terms of time-saving was very small, often statistically nonsignificant ($P < 0.05$). The tractor did not show any advantage over the animal-drawn machinery.

The tractor time required was influenced by such factors as the skill of the operator, implements used, length of run, and turning time. It was observed that the tractor required more turning time than a WTC. In straight runs, the advantage that could have been obtained in the tractor treatment was lost partly because of the requirement to operate slowly to avoid damage to the implements, which were designed for use with a WTC, and partly because of the small plot size.

Table 2 gives the range and average figures for pull force (draft) measured by a dynamometer placed in the beams of the WTCs. The data showed that it is the type of operation and not the type of WTC that determines the pull requirement, because over 90% of the pull is attributed to the implement used. Plowing and ridging are heavy operations. Regardless of pull in the range of 1600-2250 N (163-230 kgf), oxen were able to perform these operations and work continuously for 6 hours a day with normal rest periods. Similarly, the effect of the machinery system was not found to be significant on plant population and yield of sorghum and pigeonpea crops (Table 3). Further testing of the Tropicultor, Akola Cart, and Agribar revealed poor viability and transferability of the Akola Cart design. Inappropriate dimensional control and seasonal swelling and shrinking of the wooden components called for too much attention every year. As a result of this, no further design work with the Akola Cart was done.

Table 1. Average machine-hours per ha required for variouss operations with different machinery systems used iain Alfisol watershed, ICRISAT Center, 1979-80.

	Machinery systems			
	Animal-drawn WTC			
Operations	Akola Cart	Agribar	Tropicultor	Tractor
Plowing I	1.8	1.8	1.8	3.2
Cultivation	2.7	2.8	2.6	3.0
Plowing 11	3.2	3.6	NR	NR
Ridging	3.2	3.6	2.7	3.4
Bed-shaping	3.4	3.4	2.4	2.6
Fertilizer application	3.3	3.2	3.0	2.7
Planting	1.9	2.7	2.0	2.8
Interrow cultivation I	3.1	2.7	2.5	3.0
Interrow cultivation II	3.7	3.7	2.9	3.0
Total	26.3	27.5	19.9	23.7

NR = Not required.

Table 2. Average and range of pull (N) observed for various operations with different machinery systems in an Alfisol watershed, ICRISAT Center, 1979-80.

	Machinery system					
	Akola Cart		Agribar		Tropicultor	
Operation	Range	Average	Range	Average	Range	Average
Plowing	1600-2250	2000	1700-2000	1950	1800-2000	1900
Cultivation	1500-1650	1550	1300-2000	1600	l400-1700	1550
Ridging	1750-1850	1800	1700-1800	1750	1700-1800	1750
Bed-shaping	1250-1600	1500	1200-1600	1450	1450-1550	1500
Fertilizer application	1100-1400	1300	1400-1600	1500	1400-1450	1450
Planting	1150-1200	1150	1100-1250	1200	1350-1400	1400
Interrow cultivation I	1300-1400	1350	1400-1500	1450	1400-1700	1600
Interrow cultivation 11	1350-1650	1450	1050-1600	1350	1150-1600	1400

Table 3. Plant stand and grain yield obtained using different machinery systems ir an Alfisol watershed, ICRISAT Center, 1979-80.

		Machinery system				
		Animal-drawn WTC				
Crop	Factor	Akola Cart	Agribar	Tropicultor	Tractor	SE(±)
Sorghum	Plant stand ha^{-1}	168000	185000	155000	166000	10760
	Yield (t ha^{-1})	4.0	3.5	3.4	3.6	0.49
Pigeonpea	Plant stand ha^{-1}	68000	62000	69000	67000	4733
	Yield (t ha-')	0.44	0.45	0.45	0.44	0.065

Sowing and fertilizer application

Traditionally, sowing in India is done by the hand-metering of seed into a furrow opened by a country plow. A multirow wooden seed drill, called a "gorru" or "tippen", is also widely used for sowing. The use of inorganic fertilizer is relatively new among dryland farmers in India, and the sowing techniques they currently use are inadequate to meet the operational requirements if fertilizer is to be drilled at the same time as seed. Some multirow hand-metering seed drills have been modified for placing a basal dose of fertilizer along with the seed, e.g., the Royal gorru and Eenati gorru (Venkata Nadachary and Kidd 1981).

The traditional systems have several limitations that result in poor plant stands, even though the normal rate of seed application is 3 or 4 times more than that recommended (Soman et al. 1981). Traditional systems give uneven distribution of seed, which means crowding of plants at different locations in the same row and gaps elsewhere. Another limitation of this system is inappropriate placement of the seed, and delay in covering it. In Alfisols, with low soil-moisture retention capacities, any delay between opening and closing a furrow can adversely affect germination and emergence. Finally, ground coverage is slow, and traditional operations require at least two or three people. Thus, for completion of sowing of crops early in the rainy season, traditional sowing equipment is not adequate.

For moisture conservation in Alfisols, minimum soil disturbance, quick furrow closing, and proper compaction are essential for seeding. When more than 10 kg ha^{-1} of nitrogen fertilizer needs to be applied at seeding, it should be placed in a band away from the seed to avoid salt injury (Sanghi et al. 1982). The separation of seed and fertilizer appears to be more important in Alfisols and related soils than in clayey soils such as Vertisols, probably because of lower availability of moisture around germinating seeds in the former case.

During the early phase of farming systems research at ICRISAT Center, fertilizer application preceded sowing as a separate operation in both Alfisols and Vertisols. A narrow shoe-furrow opener (Fig. 3a) was developed for planting on the lines where fertilizer was already banded. With the devel-

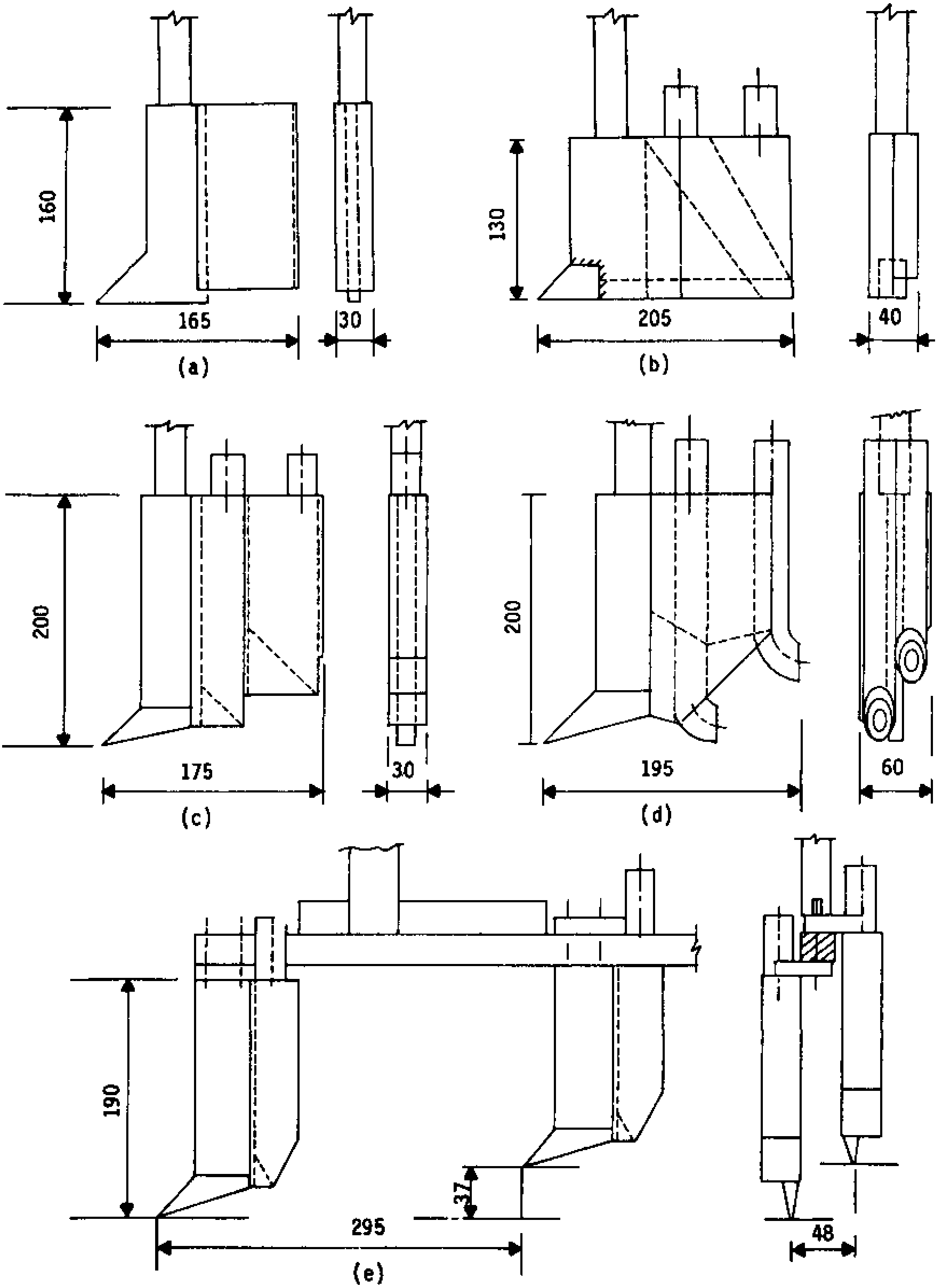


Figure 3. Furrow openers. (Measurements in mm.)

opment of a combined planter-and-fertilizer applicator a change in the furrow-opener design became necessary.

Figure 3b shows a two-chamber single-shoe furrow opener designed to cut a narrow slit for minimizing draft and soil disturbance. With this furrow opener, fertilizer was placed on one side of the seed and at the same level. Two main shortcomings of this design were found to be inadequate separation of seed and fertilizer, and clogging of the furrow opener with soil when lowered into the working position.

Another design (Fig. 3c) attempted to overcome these problems. It required fertilizer to be placed about 40 mm directly below the seed row. The furrow opener was closed at the bottom and had exits for seed and fertilizer at the rear. While this design got over the problem of clogging, seed and fertilizer separation varied from 0 to 20 mm owing to the poor flow of moist soil.

In the third modification (Fig. 3d), the furrow opener was made wide and had exits at different levels. Fertilizer was expected to fall in a band about 40 mm below and 30 mm to the side of the seed row, separated by a layer of soil. The performance of this design was also unsatisfactory because of insufficient seed and fertilizer separation. The seed tended to roll down on to the fertilizer band because the soil layer between them was thin. Covering a 60-mm wide furrow was also found to be a problem.

Finally, a double-shoe furrow opener (Fig. 3e) that keeps seed and fertilizer well separated was developed. It has two identical, narrow shoes bolted to an inverted T-frame that permits fertilizer to be placed 40-50 mm to the side and below the seed. Furrows opened by the fertilizer shoe are partially closed by the seed shoe. The seed row is covered and compacted by floating arms and a press wheel. The double-shoe furrow opener design gave adequate separation between seed and fertilizer, and performed without any problem of blockage in both Vertisols and Alfisols (ICR1SAT 1984).

A four-row planter-and-fertilizer applicator developed at ICRISAT Center permits seed and fertilizer to be metered mechanically and to be placed at required depth. This planter is suitable for a wide range of crops grown in the SAT. Seed is metered by an inclined-plate mechanism. Metering plates, made in aluminium, can be changed easily to suit a particular crop. The fertilizer application rate is controlled by an oscillatory mechanism fitted to the bottom of the hopper. Both mechanisms are driven from the left wheel of the Tropicultor on which the planter is mounted. Test results from an ICRISAT Alfisol watershed showed that the machine can cover 1 ha in 4-5 hours depending on plot size, shape, and other operational factors (Table 4). Pull forces required for sowing on Vertisols and Alfisols are given in Table 5. Sowing of four rows of any crop on Alfisols was never found to be difficult because the pull requirement was not excessive and the oxen could sustain the load for normal working hours.

Development of a rolling soil-crust breaker

Soil crusts on Alfisols impede seedling emergence. Once a crust forms over a seeded row, it needs to be

Table 4. Actual field capacity for planting and fertilizer application in different land-management practices on Alfisols, ICRISAT Center, 1980-81.

Watershed no.	Land treatment	Crop	Actual field capacity (ha h^{-1})
RW-3D	BBF	Sorghum/ pigeonpea	0.25
RW-3D	BBF	Pearl millet/pigeonpea	0.21
RW-3D	BBF	Castor/green gram	0.26
RW-3D	Flat	Sorghum/ pigeonpea	0.21
RW-3D	Flat	Pearl millet/pigeonpea	0.20
RW-3D	Flat	Castor/green gram	0.26
		Average	0.22

BBF = Broad beds and furrows.

Table 5. Pull requirement for planting and fertilizer application.

Soil	Crop	No. of rows per pass	Pull (N) Range	Pull (N) Mean	CV(%)	SE(±)
Vertisol	Maize	2	900-1400	1080	11	24
Vertisol	Sorghum/pigeonpea	3	1400-1700	1470	6	18
Alfisol	Pearl millet	3	1000-1400	1240	13	33
Alfisol	Cowpea	4	1300-1700	1530	8	25

wetted frequently or broken mechanically for satisfactory seedling emergence.

During rainless periods, application of water in the SAT is impractical, however, because of its limited availability; labor requirements and equipment cost are the other constraints. Farmers have no traditional equipment for breaking soil crusts. Therefore, a rolling crust breaker was developed that can be used on seeded rows (Awadhwal and Thierstein 1983). The manually-operated rolling crust breaker (Fig. 4), which can also be attached to a WTC, has two 150-mm diameter rollers with 16 rows of spikes 25 mm long. Spacing between the rows and the length of spike were selected to ensure that no crust was left undisturbed. The crust breaker covers a 180-mm wide strip over the seed row.

Performance of the rolling crust breaker was evaluated on Alfisol fields with sandy, sandy loam, and sandy clay soils. We examined the effect of breaking surface crusts on different pearl millet and sorghum genotypes. The pearl millet and sorghum genotypes were planted manually; about 35 mm of water was applied, by sprinkler from a height of 2 m, to produce a reasonably uniform and hard crust. A day before expected emergence, the crust surface was dry and its strength, measured with a pocket penetrometer, was in the range of 196 to 245 kPa (2.0 to 2.5 kg cm^{-2}).

The rolling crust breaker was used to break the soil crust on the seeded rows 1 day prior to the day of expected emergence. The emergence count was taken 1 week after the breaking of the crust. Seedling emergence under crusted conditions was very poor, and the use of the crust breaker increased the emergence significantly when soil moisture was not a limiting factor (Awadhwal and Thierstein 1983).

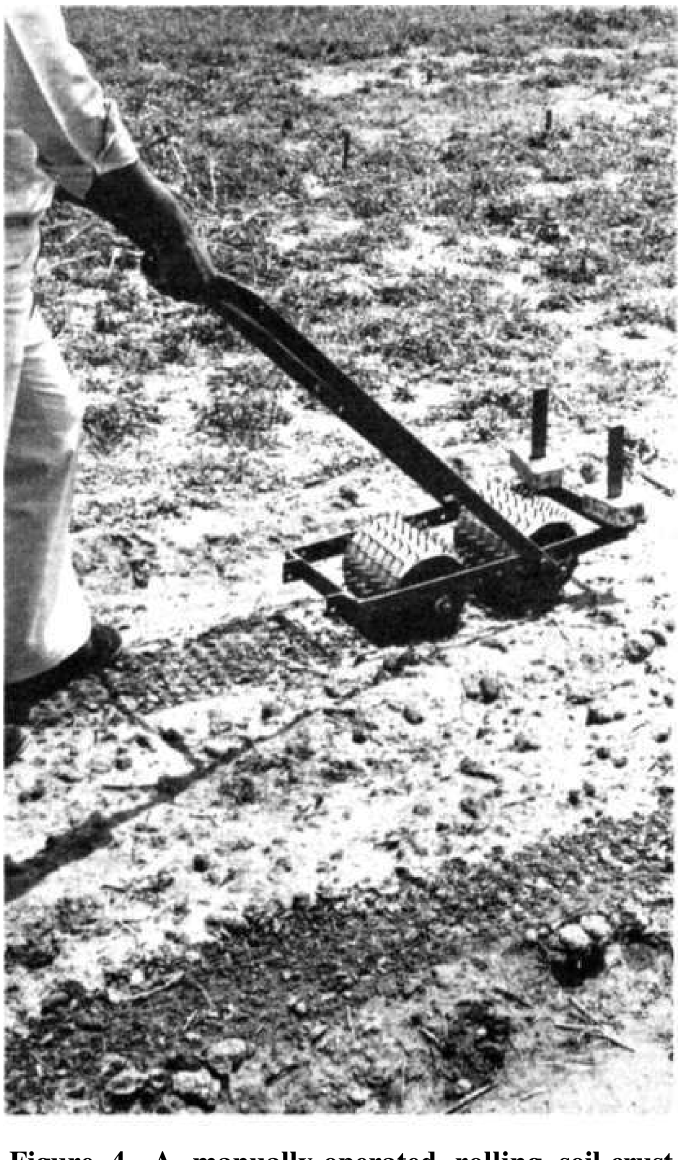


Figure 4. A manually-operated rolling soil-crust breaker.

Tillage Studies on Alfisols

Tillage experiments were conducted on Alfisols for 4 years from 1978 (Klaij 1983, Awadhwal and Thierstein 1984). The objectives of the studies were to evaluate alternative primary tillage practices and their effect on crop production, in terms of soil reaction to tillage tools, plant and soil interaction during plant establishment and early growth, and to evaluate seedbed requirements.

Tillage operations consume a large proportion of the total energy expenditure in all field operations. Hence the study also aimed to provide an understanding of the factors that can lead to the saving of energy. The experiments were conducted on a broadbed-and-furrow configuration where the traffic zone (furrow) is clearly separated from the cropping zone (broadbed). Four primary-tillage treatments evaluated, shown in Figure 5, were split-strip tillage covering the entire width of the broadbed in three successive passes of the WTC; strip plowing with right- and left-hand moldboard plows; chiseling to 120 mm depth at locations where crop rows were to follow; and shallow cultivation by duckfoot sweeps. The treatments were performed by using respective implements in conjuction with a WTC.

Variation in the rainfall pattern from one year to another, which affected moisture availability, had a greater effect on crop growth than the intensity of primary tillage. Intensive tillage by the split-strip method tended to make better seedbeds by turning and mixing the soil across the entire width of the broadbed, thus covering weeds properly. When compared with other treatments, weed intensity in split-strip tillage plots was less up to 22 days after planting, even though data were significant only at the 10% probability level (Klaij 1983). Tillage treatment did not affect weed development late in the season.

The major effect of tillage treatments was expected to be on availability of soil moisture during crop growth. Table 6 shows trends of soil moisture

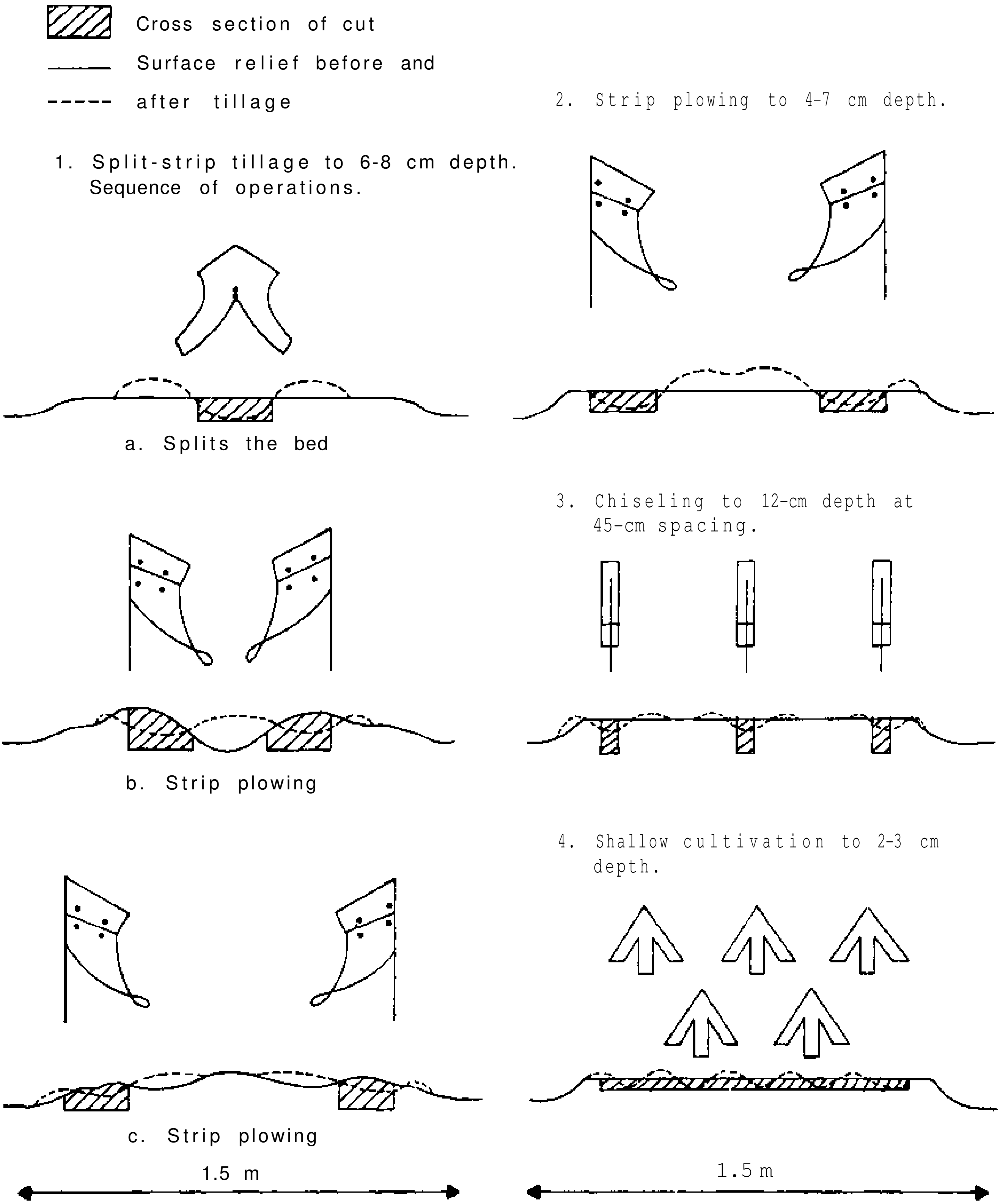


Figure 5. Four primary tillage methods for a broadbed-and-furrow system on Alfisols.

Table 6. Effect of tillage methods on soil moisture on an Alfisol during no-rain periods, ICRISAT Center, rainy season 1981.

No. of dry days	Tillage methods: Split-strip plowing	Strip plowing	Chiseling	Shallow cultivation	Mean	SE(±)
0	45	43	44	43	44	0.6
2	31	29	34	35	32	0.7
4	28	29	30	33	30	0.5
9	22	25	28	32	27	0.5

Source: Awadhwal and Thierstein 1984.

depletion in the top 20-cm layer during the early growth of the sorghum crop. Split-strip tillage holds marginally more of water, but moisture depletion during stress is faster. Consequently, at the end of dry spells moisture in intensive tillage is less than in shallow-tillage treatments.

There can be two hypotheses to explain differences in soil moisture in different tillage plots. First, the intensive-tillage treatment provided a better environment for plant growth and root development resulting in higher rates of transpiration that led to faster depletion of soil moisture. Secondly, in shallow tillage the soil is stratified in two layers: a top-tilled layer and a subsurface-untilled layer. This stratification caused discontinuity of pores, resulting in increased resistance to moisture migration. In the case of the mold board-plowed soil the entire plowed zone was in one layer with better continuity of pores, which, coupled with higher porosity, enhanced moisture loss through evaporation. These hypotheses require validation by further research (Awadhwal and Thierstein 1984).

Effect of tillage treatments on crop yield was not consistent (Table 7) and thus there is no conclusive evidence to suggest that any one treatment was better. However, split-strip tillage gave significantly ($P < 0.05$) more yield (2460 kg ha^{-1}) in a year of low rainfall (1979) than in field RA-14 which contains a fair proportion of gravel in the top layer (1120 kg ha^{-1}). Apparently soil moisture was greater only in RA-14 where the crop responded well to the increased tillage because of enhanced infiltration. In the following year the same field gave much lower yields across all treatments. Sorghum grain yield varied considerably from year to year in RW-2B, where the clay content was greater. The results did not have significant differences.

Energy expenditure in primary tillage was estimated by measuring the draft and the travel distance required to cover 1 hectare. As expected split-strip plowing consumed a much higher level of energy (28.2 MJ ha^{-1}) as compared with strip plowing (11 MJ ha^{-1}), chiseling (9.6 MJ ha^{-1}), and shallow cultivation (7.7 MJ ha^{-1}). Part of the excessive amount of energy used in the first case could be compensated for by saving one secondary tillage operation for seedbed preparation, which was otherwise necessary for effective weed control.

Table 7. Effect of primary tillage on sorghum grain yield (kg ha^{-1}) in Alfisol fields, ICRISAT Center, 1979-81.

	Field identification and year				
	RA-14		RW-2B		
Treatment	1979	1980	1979	1980	1981
Split-strip plowing	2460	1130	2970	1800	3080
Strip plowing	2140	1120	3080	1750	3010
Chiseling	1970	910	2870	1450	2680
Shallow cultivation	1950	1060	3040	1910	2870
Mean	2130	1050	2990	1740	2910
SE(±)	90	116	111	120	260

Source: Klaij 1983; Awadhwal and Thierstein 1984.

Conclusions

Improved, ox-drawn wheeled tool carriers and implements developed so far have shown considerable advantages in terms of the timeliness and quality of operations. The highest draft requirement was recorded for plowing with a set of left- and right-hand moldboard plows operating on a broadbed in the range of 1600 to 2250 N, with an average of 2000

N. For a single right-hand moldboard plow operation on flat land the draft values were in the range of 1180-1670 N, with an average of 1470 N. For other operations the draft values recorded were far less. An average pair of oxen was able to sustain these loads for a usual working period in a day. For sowing all common crops in Alfisols and Vertisols a planter-and-fertilizer applicator gave good results. It could sow sole crops as well as intercrops, and place seed and fertilizer with required precision. All these machines were drawn by a pair of oxen of average size.

A crust breaker, used either as an attachment to a WTC or as a hand-pushed implement, facilitated the emergence of seedlings and improved the stands of sorghum and pearl millet in fields where a surface crust was formed by natural drying processes. Primary tillage studies on Alfisols conducted for 4 years revealed that intensive tillage improved the pore-space and water-retention capacities of these soils, and reduced weed infestation in the early stages of crop growth. It also enhanced the risk of soil erosion in the absence of adequate crop cover. Advantages accruing from intensive tillage can therefore be realized only in conjunction with soil-conservation practices. In the years of normal and better-than-average rainfall, shallow tillage treatments gave comparable yields. It is thus clear that defining the best tillage techniques for Alfisols is a subject for further studies.

Acknowledgment

The authors make grateful acknowledgment to M.C. Klaij because the section on tillage studies is largely based on his work and Ph.D. thesis. Thanks are also due to G.E. Thierstein who led or participated in much of the research work reported.

References

Awadhwal, N.K., and Thierstein, G.E. 1983. Development of rolling-type soil crust breaker. Agricultural Mechanization in Asia, Africa and Latin America 14(4):31-34.

Awadhwal, N.K., and Thierstein, G.E. 1984. Evaluation of tillage methods suitable for light-textured Alfisols of the semi-arid tropics. Journal of Agricultural Engineering (ISAE)2l(l-2):44-54.

Charreau, C. 1977. Some controversial technical aspects of farming systems in semi-arid West Africa. Pages 313-360 in Proceedings of an International Symposium on Rainfed Agriculture in Semi-Arid Tropics, 17-22 April 1972. Riverside, California, USA: University of California.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1982. Annual report 1981.Patancheru, A.P. 502 324, India: ICRISAT. 248 pp.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1984. Annual report 1983. Patancheru, A.P. 502 324, India: ICRISAT. 271 pp.

Klaij, M.C. 1983. Analysis and evaluation of tillage on an Alfisol in a semi-arid tropical region of India. Ph.D. thesis, Soil Tillage Laboratory, Wageningen, The Netherlands.

Soman, P., Bidinger, F.R., Peacock, J.M., and Walker, T.S. 1981. Seedling establishment—a preliminary survey taken up in Aurepally during kharif 1981. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics. (Limited distribution.)

Sanghi, N.K., Prabhanjan Rao, S.B., and Bhaskar Rao, U.M. 1982. Agronomic manipulation in control of pests—a case study. Pages 168-180 in A decade of dryland agricultural research in India 1971-80. Hyderabad, India: All India Coordinated Research Project for Dryland Agriculture.

Venkata Nadachary, G., and Kidd, D.W. 1981. Eenati gorru: a wooden fertilizer seed drill. Indian Farming 31(4):33-35.

Soil Management for Increasing Productivity in Semi-Arid Red Soils: Physical Aspects

K. Vijayalakshmi[1]

Abstract

The physical constraints that limit the production of dryland crops in the semi-arid red soil regions of India, and possible ways to overcome these, are described. The main constraints are grouped together as factors that cause erosion, low water retentivity, and poor root growth. Biological and mechanical controls for soil erosion e.g., crop cover through proper choice of crops as well as geometry and off-season tillage, are described. Similarly, for more moisture retention, use of mulches and mechanical measures are also described. Along with better in-situ moisture conservation, it is necessary to harvest the runoff and use it judiciously and efficiently for better crop production. Timing of irrigation, crops that respond to irrigation best, and seepage control methods are also discussed. Poor root growth is mainly due to soil profile constraints (e.g., compaction). The effects of deep-plowing and use of crops to efficiently utilize the soil profile are additionally discussed.

Introduction

The red soils of the Deccan plateau are classified as Alfisols, Inceptisols, and Entisols. Alfisols are found in the troughs, while Inceptisols and Entisols occupy the crests of watersheds. Red soils are extensive in Andhra Pradesh and Karnataka. Two subclasses of the soil—red loamy and red sandy—are found. The red loamy soils generally occur in high rainfall situations. The red sandy soils mainly sustain rainfed crops and are generally cropped in the rainy season. Crop yields vary considerably from year to year (Table 1) due to variations in rainy-season rainfall. To increase and sustain high production, it is essential to understand the limitations of Alfisols and take remedial measures.

Table 1. Crops yields (t ha^{-1}) in 9 years under improved management on Alfisols, AICRPDA Centre, Hyderabad.

Year	Sorghum	Castor	Pigeonpea
1972	1.36	0.47	0.60
1973	4.52	1.77	1.33
1974	3.21	1.95	2.03
1975	5.37	1.92	1.95
1976	3.01	0.30	0.56
1977	4.57	0.54	0.52
1978	4.74	0.72	0.93
1979	0.%	0.29	0.00
1980	4.23	0.42	0.05

Source. A1CRPDA 1972-80.

Physical Constraints

The main physical features of Alfisols are presented in Table 2. Three major constraints to production are: (a) high runoff and soil losses; (b) low water retentivity; and (c) poor root growth.

The factors responsible for these constraints, and possible ways to mitigate their effects based on research, are discussed below.

1. All India Coordinated Research Project for Dryland Agriculture. Santhoshnagar, Hyderabad, Andhra Pradesh, India. (Now the Central Research Institute for Dryland Agriculture, at the same address.)

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

Table 2. Physical properties of Alfisols at three AICRPDA Centers.

	Hyderabad		Anantapur		Bangalore	
Characters	0-15	15-30 cm	0-15	15-30 cm	0-15	15-30 cm
Gravel (%)	22.9	8.8	23.6	60.0	0.00	0.40
Sand (%)	83.4	74.4	63.7	24.0	73.50	41.10
Silt (%)	5.0	4.0	3.2	2.6	6.20	8.00
Clay(%)	11.6	21.6	9.5	13.4	21.24	50.80
Bulk density (g cm^{-3})	1.43	1.63	NA	NA	1.64	1.42
Moisture at 0.033 MPa (1/3 bar)	12.31	17.42	NA	NA	14.73	18.03
Moisture at 1.5 MPa (15 bar)	5.84	7.49	NA	NA	7.57	13.09

NA = Not available.

High runoff and soil loss

Soil and water loss are caused by high-intensity rains, sloped lands, and the crusting nature of soils.

The best way to reduce runoff and soil erosion is by providing good vegetative cover (Table 3). Runoff is maximum in castor because the canopy does not offer good cover in the early stages. Intercropping with cowpea up to 45 days can provide the necessary extra protection, and can even partially substitute for commercial fertilizers. Cropping land to appropriate land-capability classifications helps minimize erosion. However, because of pressure on land, class IV lands are also cultivated, and the classes beyond IV have little cover due to the indiscriminate cutting of trees and overgrazing. Therefore, a major attempt is now being made to introduce agroforestry, and silvipastoral and agrohorticultural systems on these lands. In lands under cultivated crops, the row spacing, plant populations, and cropping systems are chosen to provide good cover.

Multiple, diversified slopes and shallow, light-textured soils also contribute to high erosion. Using the land under appropriate land capabilities will help stabilize and cut down erosion losses. On high slopes (>5-8%) planting trees and grass can offer adequate vegetative cover to control soil loss, maintain an ecological balance, and to enhance fuel, fiber, and water supplies. Mechanical measures, such as bunding and terracing, can also be employed to reduce soil loss.

In Alfisols runoff and soil loss also occur from surface crusting. Even though infiltration is generally high, surface sealing can keep intrinsic infiltration low. This happens especially if the soil dries fast after a good shower. Mechanical measures are used to break the crust. Also, crusting just after seeding leads to poor seedling emergence.

Table 3. Effect of crop on runoff and soil lots at Hyderabad. (Average of 1976-79.)

Crop	Runoff as % of annual rainfall	Soil loss (t ha-')
Sorghum	12.0	3.2
Pear] millet	10.8	2.0
Castor	15.7	4.0
Grass	9.5	0.6
Fallow	16.6	5.0

Source: AICRPDA 1982.

Moisture retentivity

The shallow, light-textured soils generally have poor water-holding capacity. Moisture in the soil profile can be increased by reducing direct evaporation losses and by increasing intake rates. For this, mechanical techniques such as tillage, and biological measures, are employed.

The disturbed soil will act as a mulch and reduce evaporation losses. Mulching increases water intake rates, pore space, and moisture storage (Table 4). Surface mulches have been found effective to some extent in increasing crop yields (Table 5). Organic mulches are effective but their use is limited since most organic residues are used as cattle feed.

One of the main factors contributing to low yields in SAT Alfisols is poor stands, primarily due to the extremely short seeding time available. Mulching helps conserve moisture in the seeding zone, thereby extending the seeding time. For example, off-season tillage provides soil mulch and extends the sowing time beyond a week, while direct sowing is possible only for a day or two after adequate rainfall (>25 mm).

Shallow cultivation is necessary both during the cropping season and the off-season. Cultivation during the off-season is more beneficial in years of low rainfall. For 3 years (1978-80), sorghum yielded 2.5 t ha^{-1} of grain using off-season tillage, compared with 1.87 t ha^{-1} without such tillage.

In earlier times, bunding was considered a soil- and water-conservation measure. It is now recognized that, for better moisture conservation, land treatments are essential. Cultivation on grade will help provide miniature bunds to check water flow, and provide more opportunity for water to infiltrate. Depending on the rainfall received, different land treatment practices are recommended.

At Anantapur, Andhra Pradesh, India, dead furrows at 3.6-m intervals helped conserve moisture more than sowing on flat land, increasing yield slightly (0.04 t ha^{-1}) over 0.56 t ha^{-1} without the furrows.

At Hyderabad, Andhra Pradesh, India, keyline cultivation on grade at vertical intervals of 0.5 m was found to be beneficial. In a sorghum/pigeonpea intercrop the sorghum yield with keyline cultivation was 2.81 t ha^{-1} over 2.42 t ha^{-1} in control plots. The pigeonpea yield was almost the same. The keylines can eventually be strengthened to become bunds.

The benefits from such land treatments are not spectacular, but they do aid sustained crop production over the years. For in-situ conservation, ridges and furrows may be formed later through interculture operations after 3 weeks of crop growth. This has been found effective in increasing crop yields (Table 6). This treatment also provides row drainage and helps harvest excess runoff, apart from providing more opportunity time for water to infiltrate.

In Bangalore, Karnataka, India, in narrow-spaced crops, a dead furrow can be provided at 2

Table 4. Effect of alternative mulches on physical properties of the soil.

Physical property	No mulch	Soil mulch	Straw mulch
Water intake rate (cm h^{-1})			
Initial	3.9	4.8	4.2
Final	5.1	6.6	5.7
Hydraulic conductivity at computed minimum bulk density (cm h^{-1})			
Initial	3.2	3.5	3.7
Final	4.8	5.5	5.9
Pore space (% of volume)			
Initial	37.4	45.4	40.8
Final	39.6	48.2	42.6
Soil moisture (mm)	24	31	28

Source: AICRPDA 1972-76.

Table 5. Effect of alternative mulches on pearl millet yield (t ha^{-1}).

Treatments	1973-74	1974-75 (1 month before sowing)
Soil mulch	0.34	1.74
Pearl millet mulch	0.37	1.41
No mulch	0.19	0.87

Source: AICRPDA 1972-76.

Table 6. Crop yields (t ha^{-1}) under different land treatments.

	Land treatments							
	1977		1978		1979		1980	
Cropping system	BBF[1]	FR[2]	BBF	FR	BBF	FR	BBF	FR
Sorghum/ pigeonpea	1.63/ 0.56		1.97/ 0.10	1.81/ 0.10	0.64/ 0.12	0.75/ 0.08	2.23/ 0.00	2.56/ 0.00
Sole castor	1.07		1.03	1.06	0.35	0.41	0.22	0.31

1. BBF = Broad beds and furrows.
2. FR = Flat with ridging after 3 weeks of germination.

seed-drill width intervals (i.e., at 3-m intervals). The yields of finger millet then increased from 1.12 to 1.21 t ha^{-1}.

The effect of slope and furrow length on moisture conservation, runoff soil loss, and crop yield under rainfed conditions were studied. A 60-m furrow with a grade of 0.2-0.4% is optimal from the point of view of runoff, soil loss, and yield (AICRPDA 1981-82). In soils more than 90 cm deep, graded border strips with a gradient of 0.2-0.5% across the major slope, and 11 m wide, are recommended as an alternative in the Bangalore region (Table 7). This system of land development does not require any special interterrace land treatment and is a permanent improvement.

Even though better in-situ moisture conservation is achieved through tillage and biological measures, runoff is inevitable due to high-intensity rainfall. This runoff can be harvested into dug-out ponds. A major constraint of this water-harvesting system is high seepage losses. Traditional tanks are sealed, over years, with fine fractions of soil, but this method is of no practical importance in small ponds. Different sealant materials were tried and the ones found suitable are listed in Table 8.

Because the water collected is limited, application efficiency has to be high. Existing efficient methods of irrigation, e.g., sprinkler and drip systems, need to be modified and made economically viable. At Hyderabad, Andhra Pradesh, India, water application through alternate confined furrows was advantageous. It is also essential to time supplemental watering to match the most critical stage of crop. For sorghum, heading to grain filling has been identified as the most critical phase, and watering at this time substantially increases yields (Table 9).

Water can also be used to increase cropping intensity. Depending on late rainfall, a second crop of fodder or grain can be harvested. This water could also be utilized for raising vegetable crops on a limited area, since vegetables do not generally form a major portion of farmers' diets (Table 10).

Table 7. Runoff lots in land treatments.

Treatments	Runoff as % of seasonal rainfall
Border strip	10.89
Graded bunds	26.40
Contour bunds	14.25
Broad beds and furrows	25.97

Table 8. Promising sealant materials.

Research Center	Material use	Seepage as% of control
Bangalore	Clay + sodium chloride + sodium carbonate (20:5:1)	19
	Soil: cement (5:1)	30
	Soil : cement (10:1)	42
Hyderabad	Plastic lining with brick overlay	0
	Brick lining with cement plastering	0
	Asphalt	13

Source: AICRPDA (1982).

Table 9. Effect of critical irrigation on sorghum yield t ha^{-1}).

Stage of crop	Sorghum yield
No irrigation	1.39
Vegetative phase	1.74
Flowering phase	1.92

Source: AICRPDA 1982.

Table 10. Minimal irrigation of vegetables.

Crop	Irrigation (cm)	Yield (t ha-')	Center
Chillies	0	0.21	Bangalore
	5	0.45	
Beans	0	0.11	Hyderabad
	1	1.43	

Source: AICRPDA 1982.

Root growth

When the soil profile contains little water, roots grow poorly. High bulk densities and subsoil compaction often limit the rooting profile, thereby restricting the soil use. If there is a hardpan, chiselling is generally advocated to break it. Deep-plowing with inversion is useful in areas where the subsoil is heavier and rich in nutrients. Since mechanical measures are generally costly, biological measures such as crop rotation and stubble mulching are preferable.

At Hyderabad, root growth in cereals is seriously hampered by the compact subsoil. Deep-plowing with inversion increased yields in the tillage year (Table 11). The data clearly show that deep-plowing is advantageous to sorghum in normal rainfall years, and to castor in normal and above-normal rainfall years. Therefore, in sorghum-castor rotation, it is better to deep-plow for castor. The effect of plowing is, however, transitory.

At Anantapur, deep-plowing was beneficial and, because the advantages persist for three subsequent years, it is economically viable. At Bangalore also, deep-plowing gave a beneficial effect (Table 12).

Thus, by modifying and making the best use of the natural resources of soil and water, it is possible to achieve fairly good and sustained productivity in SAT Alfisols and related soils.

Table 12. Effect of tillage on crop yields.

Center	Crop	Yield (t ha-') Shallow tillage	Deep tillage
Anantapur	Castor	1.01	1.30
	Pigeonpca	0.71	1.04
	Pearl millet	0.68	1.00
Bangalore	Groundnut	0.86	1.17
	Maize	3.20	4.51
	Pigeonpca	1.23	1.90

Source: A1CPRDA (1982).

References

AICRPDA (All India Coordinated Research Project for Dryland Agriculture). 1972-80. Annual reports. Hyderabad, Andhra Pradesh, India: AICRPDA.

AICRPDA (All India Coordinated Research Project for Dryland Agriculture). 1982. A decade of dryland agricultural research in India, 1971-80. Hyderabad, Andhra Pradesh, India: AICRPDA.

AICRPDA (All India Coordinated Research Project for Dryland Agriculture). 1972-76. Achievements of research, Anantapur, 1972-76. Hyderabad, Andhra Pradesh, India: AICRPDA.

AICRPDA (All India Coordinated Research Project for Dryland Agriculture). 1980-81, 1981-82. Progress reports. University of Agricultural Sciences, Bangalore, Karnataka, India: AICRPDA.

Table 11. Effect of tillage practice on crop yields.

Seasonal rainfall	Crop	Grain yield ($t\ ha^{-1}$) Shallow	Deep	Rainfall (mm)	Year
Subnormal	Sorghum	1.74	1.81	264	1979
	Finger millet	0.10	0.15	125	1980
	Castor	0.38	0.43	264	1979
	Castor	0.38	0.28	269	1980
	Sunflower	0.81	0.81	149	1972
	Pigeonpea	0.25	0.29	149	1972
Normal	Sorghum[1]	2.66	2.95	259	1980
	Pearl millet[1]	1.94	2.23	399	1973
	Castor[2]	0.78	1.27	622	1978
Above normal	Sorghum	2.61	2.65	610	1978
	Pearl millet	1.60	1.63	530	1973
	Castor[2]	0.96	1.27	884	1973

1. Differences are significant at 0.05 probability level.
2. Differences are significant at 0.01 probability level.

Soil Fertility Management of Red Soils

J. Venkateswarlu[1]

Abstract

The semi-arid red soils are very deficient in nitrogen and phosphorus. Zinc becomes limiting at higher production levels, and potassium is less than adequate where kaolinite is the dominant clay mineral. The critical values of soil fertility below which responses to added fertilizer would be economical are 70 ppm for exchangeable K_2O (NH_4OAc extraction method), 48 ppm for P_2O_5 (NA_2CO_3 fusion method), and 0.83ppm (DTPA extraction method) for zinc. Cereals respond to both N and P, oilseeds more to N, and legumes more to P. Synergism is conspicuous between N and P for cereals. Placement improves the efficiency of fertilizer use, because subsoils are generally infertile. While seeding, not more than 10 kg ha^{-1} N can be mixed with seed in the broad furrows. Split application of nitrogen is necessary to cover the risk of aberrant weather. Organic residue incorporation improves and sustains crop production.

Introduction

The red soils cover 59.6 million ha in India. They occur both in the semi-arid tropics (SAT) and in subhumid regions. In the SAT, red soils are found mostly in southern India. These soils are weathered, with a low clay content, varying from 10 to 20%. The predominance of kaolinite followed by illite in these soils keeps their nutrient-holding capacity low. Red soils are generally neutral to acidic and salt-free. The water intake is high unless the soil surface is crusted.

The soils are shallow to medium, and their clay content increases with depth. The subsoil, interspersed with "murram", is relatively more compact.

The red soils in the SAT are universally deficient in nitrogen, and often have a low phosphorus content. Lack of potassium might pose a problem in light soils where the dominant clay mineral is kaolinite. In continuous sole cropping (e.g., with groundnut), sublethal deficiencies of Zn, S, and Ca occur.

These soils are generally cropped in the rainy season: an early single crop in shallow soils, intercropping in medium rainfall regions, and sequence cropping with an early catch crop in relatively high-rainfall and deep-soil environments.

This paper reports several soil fertility experiments conducted in SAT regions.

Chemical Environment

The typical characteristics of some red soils collected from the 0-15 cm layer are shown in Table I. Available P_2O_5 was determined by Olsen's method, available K_2O by the IN NH_4OAc extraction method, while micronutrients were estimated by the DTPA extraction method.

The Anantapur research farm represents the Rayalaseema region and the one at Ibrahimpatanam the Telengana region of Andhra Pradesh, India. The Rayalaseema region is unique in that the soils are deficient in K, with the soil clays being predominantly kaolinitic (Anonymous 1954). The Telengana region is fairly well supplied with K, and the soil clays are mostly illitic (Desai 1942). However, the red soils of both the regions are neutral in soil reaction, salt-free, low in clay, and extremely deficient in phosphates with a sublethal deficiency of zinc.

I. All India Coordinated Research Project for Dryland Agriculture, Santoshnagar, Hyderabad, Andhra Pradesh, India. (Now the Central Research Institute for Dryland Agriculture, at the same address.)

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502 324. India: ICRISAT.

Table 1. Characters of some red soils.

Source	Soil no.	pH	E.C. x 10^{-1} mmhos cm^{-1} (1:2.5)	Clay (%)	Available nutrients (ppm)						
					P_2O_5	K_2O	Zn	Cu	Fe	Mn
Anantapur research farm	I	7.3	1.3	14.8	5.7	54.5	1.0	1.0	27.6	31.6
	2	6.7	0.6	13.8	15.0	54.5	0.9	1.0	6.2	24.3
	3	6.8	1.0	24.8	5.2	59.5	0.8	1.2	10.3	26.7
	4	7.2	1.6	10.8	2.2	50.0	0.7	0.5	6.9	14.6
	5	6.6	0.9	12.8	10.7	50.0	0.7	0.8	6.2	29.2
Ibrahimpatanam research farm	1	6.6	0.9	10.8	6.5	111.8	1.1	0.8	9.0	65.6
	2	6.9	0.6	21.8	2.5	121.4	0.9	0.5	55.2	68.0
	3	6.9	1.1	12.8	1.7	88.1	1.0	0.7	74.1	53.5
	4	7.2	1.3	12.8	3.7	69.0	1.3	0.3	49.7	31.6
	5	6.6	0.8	29.8	4.7	102.3	0.8	0.6	20.7	53.5
	6	7.1	0.8	13.8	6.0	83.3	0.7	0.7	25.5	60.7

Critical values for available P_2O_5 and K_2O

Pot experiments were conducted by Tata Rao and Venkateswarlu (1970) and Mastan Rao (1978) to assess the soil critical values for available P_2O_5 and K_2O below which responses would be economical (Waugh and Fitts 1966). The results indicate the following values:

	Soil critical values (ppm)	
Crop	P_2O_5 (Na_2 HCO_3, pH 8.5)	K_2O (NH_4 OAc, pH 7.0)
Sorghum	43	
Pearl millet		70
Maize	52	

The soil critical value (SCV) suggests a value of available nutrients below which economic responses are possible. SCVs were irrespective of productivity levels and are based on the "soil fertilization" concept.

Most of the red soils were below this critical value for phosphorus. Such soils were found in Rayalaseema with references to K. Therefore, all red soils need adequate supplies of P, while K is needed in the light red soils of Rayalaseema to produce higher yields.

"Minimal" exchangeable K

Twelve soils from the Telengana region (where illite is the dominant clay mineral) were sampled for detailed study of the dynamics of K availability. These soils had the following characteristics:

Characteristics	Range	Mean
Clay (%)	8.1 - 15.7	10.0
CEC (meq 100 g^{-1})	5.0- 9.4	8.0
Exchangeable K (ppm)	48 -226	130

Pot experiments were used to exhaust exchangeable K to a "minimal" level. The procedure suggested by Waugh and Fitts (1966) was adopted, using pearl millet as the test crop. The depletion patterns are given in Table 2.

The constant "minimal" level of exchangeable K on continuous depletion dropped from 130 ppm to 23 ppm, a level much lower than the soil critical value identified earlier. Tabatavai and Harway (1969) suggested that there would be a high correlation between constant "minimal" exchangeable K and clay percentage in Holland soils. Similarly, in the present study the relationship between these parameters was:

$$Y = 6.97 + 1.46 X \ (r = 0.675x)$$

where Y = mean "minimal" level of exchangeable K X = clay content. Similar relationships were worked out by Legg and Beacher (1952) in U.S. soils.

Yield of K (mg kg^{-1} soil) from nonexchangeable source

The K from nonexchangeable source was calculated at the "minimal" level in exhaustion studies by determining the uptake of K and calculating in mg kg^{-1} soil. It was 26 mg kg^{-1} K in these red soils, not

Table 2. Exchangeable K (ppm) in different soil samples with successive cropping using pearl millet as the test crop.

Crop	Exchangeable K (mean values of 12 soils)
Initial	130
First crop	no
Second crop	68
Third crop	54
Fourth crop	39
Fifth crop	33
Sixth crop	23
Seventh crop	23
Eighth crop	23

calculated after each exhausting crop, but estimated only after the soils come to a constant "minimal" level.

K-supplying power of soils

Vimpany et al. (1974) suggested that the K-supplying power of soil:

= Exchangeable K-"Minimar level of exchangeable K + K supply from nonexchangeable K at the exhausted ("minimal") level of K.

In the present case the average K-supplying power of red soils of Telengana:

= (130-23)+ 26

= 133 ppm.

In other words, the K-supplying power of red soils of Telengana is almost equivalent to the exchangeable K values.

Critical value for available zinc

Shankar (1971) studied the Zn availability in the red soils of both Telengana and Rayalaseema in Andhra Pradesh. The DTPA-extractable zinc was:

	DTPA-extractable zinc (ppm)	
Zone	Range	Meah
Rayalaseema	0.83-1.11	0.95
Telengana	0.50-1.53	0.91

The soil critical value, as determined by the procedure of Waugh and Fitts (1966), was 0.83. Of the 25 soils tested, 16 were below the critical value, indicating fairly widespread zinc deficiency in the Telengana region.

Fertilizer Management in the Red Soils

Responses

The responses of different crops to graded levels of N and P (Venkateswarlu and Bhaskara Rao 1979) are given in Table 3.

Table 3. Differential responses to nutrients by grain yield (t ha^{-1}).

	Nutrient level (kg ha-')			
Nutrient	0	40	80	CD (0.05)
		Sorghum		
N	0.98	1.67	3.02	0.196
P A	0.67	2.18	3.03	
		Castor		
N	0.83	1.32	1.58	0.073
P_2O_5	0.89	1.28	1.29	
		Cowpea		
N	0.48	0.48'	-	0.052
P_2O_5	0.34	0.57	0.56	

1. Tested at 20 kg ha^{-1} N level.

The data suggest the need, in general, for moderate levels of fertilizers. Further, it indicates that cereals respond both to N and P, oilseeds respond more to N, and pulses respond more to P.

Synergism

The synergism between N and P, in the case of cereals, was clear:

Treatment	Yield of sorghum (ha^{-1})
Control	0.67
40 kg ha"[1] N	0.78
30 kg ha^{-1} P_2O_5	1.16
40 kgha^{-1} N +30 kg ha^{-1} P_2O_5	2.24

Placement

The subsoils of the red soil region are generally not fertile. Vijayalakshmi and Venkateswarlu (1974) showed the need to plow in applied fertilizers so that the roots could encompass more soil volume and have better availability of both nutrients and water, thereby leading to higher yields (Table 4).

Studies on placement have indicated better use-efficiency of applied fertilizers. However, in real farm situations, placement has to be done in the same furrow because many farmers have only one seeding implement, either fixed behind the country plow, or a single-bowl seed drill with two or three tines. The former creates wide furrows and the latter narrow ones. Experiments were conducted by Anderson (personal communication 1974) with graded levels of N fertilizer, using sunflower as the test crop because it is more sensitive to salt injury than many other crops (Table 5).

The study was done in an Alfisol (sandy loam). The crop was sown following 22 mm rainfall the previous day.

The data suggest that in the broad-furrow method (behind a country plow) up to 10 kg ha^{-1} N can be mixed with seed, while with narrow furrow (tined seed drill) method only 5 kg ha^{-1} N can be mixed without detriment to seedling emergence.

Table 5. Effect of mixing N fertilizer with sunflower seed.

Furrow nitrogen applied	ON	5 N	10 N	20 N
	(kg ha^{-1})			
	Plant counts/ 5-m row			
Broad-based furrow (5 cm): applied with seed	39	34	40	26
Narrow-based furrow (1.5 cm): applied with seed	47	44	19	13

Split Application

Split application of nitrogen (75 kg ha^{-1} N) was tested on several crops in an Alfisol (sandy loam). The results are given in Table 6. The rainfall during the farming season was 665 mm for sorghum, 325 mm for pearl millet, 700 mm for sunflower and 925 mm for castor.

Even though there was no yield difference between different split applications of nitrogen, application of N through splits is suggested to cover the possible risk of rainfall aberrations at a late date during the cropping period. It also helps the farmer meet the fertilizer costs over a longer period of time.

Organic-Matter Recycling and Fertilizer Use

Organic residue incorporation, in any form, should be encouraged. Besides supplying nutrients, it also improves soil physical properties. As early as 1942, Smith reviewed the Sanborn field studies and showed that the percentage recovery of applied N would be more once organic residues are incorporated into the system. Subsequently Cooke (1977) showed the need to have a legume in the rotation or cropping system to increase the soil's organic matter content. Addition of organic matter does improve such physical properties of the soil as infiltration (Wischmeier 1966), and reduces erosion (Stewart et al. 1975). Krishnamoorthy and Venkateswarlu (1976) showed that in-situ decomposition is more useful in improving soil aggregation.

Table 4. Effect of the plowing in of fertilizers on crop yields.

Treatment	Yield of crops (t ha^{-1}) Pigeonpea[2]	Safflower[3]	Sunflower[3]
Deep-plowing[1] and subsequent fertilizer application	0.29	0.59	0.81
Application of fertilizers before deep-plowing	0.38	0.87	1.15

1. Deep-plowing up to 25 cm.
2. 20 kg ha^{-1} N and 40 kg ha' P.
3. 60 kg ha-' N and 40 kg ha^{-1}P.

Table 6. Effect of split application of N on crop yield.

Application method	Grain yield (t ha^{-1}) Sorghum	Pearl millet	Sunflower	Casto
All basal	1.54	2.54	1.09	2.73
1/2+1/2	1.31	2.33	1.18	2.41
1/2+ 1/4+ 1/4	1.45	2.57	1.39	2.66
2/3+ 1/3	1.58	2.51	1.13	2.65
1/3 + 2/3	1.80	2.56	1.28	2.68
1/3 + 2/3	1.80	2.56	1.28	2.68
CD[1] (0.05)	NS	NS	NS	NS

1. Critical difference.

Green manuring of castor

Chaudhury (personal communication 1976) conducted a study on growing cowpea as an intercrop with castor for green manuring at about 45 days. The results are given in Table 7.

The data clearly show that about 30 kg ha^{-1} N could be recovered through this practice from the 3rd year onwards.

Krishna Prasad Reddy (1978) identified the nitrogen contribution by cowpeas in a sorghum/cowpea intercrop. The results on grain yield of sorghum, the grain/fodder yield of cowpeas, and N uptake are given in Table 8.

There was no significant yield difference with cowpeas as fodder compared with a sole sorghum crop. However, when cowpeas were used as a food legume, there was a significant yield reduction, from 3.30 to 2.35 t ha^{-1}. There was an uptake difference of 13.5 kg ha^{-1} N between the grain and fodder systems. These results are in conformity with the findings of Dayal et al. (1967), and Singh and Roy Sharma (1969).

Table 7. Yield of castor under green nanuring.

Treatment N (kg ha^{-1})	Treatment P_2O_5 (kg ha^{-1})	Year/grain yield (t ha') 1976	1977	1978	Average
0	0	0.24	0.53	0.49	0.42
10	40	0.33	0.67	0.80	0.60
40	40	0.47	0.91	0.98	0.78
10'	40	0.37	0.81	0.98	0.72

1. Cowpea grown in between castor rows and incorporated at 45 days.

Alley cropping

Alley cropping, a method originally developed at the IITA (International Institute for Tropical Agriculture), is perhaps more suited to the red soil region in the SAT. Preliminary trials conducted by Venkateswarlu et al. (1981, p. 10) show two advantages of having arable crops: no yield reduction (Table 9), and a fodder yield of 4 t ha^{-1}.

Residue incorporation

Mohd. Shakeel Hameed (1978) studied nutritional and physical parameters of the soil before and after 5 years of organic residue incorporation in both red sandy loam and red loamy sand. The organic residue incorporated either through cowpea or pearl millet was 20 kg ha^{-1} N. Cowpea-pearl millet rotation followed, and only 20 kg ha^{-1} P_2O_5 or 20 kg ha^{-1} N was applied to the respective crops. The soil data are given in Table 10.

All physical parameters improved. There was significant increase in available N and P_2O_5, but avail-

Table 9. Effect of leucaena on crop yield.

Cropping system	Average grain yield (t ha^{-1})
Castor	0.43
Castor + leucaena	0.49
Sorghum	2.03
Sorghum + leucaena	2.11
Pearl millet	0.63
Pearl millet + leucaena	0.70

Table 8. Grain and straw yields of sorghum and cowpea and N uptake by sorghum under different intercropping systems.

Systems	Fertilizer used (kg ha') N	Fertilizer used (kg ha') P_2O_5	Yield (t ha-') Sorghum Grain	Sorghum Fodder	Cowpea Grain	Cowpea Fodder	N-uptake (kg ha-')
Cowpea (grain)	0	30	1.93	5.59	0.24	-	53.7
Cowpea (grain)	30	30	2.35	5.13	0.22	-	57.9
Cowpea (grain)	30'	30	2.35	5.41	0.25	-	63.6
Cowpea (fodder)	0	30	2.74	5.70	-	2.99	65.5
Cowpea (fodder)	30'	30	3.10	5.70	-	2.71	77.4
Cowpea (fodder)	30	30	2.87	6.14	-	2.82	76.4
Without cowpea	30	30	3.30	5.88	-	-	69.8
CD (0.05)			0.66	NS	-	-	12.90

1. N for sorghum only.

Table 10. **Physical and chemical soil properties as affected by organic residue incorporation,**

Soil constituent	Initial value		After 5 years with crop residue + fertilizers[1]	
	Red sandy loam	Red loamy sand	Red sandy loam	Red loamy sand
Mean weight diameter (mm)	2.63	3.21	3.04	4.19
Hydraulic conductivity (cm h^{-1})	4.19	2.34	10.5	8.0
Bulk density (g cm^{-3})	1.81	1.73	1.69	1.65
Soil crusting (penetrometer reading)	35	40	18	11
Moisture content at field capacity (g $100g^{-1}$)	15.7	12.4	19.0	12.9
Available N (kg ha^{-1})	284	235	307	286
Available P_2O_5 (kg ha^{-1})	5.5	6.6	14.0	14.0
Available K_2O (kg ha^{-1})	256	269	254	234

1. 20 kg N for cereal (pearl millet) and 20 kg P_2O_5 for pulse (cowpea) in rotation.

able K was not affected in the sandy loam. However, it decreased in the loamy sand by 35 kg ha^{-1}. Bairathi et al. (1974) showed similar effects for N, Raheja et al. (1971) for P_2O_5, and Sahu and Nayak (1971) for K_2O. Soil aggregation and other physical properties improve with organic additions (Biswas et al. 1964).

The grain yield (in t ha^{-1}) in the treatments was as follows.

	Pearl millet	Cowpea
Control (only fertilizer)	1.52	0.45
Fertilizer + organic residue incorporation	1.82	0.49

Incorporation of part of the residues of a previous crop helps sustain crop production at low fertility. It not only improves the physical properties (e.g., it reduces soil surface crusting), but it also maintains or increases the levels of major nutrients in the soils.

References

Anonymous. 1954. Memoirs of Department of Agriculture, Madras.

Bairathi, R.C, Gupta, N.M.,and Seth, S.P. 1974. Effect of different legume crop residue on soil properties, yield, and nutrient uptake by succeeding wheat crop. Journal of the Indian Society of Soil Science 22:304-307.

Biswas, T.D., Das, B., and Verma, H.K.G. 1964. Effect of organic matter on some physical properties of soil in the permanent manurial experiment. Bulletin of the National Institute of Sciences, India 26:142-147.

Cooke, G.W. 1977. The role of organic matter in managing soils for higher crop yields—a review of the experimental evidence. Pages 53-64 in Proceedings of the International Seminar on Soil Environment and Fertility Management in Intensive Agriculture.

Dayal, R., Singh, G., and Sharma, R.C. 1967. Growing of legume and cereal mixture under dry farming conditions. Indian Journal of Agronomy 12:126-131.

Desai, A.D. 1942. The nature and relationships of the black cotton soils and red earths of Hyderabad, Deccan. Bulletin no. 10. Hyderabad, Andhra Pradesh, India: Department of Agriculture.

Krishnamoorthy, Ch., and Venkateswarlu, J. 1976. Nutrient availability—concepts and relationships. Pages 65-92 in Soil fertility—theory and practice (Kanwar, J.S., comp. and ed.). New Delhi, India: Indian Council of Agricultural Research.

Krishna Prasad Reddy, K. 1978. Nitrogen contribution by cowpea (Vigna unguiculata) in crop sequence and intercropping. M.Sc. thesis, Andhra Pradesh Agricultural University, Hyderabad, Andhra Pradesh, India.

Legg, T.O.,and Beacher, R.L. 1952. The potassium supplying power of representative Alabama soils. Soil Science Society of America Proceedings 16:210-214.

Mastan Rao, C. 1978. Phosphorus adequacy limit at various levels of nitrogen. M.Sc. thesis, Andhra Pradesh Agricultural University, Hyderabad, Andhra Pradesh, India.

Mohd. Shaheel Hameed. 1978. Physico-chemical changes with different systems of organic recycling in the semi-arid red soil region. M.Sc. thesis, Andhra Pradesh Agricultural University, Hyderabad, Andhra Pradesh, India.

Raheja, S.K., Prasad, R., and Jain, H.C. 1971. Long-term fertilizer studies in crop rotations. Pages 881-903 in Proceedings of the International Symposium on Soil Fertility Evaluation, 9-14 Feb 1971, New Delhi, India. Vol. 1. New Delhi, India: Indian Agricultural Research Institute.

Sahu, B.N.,and Nayak, B.C. 1971. Soil fertility investigations under continuous application of ammonium sulphate alone and in combination with organic manures in the Bhubaneswar long-term fertility trial. Pages 873-879 in Proceedings of the International Symposium on Soil Fertility Evaluation, 9-14 Feb 1971, New Delhi, India. Vol. 1. New Delhi, India: Indian Agricultural Research Institute.

Shankar, A. 1971. Evaluation of response of maize to added zinc in the red soils of Pochampad, Anantapur and Ibrahimpatanam. M.Sc. thesis, Andhra Pradesh Agricultural University, Hyderabad, Andhra Pradesh, India.

Singh, A., and Roy Sharma, R.P. 1969. Note on nitrogen contents of the tops and roots of three nitrogen legumes in northern India. Indian Journal of Agricultural Sciences 39:920-924.

Smith, G.E. 1942. Sanborn field: fifty years of field experiments with crop rotation, manure, and fertilizer. Bulletin, Missouri Agricultural Experiment Station 458:61.

Stewart., B.A., Woorhiser, D.A., Wischmeier, W.H., Caro, J.M.,and Frere, M.H. 1975. Control of water pollution from crop lands. Washington, D.C., USA: U.S. Department of Agriculture and Environmental Protection Agency.

Tabatavai and Harway, J.J. 1969. Potassium supplying power of Iowa soils at the 'minimal' levels of exchangeable potassium. Soil Science Society of America Proceedings 16:210-214.

Tata Rao, U., and Venkateswarlu, J. 1970. Crop response to available phosphorus and potassium in soils of dry farming centres of Anantapur and Ibrahimpatanam. Andhra Pradesh, India: Andhra Pradesh Agricultural University, Radiotracer Laboratory.

Venkateswarlu, J., and Bhaskara Rao, U.M. 1979. Relative response of different crops to fertilizer phosphorus in semi-arid red soils. Bulletin of the Indian Society of Soil Science 12:404-407.

Venkateswarlu, J., Venkat Reddy, N., Das, R.B., and Rao, U.M.B. 1981. Newsletter on Leucaena.

Vijayalakshmi, K.,and Venkateswarlu, J. 1974. Research on soils and water use. Andhra Pradesh Agricultural University Technical Bulletin 4:8-13.

Vimpany, I., Bradley, J., and Wright, W. 1974. The use of two potassium soil tests to predict potassium fertilizer requirements. Proceedings of the Australian Soil Science Conference 3(a):21.

Waugh, D.L.,and Fitts, J.W. 1966. Soil test interpretation studies: laboratory and plot plants. Technical Bulletin no. 3, International Soil Testing Series. Raleigh, North Carolina, USA: North Carolina State University.

Wischmeier, W.H. 1966. Relation of field-plot runoff to management and physical factors. Soil Science Society of America Proceedings 30:272-277.

Limitations and Prospects of Crop Production in SAT Alfisols

R.P. Singh and S.K. Das[1]

Abstract

The Alfisols of the semi-arid tropics (SA T) of India are generally shallow with compact subsoil and undulating topography. They are characterized by low water- and nutrient-holding capacity. Surface soil crusting adversely affects crop stand establishment. Graded bunding for shallow to medium Alfisols and graded border strips for deep soils are appropriate soil and water conservation measures. Sowing fiat on grade of 0.3-0.5% and ridging later increased the yield of sorghum by 10-15%. Deep-plowing once in 3 years is a useful practice for soils having a compact subsoil. Improved crop management practices are required for optimum utilization of resources. Moderate and balanced fertilizer use increases and stabilizes productivity. Integrated nutrient management for the otherwise nutrient-deficient Alfisols is needed. Other aspects of improved crop management are proper crop stand establishment through timely operations, use of improved seeds, precision in fertilizer placement, timely weed control, and effective plant protection measures. Future research needs are emphasized.

Introduction

The semi-arid tropics (SAT) in India have predominantly two types of soils: Vertisols and Alfisols. The Alfisols are spread across Andhra Pradesh, Karnataka, and Tamil Nadu. In contrast to the Vertisols, the Alfisols are characterized by low water- and nutrient-holding capacities, which limit high and stable yields. In fact, a majority of shallow and undulating Alfisols are not suitable for crop production, but population pressure has brought them under cultivation, resulting in ecological deterioration.

The problems of farming Alfisols were, identified by a research group of the All India Coordinated Research Project for Dryland Agriculture (AICRPDA) in the early 1970s. Some useful research relevant to site-specific problems has been done, but because the problems are varied and complex, there is still much to be accomplished.

An examination of the problems reveals that they fall mainly under three broad categories:

- land and water management systems, including tillage;
- nutrient management, including application of amendments; and
- crop stand establishment.

Land Treatment: a Prerequisite

Appropriate land treatments are a prerequisite to increasing and stabilizing crop production on Alfisols. In the past, emphasis was on contour bunding as a potent tool for effective soil and water conservation. The practice, however, was not adopted by dryland farmers. Graded bunding with grassed waterways leading to a tank was considered a feasible alternative on shallow to medium soils. In deep Alfisols—like the ones encountered in the Bangalore

1. All India Coordinated Research Project for Dryland Agriculture, Santoshnagar, Hyderabad, Andhra Pradesh, India. (Now the Central Research Institute for Dryland Agriculture, at the same address.)

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT

region of Karnataka—graded border strips were considered a more effective measure for soil and water conservation (Hegde et al. 1987). For soils that were not too problematic, cheaper methods of soil and water conservation were devised, such as sowing flat on a grade of 0.3-0.5% and ridging 3 weeks after sowing, which increased yields by 10-15%. Keyline cultivation was considered a feasible and practical proposition. However, this practice by itself did not give spectacular results.

In soils with compact subsoils, like the ones encountered in the Anantapur region of Andhra Pradesh, nothing worked as effectively as deep-plowing once in 3 years and making dead furrows at intervals of 3-6 m, depending on the slope (Subbarami Reddy et al. 1978). Deep-plowing was instrumental in: bringing about a temporary change in textural profile; bringing unused nutrients to the surface for use by crop plants; better root proliferation of cereals and deeper root penetration of tap root crops (e.g., castor, bean, and pigeonpea); and better water intake.

It is not known how long the effects of deep-plowing last and whether farmers can afford the practice.

Improving the Moisture- and Nutrient-holding Capacity

The main research consideration should be how best to improve the moisture- and nutrient-holding capacity of these otherwise shallow, weathered, sloped, and degraded soils. Moisture alone does not lead to quantum jumps in crop yield; it should be coupled with an adequate and timely nutrient supply. Since the moisture- and nutrient-holding capacity of these soils is limited, even with moderate doses of nutrients, yields are often increased. What is perhaps required is more frequent application of nitrogen at the appropriate time. It is recommended to apply the full dose of phosphorus and potash, and at least half the recommended dose of nitrogen at sowing. Deep placement of the fertilizer mixture pays rich dividends. Fertilizer placement at sowing imparts early seedling vigor to plants and offsets pest incidence. To be effective, the top dressing of nitrogen should follow effective weed control. Very few studies to date seem to have to brought out the precise relationships between weed control and nutrient supply, and between moisture availability and fertilizer use.

Application of nutrients (nitrogen, phosphorus, and potash) to acidic soils is of little use unless the main malady is addressed. Studies show that application of lime is a prerequisite for getting the best out of the nutrients applied. At times, micronutrients such as zinc, sulfur, etc., hold the key to increased crop production.

Scientific nutrient management, therefore, is the prime factor in bringing about major and perceptible changes in crop productivity. Since the soils are shallow, and have a poor nutrient-supply base, some effective and far-reaching steps need to be taken to improve the base. The remedy seems to lie in site-specific residue management.

The work carried out at the Bangalore AICRPDA center has conclusively proved that application of maize residues at the rate of 4 t ha^{-1} increased the yield of finger millet 25% after maize in the 2nd year. The practice increased the organic matter in the soil. After 5 years the organic matter of the soil increased from 0.55% in the control plot to 0.90% in the plot receiving maize residue at the rate of 4 t ha^{-1} a^{-1} (Hadimani et al. 1982). With improvement in the organic matter content, the moisture- and nutrient-holding capacity also improved, and problems such as surface soil crusting are reduced. The major efforts in the future should be to evolve an integrated nutrient supply system for the Alfisols that is acceptable to farmers. Inclusion of legumes in the cropping systems is vital since organic manures are becoming increasingly scarce.

We have yet to understand the microflora found in these soils. Understandably, these soils will have a poor microbiological base because of limited moisture and low organic matter content. This important aspect calls for immediate attention and concerted research effort.

Crop Stand Establishment

Poor crop stands are common on Alfisols as a result of characteristic surface crusting. Crop stand is also directly related to moisture availability in the soil profile, more particularly in the seeding zone. These soils become charged quicker because of better water absorption, but they dry out even faster. This phenomenon adversely affects both shoot and root growth. Further, because of the predominance of kaolinite in the soil complex, moisture release from the soil is faster, as are transpiration losses. Timely sowing of rainy-season crops, capitalizing on the most opportune moisture availability period, is important. Advancing the sowing time of postrainy season crops is also an important component of increased crop productivity. While this is more relevant to black soils, it is nonetheless crucial in such a double-crop system as cowpea/ finger millet in the deep Alfisols of the Bangalore region.

Timely sowing is essential, as is the use of drills that ensure more coverage and uniform and precise placement of both seeds and fertilizer in the moist zone. Even with an optimal crop stand, many natural factors work against the crops. A short dry spell at seedling stage, soil pest infestations (termites, white grubs, etc.) or a nonfertilized crop, can prevent an initial optimal plant stand from reaching maturity. During the life cycle of the crop, many such factors continue to operate. These have to be kept in check.

The improved crop management practices discussed provide reasonable insurance against many risks. There is no short cut to the package of improved agronomic practices. Each component of the package has a role to play, depending on the crop and the environment. Experience has shown that improved seeds, optimal fertilizer levels, and timely and effective plant protection measures are the strong links in the chain.

Future Research Thrusts

A research group such as AICRPDA should address itself to the following research mandate:

- Dovetailing land use with the moisture- and nutrient-holding capacities of the soil. Alternate land-use systems seem to be more promising than annual cropping on shallow, weathered, and degraded Alfisols.
- Land treatments commensurate with the rainfall pattern, topography, and moisture-storage capacity of the soil.
- An integrated nutrient supply system that improves the moisture- and nutrient-holding capacities of the soil.
- An integrated pest management system conducive to the environment and the ecosystem.
- A technically sound, and economically feasible water-harvesting and recycling system to stabilize dryland crop yields in general, and cash crops (e.g., groundnut) in particular.
- The design and fabrication of more efficient agricultural implements, ensuring timeliness and precision in field operations.
- A more promising postharvest technology for dry regions.

References

Hadimani, A.S., Hegde, B.R., and Satyanarayana, T. 1982. Management of red soils. Pages 689-700 in Review of soil research in India. Part II. Transactions of the 12th International Congress of Soil Science, 8-16 Feb 1982, New Delhi, India. New Delhi, India: Indian Agricultural Research Institute.

Hegde, B.R., Channappa, T.C., and Anand Ram, B.K. 1987. Management alternatives for increased productivity of red soils: experience in Karnataka. (In this volume.)

Subbarami Reddy, D., Ramachandra Reddy, D., and Acharya, G.V.N. 1978. Studies on water intake and hydraulic conductivity in shallow and deep ploughing operations under rainfed agriculture at Anantapur. Annals of Arid Zone 17(3):291-297.

Some Aspects of Crust Formation on Soils in Semi-Arid Regions

Willem B. Hoogmoed[1]

Abstract

Literature on the effect of crust or seal formation on infiltration under rainfall is reviewed. A research approach is described to analyze data on the rainfall intensity of natural rain showers in combination with data on infiltration through sealing soil surfaces under simulated rainfall in a computer model. The effect of tillage and surface configuration may be predicted with this model. Some results of fieldwork in Israel and Mali are presented.

Introduction

Extensive areas in semi-arid regions have soils of low structural stability, particularly Alfisols that are known for their tendency to form seals and crusts at the surface. This sealing problem is generally aggravated by heavy and intensive rainfall in the semi-arid tropics (SAT). Soil-crusting problems are reported by Jones and Wild (1975) in an extensive review on the soils of West Africa. They quote, among many others, reports of Charreau and Tourte (1967), Lawes (1961), Evelyn and Thornton (1964), and Kowal (1968) on crust formation that leads to infiltration and aeration problems. The negative effects of continuous cultivation, resulting in the formation of a "single-grained" soil structure that increases the risk of erosion are mentioned by Martin (1963) and Siband (1972). Agnew (1982), did not find any crusting on typical Sahelian soils near Niamey in Niger. Crust formation in U.S. soils is discussed in detail by Cary and Evans (1974). In this report, Kemper and Miller list a number of possible approaches for management of crusting soils. Crust formation on Israeli soils is reported by Hillel (1960) and Rawitz et al. (1981).

Crusts may impede seedling emergence and reduce water infiltration, and possibly air movement. In this respect, two main types of crusts should be distinguished.

1. A crust that is easily visible, with a thickness of at least a few millimeters, created by the destruction of aggregates by direct raindrop impact or immersion. This crust will reduce infiltration and, when dry, form a barrier against seedling emergence. This type of crust is formed on an aggregated (loamy, clayey) soil. A subdivision may be made immediately below the dispersed layer (seal) at the surface where, a "washed-in" layer of fine material from the surface fills up voids between aggregates; or, the voids may remain open, but the aggregates will be cemented to each other by the wetting and drying cycle (Fig. 1). Compaction of the surface (e.g., by a planter press-wheel) may intensify the crusting process.

2. A crust (or seal) that is hardly noticeable and having an effective thickness of less than 0.1 mm. This crust does not hinder seedling emergence, but may seriously impede infiltration. Even on fine sandy soils with only a small percentage of clay or silt (5% of particles < 50 um) this type of crust is observed. The impact of raindrops separates clay and silt particles which are then transported by the infiltrating water. During this process the small particles clog the pores.

Crusts of the first type will generally impede emer-

1. Tillage Laboratory, Agricultural University, Wageningen, The Netherlands.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

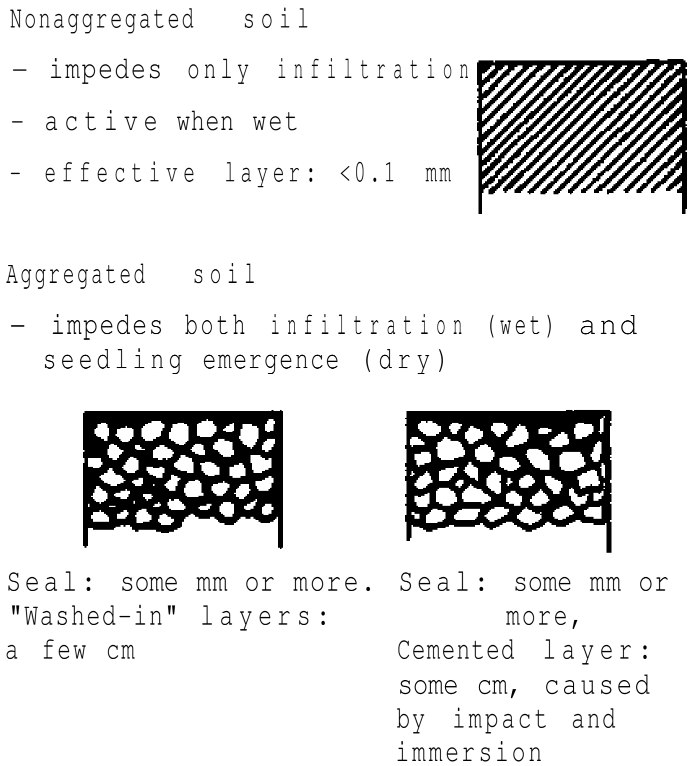


Figure 1. Different types of seals or crusts.

gence when they have dried and strengthened. The second type of crusts are effective in reducing infiltration when wet.

This paper focuses only on the effects on infiltration; the effects on seedling emergence have been reviewed by Goyal (1982). Basic research on crust formation was carried out by Mclntyre (1958) and Tickett and Pearson (1965). They found the conductivity of a seal (1-2 mm) at the surface to be several times lower than that of the layers underneath. The quick decrease in infiltration rate because of crusting was also found by Schmidt et al. (1964). Chen et al. (1980) found that a barrier may form even on very light soils.

The effect of the length of exposure and the wetting and drying cycles on infiltration were investigated and reported by Hillel (1960) and Edwards and Larson (1969). Hillel found that the degree of wetting determines the changes in porosity of the surface layer, which is highest in saturated conditions. The actual densification occurs in the shrinking phase during drying. Edwards and Larson found that, although conductivity of a seal drops considerably, an increased suction gradient in the same layer partially offsets the decrease in infiltration rate. Moldenhauer and Long (1964) showed that the effect of rainfall energy on infiltration rate over a range of textures was relatively low, but the effect on soil loss was strongly correlated with texture. Mannering (1967) found that the surface sealing on different soils could be explained, for the most part, by primary variables (texture, pH, etc.).

Although it is generally assumed that rain energy is the prime factor in crust formation, Farres (1978, 1980) found the intensity or frequency of impacts of the raindrops to be very important. Kinnell (1982) reports possible effects due to drops of different sizes on aggregate breakdown.

Modeling techniques incorporating crust formation were used by Edwards et al. (1980), Moore (1981a, b), and Whisler et al. (1979). Models may be based on steady-state condition of the seal, or take into account the formation of a seal during infiltration. A major problem is a measuring technique to obtain reliable data for use in the models.

An integrated approach on small watersheds, including the effects of cultivation on microrelief, crust formation, and runoff, was presented by Moore et al. (1980).

Methodology

From 1976 to 1981, experiments were carried out in a Dutch-Israeli project on improvement of tillage and soil-management practices in semi-arid regions (Rawitz et al. 1981). One of the principal aims of this project was to identify major constraints in tillage practices as well as in related research.

The most important objective of tillage in the SAT is probably improvement of water availability to the crop. The low infiltration rates of unstable, sandy soils—the result of crusting and sealing—can be improved by appropriate soil-tillage measures. Field experiments in Israel and Mali (West Africa), studied changes in the hydrological properties of the soil as a result of tillage, and crop response to tillage. The approaches to investigate and analyze the problems are described.

Rainfall simulation

Field experiments using natural rain showers can be designed to investigate the effect of rainfall on water balance. But rainfall is very erratic and unpredictable in the SAT. A rainfall simulator is a powerful research tool, and allows many experiments to be conducted, particularly in periods of low farming activity. The simulator used in our experiments was designed in Israel by Morin et al. (1967). After elaborate testing, a simulator capable of producing rainfall with realistic energy was developed. Crusts are formed by simulated rain, and the effect on the infiltration rate is measured by monitoring the runoff rate from the plots. The maximum plot size with this simulator is 1.5 * 1.5 m. Because of its dimensions, the machine is easily transportable.

Infiltration measurements

The infiltration rate of a crusting soil under uniform-intensity rainfall shows a typical curve in time (Fig. 2a). Morin and Benzamini (1977) found that, when the infiltration rate was plotted against rainfall depth, the curves were closely similar for different rainfall intensities. This phenomenon is valid only when crust formation is by actual impact of rain-drops, not by immersion. Under these conditions, the assumption that rainfall depth governs crust formation would mean considerable savings in the number of simulator runs required; use of just one (characteristic) rainfall intensity may suffice. The general equation of infiltration rate in relation to rainfall depth is a Horton-type equation:

$I(t) = (I_i - I_f).e^{-\alpha P.t} + I_f$, where

$I(t)$ = infiltration rate as a function of time (mm min^{-1});
I_i = Infiltration rate at $t = 0$ (mm min^{-1});
I_f = Infiltration rate at $t = \infty$ (mm min^{-1});
α = Empirical constant;
p = Rainfall intensity (mm min^{-1}); and
t = Time (min).

For a certain soil type, curves can be determined for typical situations: tillage history, degree of crusting, moisture content, etc. Morin and Benzamini (1977) distinguish three typical curves: a dry uncrusted soil, a dry crusted soil, and a wet crusted soil.

Rainfall analysis

The actual occurrence of runoff is determined by the rainfall depth and intensity. When rainfall distribution in a rain shower is known, infiltration and runoff can be calculated using curves produced by the simulator work. Rainfall can be accurately analyzed by processing charts from recording rainfall gauges using a computer model developed by Morin and Jarosch (1977) and extended by the author. From this analysis, two major types of data become available: (a) rain characteristics, with information on intensity distribution and related energies, allowing calculation of various crosivity indices; and (b)

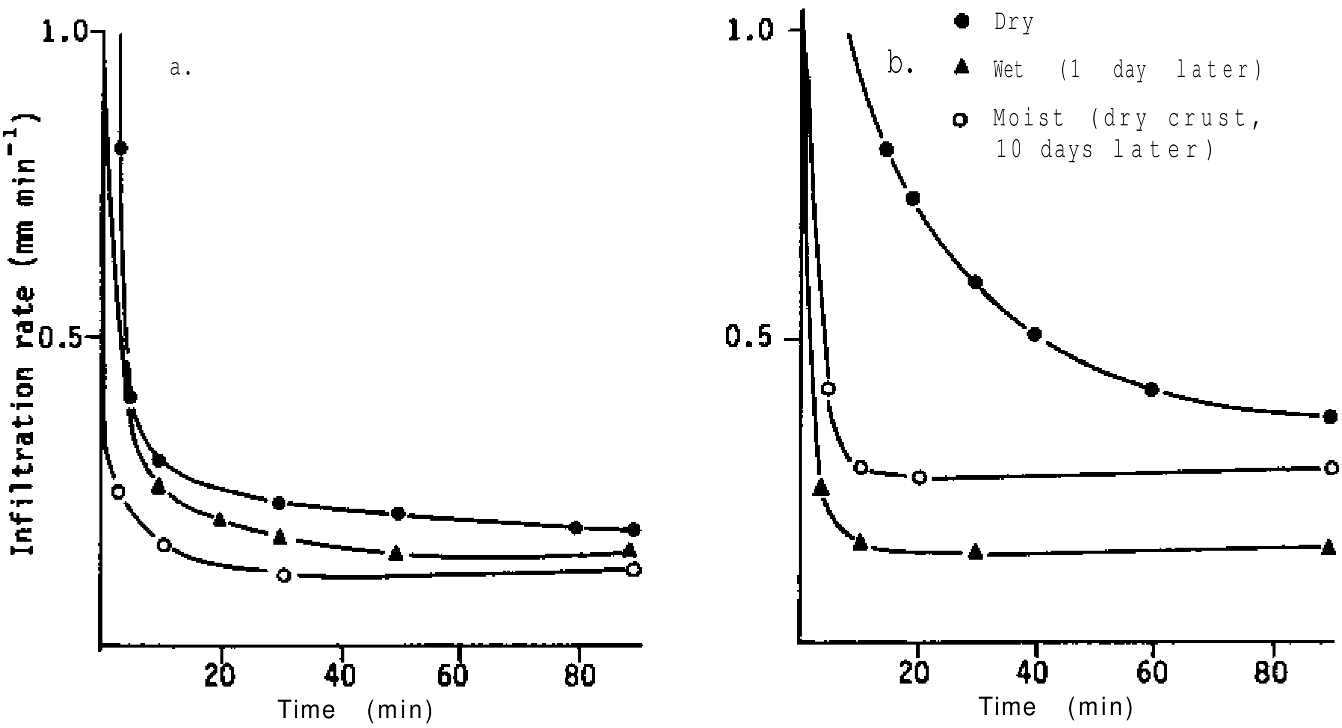


Figure 2. Infiltration rate in relation to time for an undisturbed soil (a) and the same soil with the crust removed superficially (b).

runoff that may be expected under various tillage or soil-management systems. Use of rainfall simulators necessitates employing a scaling factor, to extend the results from small plots to field-scale plots. This is done for runoff by assuming values for surface storage and detention (SS), a parameter caused by surface roughness and slope. In the computer program, runoff is calculated for a range of SS values. These values may be obtained from relief-meter measurements or from an extra simulator run.

Infiltration and redistribution

Although this may be of secondary interest, moisture movement and distribution in the soil profile can be calculated with the aid of a digital computer simulation program (Hoogmoed 1974). This is a model that uses the Darcy equation for water movement between layers, dividing the profile in depth. The input required, apart from the infiltration and evaporation data, is the retention curve (moisture

Table 1. Soil analysis of the Israeli soil, used in the experiments.

The soil is a buff-colored loessial Sierozen, typical of the northern Negev Plains. The profile is deep and fairly uniform, with soft lime concretion in the lower horizons. The texture is a fine sandy loam or loam. The soil is calcareous, slightly alkaline, and of low structural stability.

A. Soil physical properties (0-50 cm layer)

1. Mechanical composition (USDA Classification):
   Coarse sand 5% (containing 8.4% lime)
   Fine sand 47% (containing 12.3% lime)
   Silt 30% (containing 29.5%lime)
   Clay 18% (containing 14.3%lime)
   The soil contains no gravel or stones.
2. Particle density: 2.66 g cm^{-3}.
3. Hydraulic conductivity. The relation of K to matric suction head h can be represented empirically as:

$$K = \frac{4800}{h + 700} .$$

4. Field bulk density (mean values for 0-50 cm depth):
   by core sampler 1.41 g cnr^3;
   by gamma-ray gauge: 1.43 g cnr^3.
5. Field infiltration rate (by ring and sprinkler tests):
   "final" rate 5-8 mm h^{-1}.
6. Field capacity (approximate):
   18% by mass (25% by volume).
7. Permanent wilting percentage (approximate):
   7-8.5% by mass (10-12% by volume).
8. Structural stability:
   The soil, being of desert dust origin and containing little organic matter, is normally of unstable structure. Wet-sieving tests showed that in the 0-20 cm layer the percentage of stable aggregates > 0.25 mm is below 15%.

B. Soil chemical properties (0-50 cm depth, unless otherwise stated)

1. pH of saturated paste (38% water by mass): 7.5-8.2.
2. Cation exchange capacity (milliequivalents per 100 g): 26-30.
3. Exchangeable sodium percentage:
   6.5% in surface crust (0-2 cm);
   5.5% in soil below.
4. Calcium carbonate content: 17% in upper horizon, increasing to about 25% at a depth of 150 cm.
5. Organic matter content: In the upper 20 cm: 0.8%; at depths greater than 40 cm: ± 0.5%.
6. Total soluble salts:
   ± 0.106% in surface crust (0-2 cm);
   ± 0.086% below the crust.

content—tension) and the relation between moisture content or tension, and hydraulic conductivity (K). Determination of the K values for sandy soils is particularly difficult although the "hot-air" laboratory method, as described by Arya et al. (1975), gave reasonable results when sufficient replications were done.

Field Experiments

Israel

Experiments were carried out mainly on a loessial soil (Table 1) located in the northern part of the Negev. A number of experiments investigated the effect of tillage systems and surface configuration on the water balance and yields of wheat and sorghum. Results are given in the final report of the project (Rawitz et al. 1981), and are summarized in Rawitz et al. (1983) and Morin et al. (1984). Some of the main results of the effect of surface configuration on runoff are shown in Table 2. In the Mediterranean climate of Israel the tied-ridging system performed very well in terms of moisture conservation in below-average rainfall seasons.

Mali

The soils under investigation in Mali were classified as Alfisols (Table 3). The magnitude of the crusting (sealing) on this soil was determined. Visual observation during rainfall showed that, immediately after the start of rainfall, water collected at the surface. One of the possible causes was considered to be the hydrophobic character of the surface, a repellency caused by algae living at the soil surface of natural pastures in particular. In laboratory trials it was found that, after a few minutes, this layer becomes saturated with water and does not impede water movement. Runoff is caused by a truly physical seal. This seal is clearly of the second type described earlier. For quantification, various

Table 2. Some results from experiments in Israel.

Runoff and soil erosion from a wheat experiment, winter 1980-81

	Storm of 10-12-80 (Rainfall -= 64 mm)		Storm of 11-1-81 (Rainfall = 35 mm)		Seasonal total	
Treatments	Runoff (mm)	Soil erosion (kg ha-')	Runoff (mm)	Soil erosion (kg ha-')	Runoff (mm)	Soil erosion (kg ha-')
Control: sown on flat	I4.3± 0.8	228± 30	3.5 ± 0.03	65 ± 9	17.8	293
Fallow plots	15.0± 0.7	301 ± 52	6.6 ± 0.1	96 ± 32	21.6	397
1.6-m wide beds	6.7 ± 0.8	120± 15	I.2± 0.3	36 ± 11	7.9	156
0.6-m wide beds	6.5 ± 0.9	145 ± 25	0.9 ± 0.4	27 ± 20	7.4	72

Effect of surface configuration on wheat yield (t ha')

Treatment	Replication no. 1	2	3	Average	F (based on control treatment)
Control: sown on flat	0.892	1.017	0.975	0.975	
Tied ridges, 1.6-m width bed	1.242	1.483	1.483	1.403	22.3**
Tied ridges, 0.6-m width bed	0.808	0.792	1.292	0.964	0.004 NS

•• Significant at the 0.01 level.
NS = not significant.

Table 3. Soil analysis of the Mali soils (data as in source document). The rainfall simulator work was carried out on the S1 soil.

	Sable S1						Sable S2			Argile D1					Limon L			
Classification:																		
Soil survey staff (1975)	Ultic Haplustalf						Udic Ustochrepts			Aeric Haplaquept					Ustalfic Ustochrept			
FAO-Unesco (1977)	Eutric Nitosol						Chromic Cambisol			Gleyic Cambisol					Chromic Cambisol			
Aubert et Duchaufour (1956)	Sols fersiallitiques						Sols ferrugineux			Sols hydromorphes minéraux					Sol ferrugineux			
Nom local	Séno						Séno			Moursi					Danga			
Profondeur	croûte	0-10	30	80	150	350	5-15	60	150	0-1	0-5	10-15	40	130	5-15	40	60	100
Argile <2 µm	-	5.9	12.7	8.7	10.0	-	3.7	8.3	9.5	18.7	20.4	41.2	40.8	37.3	9.8	23.2	23.0	35.8
Limon fin 2-16 µm	-	0.8	1.0	2.5	1.0	-	0.8	1.8	1.2	9.3	8.2	4.5	4.0	5.1	3.3	3.5	4.2	3.7
Limon grossier 16-50 µm	-	19.4	17.5	13.0	13.3	-	13.8	15.6	13.7	29.5	31.5	24.5	24.5	26.8	26.8	26.0	24.5	22.5
Sable très fin 50-105 µm	-	60.6	56.1	64.2	65.4	-	29.2	27.7	27.8	20.1	20.4	13.7	14.9	14.0	24.9	15.9	16.8	14.0
Sable fin 105-200 µm	-									7.3								
Sable grossier >200 µm	-	13.8	12.7	11.6	10.3	-	52.5	46.6	47.8	14.9	19.5	16.1	15.8	16.8	35.2	31.4	31.5	24.0
Classification texturale*	-	La	Ls	Sl	Ls	-	Sl	Sl	Ls	L	L	A	A	La	Ls	L	L	La
pH-eau	6.3	6.1	5.5	5.8	5.4	8.8	6.1	5.5	5.4	-	5.7	5.8	6.1	6.4	5.8	5.8	5.8	6.0
pH-KCl	5.9	5.3	4.0	4.0	4.4	7.4	5.1	4.1	4.2	-	4.2	3.9	3.9	4.1	4.3	3.9	3.8	3.9
Carbone (C) (g kg^{-1})	-	5.6	2.6	1.9	1.6	1.4	2.5	1.9	1.2	-	3.9	2.8	1.3	1.5	3.5	4.0	0.6	1.0
Acote (N) (g kg^{-1})	-	0.17	0.10	0.03	0.03	0.32	0.07	0.04	0.04	-	0.29	0.24	0.11	0.06	0.21	0.13	0.10	0.11
Rapport de masse C/N	-	33	26	63	53	4	36	48	30	-	13	12	12	25	17	31	6	9
P-total (mg kg^{-1})	-	135	218	201	223	100	65	87	96	-	127	118	100	83	79	92	87	92
P-Bray I (mg kg^{-1})	-	7	6	17	24	2	3	1	1	-	3	1	0	1	1	1	1	0
K-assimilable (mg kg^{-1})	-	78	105	78	78	-	43	20	31	-	148	94	109	121	47	51	62	94
CEC du sol (pH = 7) (meq kg^{-1})	-	23	36	31	33	31	11	18	20	-	60	109	0.122	0.130	0.036	0.064	0.070	0.119
Rapport Na/CEC	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rapport K/CEC	-	0.08	0.08	0.07	0.06	0.06	0.10	0.03	0.04	-	0.06	0.02	0.02	0.02	0.03	0.02	0.02	0.02
Rapport Ca/CEC	-	0.66	0.29	0.29	0.35	0.67	0.61	0.35	0.21	-	0.46	0.38	0.48	0.61	0.54	0.43	0.47	0.65
Rapport Mg/CEC	-	0.26	0.26	0.24	0.15	0.30	0.27	0.23	0.28	-	0.31	0.35	0.31	0.25	0.23	0.26	0.24	0.17
Saturation en bases	-	1.00	0.63	0.60	0.56	1.03	0.98	0.61	0.53	-	0.83	0.75	0.81	0.88	0.80	0.71	0.73	0.84
EC (115) à 25°C (mS m^{-1})	-	3	0.3	3	3	6	2	3	3	3	3	3	3	3	3	7	3	
Densité apparente (kg m^{-3})		1.480	1.380	1.350	1.580	1.530	1.440	1.270	1.560	1.550	1.650							

*Sl = Sable limoneux, Ls = Limon sableux, L = Limon, La = Limon argileux, A = Argile; Sl = loamy sand, Ls = sandy loam, L = loam, La = clayey loam, A = clay.

Source: Unité de sol (suivant carte Stroosnijder et al. 1977).

infiltration/runoff measurements were done using a double-ring infiltrometer, a simple drip-type simulator, and an elaborate rotating-disk simulator.

The reason for using all these systems was a combination of logistics and a growing understanding of the mechanism of seal formation. Comparison of infiltration rates, as determined by the double-ring system, with the infiltration rates deduced from field-scale water-balance studies, showed large differences. The rates determined with the rings were higher by some orders of magnitude. When the rotating-disk simulator was used, the infiltration rates were comparable with those deduced from water-balance studies. The differences between the systems, shown in Figure 3, are explained by the differences in energy of the irrigation water applied: zero in the double-ring system, low using the drip-type simulator (where drops fall from a height of 1 m only), and close to natural rain in the rotating-disk type. Clearly, the impact of the raindrops must be large enough to cause a detachment of the silt and clay particles from the sand grains. These particles in the infiltrating water subsequently block the pores between the grains immediately underneath. This sealing is a fast process.

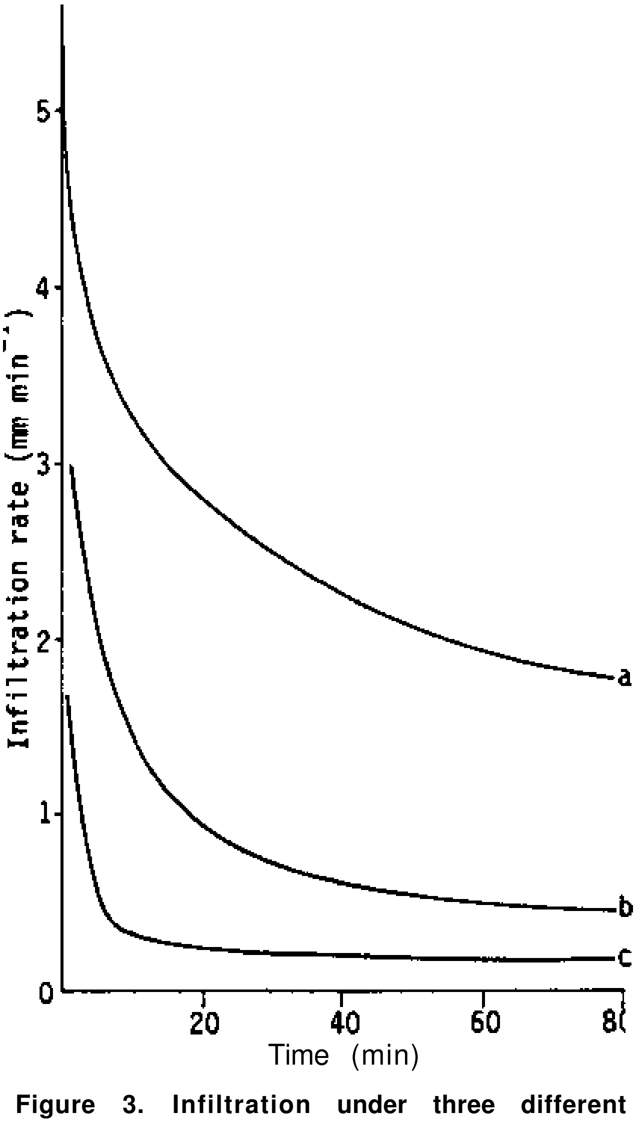


Figure 3. Infiltration under three different infiltrometers.
a = double-ring infiltrometer (If > 100 mm h^{-1}); b = drip-type rain simulator (If approx. 35 mm h^{-1}); c = rotating-disk type rain simulator (If approx. 15 mm h^{-1}).

Figure 2 shows typical infiltration rate-time curves for simulator runs, with rainfall intensity at 49 mm h^{-1}. Part a of this figure shows infiltration on a permanently crusted soil, as may be found under natural pastures. There is hardly any difference between the various conditions. Part b shows infiltration rates under the same rain intensity after the surface layer of approximately 1 cm has been carefully removed (without disturbing the subsoil). Here the quick restoration of the curve is shown: after three showers, the final infiltration rate is down to the initial value. A tillage operation such as plowing or ridging will loosen the top 10-15 cm, and therefore the infiltration rate will be high. However, this effect will also disappear rather quickly, as shown in Figure 4.

To increase the total volume of water infiltrated under rainfall, two options are available: an increase of the surface storage, or an increase in the infiltration rate. These two possibilities are worked out for a number of years by using the rainfall analysis program described earlier. The results are shown in Table 4. For this calculation, assumptions were made. (a) The tillage (plowing) operation took place

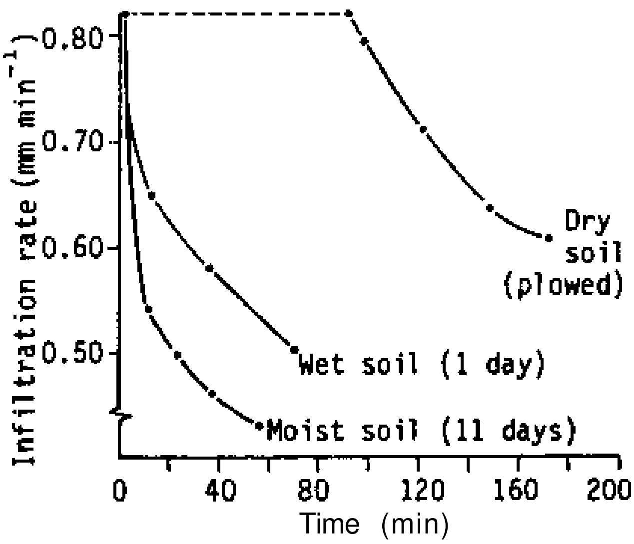


Figure 4. Effect of tillage (plowing, 10 cm deep) and subsequent surface sealing on the infiltration rate.

Table 4. Absolute and relative amounts of runoff at Niono for different tillage practices and surface-storage values (SS), for three growing seasons.

Year	Rain mm	Tillage treatment	SS = 1.0 mm Runoff (mm) mm	%	SS = 10.0 mm mm	%
1977	368	Tillage	76	18	11	3
		No-tillage	155	41	48	13
1978	271	Tillage	49	18	19	7
		No-tillage	104	38	33	12
1979	361	Tillage	80	22	38	11
		No-tillage	141	39	70	19

after the first shower, hence, for the subsequent showers, curves (Fig. 4) were used taking into consideration the restoration of the crust, (b) For the "no-tillage" operation, curves as shown in Figure 2 were used. (c) The SS values were assumed to last during the entire season.

It is clear that the effect of a permanent storage of 10 mm, and tilling at the beginning of the season, are most effective for runoff control. On the other hand, a 10-mm storage without tillage (as may be possible in a permanent tied-ridging system) is still slightly better than tillage and subsequent smoothing by the weather, given the assumed 10-mm storage.

Acknowledgment

The work reported here was carried out in cooperative projects. I gratefully acknowledge the contributions by Prof. E. Rawitz and Dr J. Morin of the Soils and Water Department of the Hebrew University, Israel, and Dr L. Stroosnijder, Soil Physics Laboratory, at Wageningen Agricultural University, The Netherlands.

References

Agnew, C.T. 1982. Water availability and the development of rainfed agriculture in South-West Niger, West Africa. Transactions of the Institute of British Geographers 7(4):419-457.

Arya, L.M., Blake, G.R., and FarreU, D.A. 1975. A field study of soil water depletion patterns in presence of growing soybean roots. I. Determination of hydraulic properties of soil. Soil Science Society of America Proceedings 39:424-430.

Cary, J.W., and Evans, D.D. (eds.) 1974. Soil crusts. Technical Bulletin no. 214. Tucson, Arizona, USA: University of Arizona, Agricultural Experiment Station. 58 PP.

Charreau, C., and Tourte, R. 1967. Le role des facteurs biologiques dans l'amelioration du profil cultural dans les systemes d'agriculture traditionnel de zone tropicale seche. Colloque sur la Fertilite des Sols Tropicaux, Tananarive 2:1498-1517.

Chen, Y., Tarchitzky, J., Brouwer, J., Morin, J., and Banin, A. 1980. Scanning electron microscope observations on soil crusts and their formation. Soil Science 130(l):49-55.

Edwards, W.M., and Larson, W.E. 1969. Infiltration of water into soils as influenced by surface seal development. Transactions of the American Society of Agricultural Engineers 12(4):463-465, 470.

Edwards, W.M., van der Ploeg, R.R., and Ehlers, W. 1980. Effect of hydraulic properties on crust and plow layer horizons on infiltration during heavy rainfall. Zeitschrift fuer Pflanzenernaehrung und Bodenkunde I43(l):84-92.

Evelyn, S.H., and Thornton, I. 1964. Soil fertility and the response of groundnuts to fertilizers in the Gambia. Empire Journal of Experimental Agriculture 32:153-160.

Farm, P.J. 1978. The role of time and aggregate size in the crusting process. Earth Surface Processes 3(3):243-254.

Farres, P.J. 1980. Some observations on the stability of soil aggregates to raindrop impact. Catena 7(2-3):223-231.

Goyal, M.R. 1982. Soil crusts vs. seedling emergence: review. Agricultural Mechanization in Asia 13(1)62-78.

Hillel, D. 1960. Crust formation in loessial soils. Transactions of the International Soil Science Congress 7:330-339.

Hillel, D. 1964. Infiltration and rainfall runoff as affected by surface crusts. Transactions of the International Soil Science Congress 8:53-62.

Hoogmoed, W.B. 1974. [A simulation model for long-term prediction of water movement in soils. Student report.] (In Nl.) Wageningen, The Netherlands: The Agricultural University, Tillage Laboratory. 40 pp.

Hoogmoed, W.B., and Stroosnijder, L. 1984. Crust formation on sandy soils in the Sahel. I. Rainfall and infiltration. Soil and Tillage Research 4(l):5-23.

Jones, MX, and Wild, A. 1975. Soils of the West African savanna. Commonwealth Bureau of Soils Technical Communication no. 55. Farnham Royal, Slough, UK: Commonwealth Agricultural Bureaux. 246 pp.

Kemper, W.D., and Miller, D.E. 1974. Management of crusting soils: some practical possibilities. Pages 1-6 in Soil crusts (Cary, J. W., and Evans, D.D., eds.). Technical Bulletin no. 214. Tucson, Arizona, USA: University of Arizona, Agricultural Experiment Station.

Kinnell, P.I.A. 1982. Laboratory studies on the effect of drop size on splash erosion. Journal of Agricultural Engineering Research 27:431-439.

Kowal, J. 1968. Physical properties of soil at Samaru, Zaria, Nigeria: storage of water and its use by crops. I. Physical status of soils. Nigerian Agricultural Journal 5:13-20.

Kowal, J. 1972. Study of soil surface crusts in the loess plain soils of northern Nigeria. Nigerian Journal of Science 6(1):93-100.

Lawes, D.A. 1961. Rainfall conservation and the yield of cotton in northern Nigeria. Empire Journal of Experimental Agriculture 29:307-318.

Mannering, J.V. 1967. The relationship of some physical and chemical properties of soils to surface sealing. Ph.D thesis, Purdue University, Lafayette, Indiana, USA.

Martin, G. 1963. Degradation de la structure des sols sous culture mechanises dans la vallee du Niari. Cahiers ORSTOM, Serie Pedologie 1(2):8-14.

McIntyre, D.S. 1958. Permeability measurements of soil crusts formed by raindrop impact. Soil Science. 85(4): 185-189.

Moldenhauer, W.C., and Long, D.C. 1964. Influence of rainfall energy on soil loss and infiltration rates. I. Effect over a range of texture. Soil Science Society of America Proceedings 28(8):813-817.

Moore, I.D. 1981a. Infiltration equations modified for surface effects. Journal of the Irrigation and Drainage Division, American Society of Civil Engineers 107(IRl):71-86.

Moore, I.D. 1981b. Effect of surface sealing on infiltration. Transactions of the American Society of Agricultural Engineers 24(6): 1546-1552, 1561.

Moore, I.D., Larson, C.L.,and Slack, D.C. 1980. Predicting infiltration and micro-relief surface storage for cultivated soils. Bulletin, Water Resources Research Center, University of Minnesota, no. 102. 122 pp.

Morin, J., and Benzamini, Y. 1977. Rainfall infiltration into bare soils. Water Resources Research 13(5):813-817.

Morin, J., Benzamini, Y., and Michaeli, A. 1981. The effect of raindrop impact on the dynamics of soil surface crusting and water movement in the profile. Journal of Hydrology (Netherlands) 52(3-4):321-335.

Morin, J., Goldberg, D., and Seginer, I. 1967. A rainfall simulator with a rotating disk. Transactions of the American Society of Agricultural Engineers 10:74-77, 79.

Morin, J., and Jarosch, H.S. 1977. Runoff rainfall analysis for bare soils. Pamphlet no. 164. Bet Dagan, Israel: Agricultural Research Organization. 22 pp.

Morin, J., Rawitz, E., Hoogmoed, W.B., and Benzamini, Y. 1984. Tillage practices for soil and water conservation in the semi-arid zone. III. Runoff modeling as a tool for conservation tillage design. Soil and Tillage Research 4(3):215-224.

Powell, D.M., and Steichen, J. 1982. An infiltration model including transient soil crust formation. ASAE Paper no. 82-2031. St. Joseph, Michigan, USA: American Society of Agricultural Engineers 12 pp.

Rawitz, E., Hoogmoed, W.B.,and Morin, J. (eds.) 1981. Development of criteria and methods for improving the efficiency of soil management and tillage operations, with special reference to arid and semi-arid regions. Wageningen, Netherlands: Agricultural University, Tillage Laboratory, and Rehovot, Israel: Hebrew University, Department of Soils and Water. 260 pp. + 5 appendices.

Rawitz, E., Morin, J., Hoogmoed, W.B., Margolin, M., and Etkin, H. 1983. Tillage practices for soil and water conservation in the semi-arid zone. I. Management of fallow during the rainy season preceding cotton. Soil and Tillage Research 3:211-231.

Schmidt, B.L., Schrader, W.D., and Moldenhauer, W.C. 1964. Relative erodibility of three loess derived soils in Southwestern Iowa. Soil Science Society of America Proceedings 28:570-574.

Siband, P. 1972. Etude de revolution des sols sous culture traditionnelle en Haute-Casamance: principaux resultats. Agronomie Tropicaie 27:574-591.

Smiles, D.E., Knight, J.H., and Perroux, K.M. 1982. Absorption of water by soil: the effect of a surface crust. Soil Science Society of America Journal 46(3):476-481.

Stroosnijder, L., and Hoogmoed, W.B. 1984. Crust formation on sandy soils in the Sahel. II. Tillage and its effect on the water balance. Soil and Tillage Research 4(4):321-337.

Stroosnijder, L., and Kone, D. 1982. Le bilan d'eau du sol. Pages 133-165 in La productivitedespaturagessaheliens: une etude des sols, des vegetations et de l'exploitation de cette ressource naturelle (Penning de Vries, F.W.T., and Djiteye, M.A., eds.). Agricultural Research Report no. 918. Wageningen, Netherlands: PUDOC (Centre for Agricultural Publishing and Documentation).

Tickert, J.L., and Pearson, R.W. 1965. Some characteristics of soil crusts formed by simulated rainfall. Soil Science 99(6):407-413.

Whisler, F.D., Curtis, A.A., Niknam, A., and Romkens, M.J.M. 1979. Modeling infiltration as affected by soil crusting. Pages 400-413 in Surface and subsurface hydrology (Morel-Seytoux, H.J., ed.). Fort Collins, Colorado, USA.

Management Alternatives for Increased Productivity of Red Soils: Experience in Karnataka

B.R. Hegde, T.C. Channappa, and B.K. Ananda Ram[1]

Abstract

Red soils in Karnataka occupy more than 50% of the cultivated area. They are characterized by low moisture retention, low cation exchange capacity and phosphorus content, but a high rate of infiltration. High soil erosion and crust formation limit crop production. Cropping is most common in the rainy season, especially on shallow soils. Contour bunds for low-rainfall areas, and graded bunds for medium-deep soils with seasonal rainfall more than 700 mm, are recommended; deep red soils are suitable for border-strip layout. Off-season tillage has been found to increase infiltration and to improve crop yields. No interterrace treatments, e.g., broadbeds and furrows or a furrow every 3 m, increased either the moisture status or the crop yields significantly. Beds and furrows were used mainly as disposal systems, whereas a ridge-and-furrow system, adopted for maize, reduced runoff losses. Nevertheless, the use of furrows in changing the direction of flow along a less erosive gradient is beneficial in controlling erosion in an interbunded area. Extension of land management practices to farm situations is complicated by the fact that holdings are small. Developing waterways as community works, and restricting other developmental activities to existing holdings, are suggested as alternatives to current soil-conservation efforts.

Introduction

Red soils occupy 45% of the geographical area in Karnataka; 10% of this area has mixed red and black soils, and another 10% laterite soils. Presently, 60% of the area in the red soil regions is under cultivation.

Red soils are highly erodible. Nearly 80% of the red soils are considered as requiring some type of conservation measure (Anonymous 1964). During normal seasonal rainfall (850 mm), soil loss of 2.3-7.7 t ha^{-1} and runoff of 260-370 mm have been reported (Krishnamurthy 1971). Research on the farm at the All India Coordinated Research Project for Dryland Agriculture (AICRPDA), Bangalore, indicated that 20-35% of seasonal rainfall is lost annually through runoff, and the soil losses ranged from 3 to 6 t ha^{-1}. Bunding is an accepted soil conservation practice in Karnataka. By the end of 1982, out of the estimated 6.8 million ha in need of soil conservation, 3.06 million ha had already been covered, and this included both red and black soils suitable for bunding.

Systematic studies on the management of red soils in Karnataka have been few. Intensive studies were possible only after the establishment of AICRPDA in 1970. Efforts have since been made to evaluate bunding systems, interterrace management, tillage practices to improve infiltration and the retention of moisture, and cropping systems to suit the resources. Resource-conservation studies have been taken up on a watershed basis, and the idea extended to on-farm situations. This paper attempts to highlight the major observations in various fields of study.

1. All India Coordinated Research Project for Dryland Agriculture (now the Central Research Institute for Dryland Agriculture), University of Agricultural Science, GKVK., Bangalore, Karnataka 560 065, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

Rainfall and Soil

The seasonal rainfall at the AICRPDA Centre farm is 886 mm, over the period May to November. There are two rainfall peaks: the first, of about 110 mm, is in May and the second, of 160-200 mm, is in September-October. Although the soils are deep, only rainy-season cropping is common because of their moderate moisture-holding capacity.

The soils in the farm area belong to Vijayapura series, and are classified as Oxic Haplustalf. According to the FAO classification, these soils are Ferric Luvisols. They are reddish-brown lateritic soils derived from granite gneiss under a subtropical semi-arid climate. They are sandy loam to sandy clay loam in texture, becoming finer with depth. These soils are deep, and possess good drainage. They have moderate moisture-holding capacity. Surface sealing and crusting are quite common. They are slightly acidic, low in organic matter and available P_2O_5, and respond well to P application. The P-fixation capacity of the soils is about 40%.

Runoff and Soil Loss Under Different Crop Canopies and Management

The average runoff under cultivated conditions was found to be 20-35% of rainfall during the cropping season. Crops such as maize were more efficient in reducing runoff and soil loss compared with crops such as groundnut and finger millet (Fig. l). The practice of earthing-up in maize might have also contributed to this phenomenon. By comparison, runoff of only 7-12% was recorded from an adjacent forest area (a eucalyptus plantation).

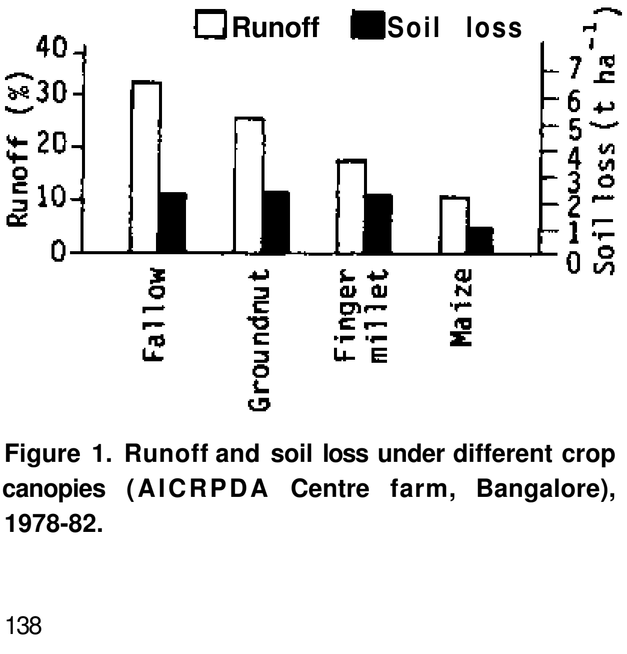


Figure 1. Runoff and soil loss under different crop canopies (AICRPDA Centre farm, Bangalore), 1978-82.

Mechanical Structures for Soil and Moisture Conservation

Contour bunds of 0.6-0.8 m^2 cross section are very common in red soils (Joshi 1976). The bunding program sponsored by the Karnataka government is, primarily, contour bunding. But the system has not been fully accepted by farmers because it poses several problems, e.g.: (1) water stagnation near the bund, (2) loss of a substantial area under bunds, (3) difficulties in maintenance, and (4) the small size of holdings. During 1971, studies on various alternatives to contour bunds were initiated at the Centre's farm. From 1977, the studies were continued on a watershed basis. The results indicate that border strips of 10-12 m width and 100-150 m length, and graded bunds (0.2-0.4% gradient) of a cross section of 0.5 m^2, are suitable alternatives for contour bunds on these deep, red soils (Table 1).

As the cut-and-fill in the border-strip layout is restricted to 15 cm, the width is automatically decided by the slope of the land. The graded bunds cost less than contour bunds to construct (about Rs 300 ha^{-1}); the estimated cost of border-strip construction is Rs 1500 ha^{-1}. One of the basic requirements, both for graded bund and border strips, is a protected waterway. Fortunately, in the red soil regions of Karnataka, waterways already exist. They need only to be modified to the suitable shape and size, and drop structures are required at appropriate distances.

Tillage Operations

Tillage operations before the onset of the rainy seasons are essential for increasing infiltration and for effective weed control (Table 2). In Anantapur, deep tillage of shallow red soils with a compact subsurface helped open up the compact murram layer and increased the infiltration from 3.5 to 6.0 cm h^{-1}. The depth of root penetration increased by 15-20 cm, and the crop yields improved.

Good land preparation is essential in red soils. Even one additional plowing with a moldboard plow to a depth of 15 cm increased the finger millet yield by 44% in the villages around Bangalore (Table 3). Off-season tillage is practiced whenever opportunities arise to obtain a good seedbed and effective weed

Table 1. Effect of land treatment on runoff and finger millet yield on land with a 3% slope.

Land management treatment	Runoff as % of seasonal rainfall	Yield of finger millet (kg ha-')	Percentage of yield increase over control
Farmers' field bunds along the boundary (control)	28.0	722	
Contour bunds	20.6	913	26.5
Graded bunds	23.2	960	33.8
Graded bunds with interterrace management (furrow at 3 m)	22.3	1728	70.0
Graded border strips	17.5	1102	52.6
Broad beds and furrows	23.8	901	24.8

Source: AICRPDA 1977-82.

Table 2. Soil moisture as influenced by plowing before the onset of the rainy season.

Depth of soil (cm)	Moisture percentage after total of 81 mm rainfall in May: Plowed area	Unplowed area
0-15	10.7	3.6
15-30	13.2	7.1
30-60	13.3	8.7
60-90	13.4	Dry

Source: AICRPDA 1977-82.

Table 3. Effect of moldboard plowing on the yield of finger millet (kg ha^{1}).

System	1981	1982
Local practice (wooden plowing 2-3 times)	1220	1040
One additional moldboard plowing in July	1670	1570

Source: AICRPDA 1977-82.

control. Summer tillage usually resulted in increased yields. Surface tillage under crusted soil conditions is essential for reducing runoff.

The Crust Problem

One of the serious problems of crop production in red soils is the formation of a surface crust. Crusting just after seeding results in the poor emergence of seedlings. The problem is more serious with small-seeded cereals such as finger millet, pearl millet, and sometimes with sorghum, that have a weak plumule. Tilling with a thorny brush harrow may help overcome this problem if crust formation occurs within 1-2 days after seeding. Seeding on the side of a ridge—which is less prone to crust formation—and mulching the seed lines with organic residues to minimize the beating action of the rain and increasing moisture status, are some of the other possible remedies.

Efforts are under way at the AICRPDA Centre farm at Bangalore to perfect a rotary-type spiked roller that can be used on crusted soil. The spikes of this roller will penetrate the soil up to a depth of 2 cm and disturb only the surface soil, without damaging the emerging seedlings. Results from experimental plots have been quite encouraging.

Crop residues, partially incorporated into the surface soil, have been found to reduce substantially the strength of the crust. In one study, the crust strength dropped to 1.13 kg cm^{*2} from the original 3.15 kg cm'^{2} in control plots following the application of 4 t ha^{-1} of straw. Straw application also increased the soil moisture and germination percentage of finger millet (Ranganatha 1976).

Studies at this research farm indicate that an addition of 4 t ha^{-1} of maize residue has a beneficial effect on the subsequent crop. In 1982, a finger millet crop, grown after incorporation of maize residue, yielded 3528 kg ha^{1} in contrast with 2521 kg ha^{-1} without such treatment. The soil moisture in the surface 15 cm depth was 11.2% in residue-incorporated plots, but only 8.5% in control plots.

Interterrace Management

Studies on interterrace land treatments were initiated in 1974, when furrowing across the major slope was compared with normal cultivation practices in the region. More systematic comparisons of two important crops in the region, namely, finger millet and maize, were initiated in 1977 as a collaborative project between AICRPDA and ICRISAT. The specific objectives of the project were: (1) to study suitable land treatments to achieve effective in-situ soil and water conservation; (2) to devise systems for the safe disposal of runoff to avoid waterlogging in the terraced area; and (3) to increase crop yields through the efficient use of rain water, and develop systems of raising crops integrated with land treatments.

Experimental area

The study area was 8 ha and had a slope of about 2.5%. Graded bunds of 0.35 m^2 cross section were constructed at 1-m vertical intervals and with a gradient of 0.2-0.4%. The bunds have been maintained as permanent structures and serve as keylines for all agricultural operations. The crops were always sown parallel to the bund, and the crop rows maintained on the same gradient as the bund. The area between the bunds was smoothed and, at the end of the bund, protected waterways were developed.

Treatments

The treatments, imposed in different years, are indicated in Table 4. All the treatments were incidental to cultivation, and no permanent structures were maintained between the bunds. For finger millet, broadbeds and furrows, as well as a furrow after two seed-drill widths, were created, using seed drills specially designed for the purpose and priced within the reach of the common cultivator. The furrows were initially opened at the time of sowing, and subsequently deepened 2-3 times during crop growth, using either furrow openers or ridgers. With the exception of land treatments, all other cultivation practices were unchanged in different treatments. In the case of maize, the traditional practice in the region is to sow on flat land and earth up at 45 days. In the broadbed-and-furrow system, however, earthing up was not done.

The influence of land treatments on crop yields in different years is shown in Table 4. The following broad conclusions were drawn from the observations.

1. Furrows across the slope at 3-m interval were beneficial, whereas furrows at closer intervals (1.5 m) reduced the yield.
2. When the broad bed -and-furrow system was adopted in finger millet, 20% of the crop rows had to be sacrificed to accommodate one furrow

Table 4. Effect of land treatment on crop yield at AICRPDA Centre farm, Bangalore.

		Grain yield (kg ha^{-1})					
		1977	1978	1979	1980	1981	1982
Land treatment	Rainfall (mm)	543	583	773	321	476	498
Crop: finger millet							
Flat-on-grade		2578	2458	1767	3078	1115	3638
Flat-on-grade but corrugating in the last intercultivation		2266	2295	-	-	-	-
Furrow after 2 seed-drill widths (3-m interval)		-	-	1937	2809	1208	3438
Broad bed -and-furrow system (furrow at 1.5 m)		2332	2669	1697	2786	-	3360
Border strip bunds (bunds at I l-m intervals)		-	-	-	-	949	3678
Crop: maize							
Flat-on-grade and ridging up later		3773	2760	2256	2491	2361	-
Dibbling on the side of the furrow		3225	2250	-	-	-	-
Broad bed-and-furrow system		2789	2547	2435	2258	2499	

Source: AICRPDA 1977-82.

after every four rows (one seed-drill width). Nevertheless, yield was maintained on close par with the flat system. Studies in 1979 showed that the loss is compensated by the better growth of the crop in rows on either side of the furrow. Even the rows at the center of the bed contributed more to grain yield than rows in the flat-on-grade sowing.

3. Furrows served as efficient water-disposal systems with finger millet; they were useful in reducing erosion in the interterraced area.
4. Construction of small bunds at 11-m intervals (border-strip bunds) was more advantageous in the case of finger millet when compared with the flat system of cultivation.
5. For maize, the broadbed-and-furrow system was as effective as earthing-up after 45 days.

Runoff studies

Runoff studies were made during 1980 and 1981 with maize and during 1982 with finger millet. H-flumes with automatic liquid-level recorders were installed in the maize, one each in the broadbed-and-furrow system and the ridge-and-furrow system. The area from which runoff estimates were made was about 0.25 ha in each treatment. When the broadbed-and-furrow system with maize was compared with flat-on-grade sowing and ridging later, the runoff was higher in the broadbed-and-furrow system (AICRPDA 1980-82). There were similar results for finger millet.

Soil moisture status

In none of the years did land treatments offer any distinct advantage; the small differences observed appeared to be mainly due to sampling errors. Auger sampling cannot, however, be completely relied upon as a method to indicate the small variations due to treatments.

Stability of raised land configurations

With maize, ridges formed after earthing up were stable, and no breaches were observed. In the case of furrows across the slope in finger millet, they were silted up and had to be deepened 2-3 times during the crop-growing period. The small bunds at 11-m intervals were not stable and were breached during high-intensity rainfall.

Economics of cultivation

The land treatments were imposed at sowing or shortly thereafter. As such, there was not much difference in the procedure adopted for land preparation. The extra expenditure and labor involved in deepening the furrows is very small. But, in the case of maize, 12-15 men are required to earth up the crop rows manually.

None of the land treatments brought about appreciable changes in either yield or soil-moisture status. The red soils have a fairly high infiltration rate, and, if the soil surface is kept loose by intercultivation, sufficient rainwater can be stored in the soil profile. Broadbeds and furrows appear to be mainly disposal systems, whereas the ridge-and-furrow system, adopted for maize, reduced runoff. Still, the advantage of such furrows in changing the direction of flow along a less erosive gradient is of great significance in controlling erosion in the interbunded areas.

The studies conducted so far have not provided sufficient information on runoff, and observation on soil loss was not recorded. Results on soil-moisture status are inconclusive, mainly because of sampling errors.

Hydrological Studies

The specific objectives were as follows.

1. To derive from the design of small agricultural watersheds criteria for improved resource management that will more effectively conserve rainfall and soil, and, when it is integrated with improved crop production systems, to increase productivity and assure dependable crop harvests.
2. To obtain quantitative data on runoff, soil-moisture fluctuations and deep-percolation losses that occur under different land-development or interterrace management systems in use for growing crops common in the area.
3. To increase crop yields through the more effective utilization of rainfall by adopting in-situ moisture-conservation practices, and through supplemental irrigation using runoff water, harvested and stored in farm ponds.

An agricultural watershed of 17 ha was laid out into three subwatersheds, comprising contour bunds, graded bunds, graded border strips, traditional practices of boundary bunds and the interterrace management of broad ridge and furrows. Each subwatershed, comprising one of the treatments, was installed with a Parshall or a Cutthroat flume for measuring runoff. The runoff was, ultimately, led to flow into existing ponds through well-developed grassed waterways.

The main crop in the drylands of the region being finger millet, that crop was grown each of the 4 years of the study (although the varieties were different). For sowing, bullock-drawn seed drills or seed-and-fertilizer drills were used in all the treatments except in the broadbeds and furrows, where either a Tropicultor, or seed drills with furrow openers, were used.

The crop yields in these studies varied considerably, and no definite conclusions could be drawn from yield data alone. Even the soil-moisture conditions in various treatments were inconsistent.

The runoff estimates from 1979 to 1981 are presented in Table 5. As shown, runoff was least in contour bunds followed by graded border strips. But the use of contour bunds did not result in higher yield because of other problems, such as water stagnation near the bunds.

The following general conclusions were drawn.

1. Graded border strips with 0.2-0.4% gradient appear to be the most suitable land management practice for red soils with sufficient depth (more than 1 m).
2. Alternatively, graded bunds with a gradient of 0.2-0.4% are preferrable with interterrace management systems.
3. About 20% (average) loss of rainwater has been found inevitable, but it is available for harvesting in the ponds.

On-farm Research

Soil-conservation practices have their limitations when implemented on farmers* fields. The size of the holdings, being less than 2 ha in over 80% of the cases, creates difficulties in the construction of contour and graded bunds on a watershed basis. Nevertheless, there is no alternative to constructing carefully planned bunds and protected waterways for the disposal of surplus water. Fortunately, waterways exist between most farm boundaries. What is needed is an improvement of these waterways and development of the land within the farmers' own boundaries. Such attempts have been made by the Operational Research Project in the villages near the AICRPDA research farm at Bangalore. The existing waterways between the boundaries are first widened and stabilized by vegetation, as well as drop structures. Thereafter the land within each holding is used for systematic development.

Two major difficulties are posed even with this approach. First, as the bunds and border strips have to be planned within the holdings, it is often difficult to align them on the required grade, thereby necessitating extra cutting and filling. Secondly, a farmer may strongly resist the digging of a waterway through his holding, even when such alignment is

Table 5. Influence of different land treatments on runoff at AICRPDA Centre farm,, Bangalore.

Year	Observations	Traditional practice (field bunds) TI	Contour bunds 12	Graded bunds T3	Graded border strips T4	Broadbed-and-furrow system (finger millet seed drill) T5	Broadbed-and-furrow system (Tropicultor) T6
1979	Total rainfall (mm)			1105			
	Rain causing runoff (mm)	812	851	699	760	848	850
	Runoff as % of total rainfall	20.8	19.4	12.7	17.0	15.7	24.4
1980	Total rainfall (mm)			654			
	Rainfall causing runoff (mm)	312	338	313	398	302	367
	Runoff as % of total rainfall	14.1	7.3	12.7	6.3	10.3	14.6
1981	Total rainfall (mm)			729			
	Rainfall causing runoff (mm)	381	404	432	412	487	408
	Runoff as % of total rainfall	12.7	9.3	13.5	7.4	11.9	11.2

TI: Farmers' method of crop management:: low level of fertility, local seed. sowing by broadcasting.
T2 to T6: improved method ol crop mana gemcnt: recommennded level of fertilizer. improved seeds, and seed-drill sowing.

unavoidable. The only solution is to compensate him suitably for the loss of land. This may call for suitable amendment to the existing land-improvement act.

Acknowledgment

The authors acknowledge with gratitude the guidance and encouragement given by Dr G.V. Havanagi, now Professor of Agronomy, Agricultural College, Bangalore, who worked as Chief Scientist at the Dryland Agriculture Project from its inception up to 1980. Most of the studies reported in this paper were initiated during his time in office.

References

AICRPDA (All India Coordinated Research Project for Dryland Agriculture). 1977-82. Annual reports of Bangalore Centre. Bangalore, Karnataka, India: University of Agricultural Sciences.

Anonymous. 1964. Planning Commission of India, PED Publication 41. New Delhi, India: Planning Commission.

Hegde, B.R., Channappa, T.C., and **Ananda Ram, B.K. 1981**. Water harvesting and recycling in the red soils of Karnataka. Indian Journal of Soil Conservation 9:107-115.

Joshi, P.G. 1976. Soil and water conservation techniques. Bangalore, Karnataka, India: Department of Agriculture. 371 pp.

Krishnamurthy, K. 1971. Dry farming problems in Mysore. U.A.S. Research Series no. 12. Bangalore, Karnataka, India: University of Agricultural Sciences.

Ranganatha, B.R. 1976. Studies on soil crust and its effect on seedling emergence. M.Sc. thesis. University of Agricultural Sciences, Bangalore, Karnataka, India.

Erosion and Runoff Measurements from Semi-Arid Rangeland in Southwestern USA: an Overview

Gary W. Frasier and Kenneth G. Renard[1]

Abstract

The research program at the Southwest Rangeland Watershed Research Center in Tucson, Arizona, USA, is aimed at obtaining information for assessing present and future water potential, developing water-management techniques, providing design concepts for flood and sediment control, evaluating nonpoint source pollution, developing rangeland revegetation techniques, and water-harvesting / runoff farming techniques. Current studies are involved with (1)precipitation intensity and areal distribution; (2) infiltration and channel losses; (3) hydrologic balance of semi-arid rangeland watersheds; (4) runoff hydraulics and flood-water yield frequency relations; (5) erosion and sediment transport; (6) surface and groundwater quality; (7) vegetation manipulation and rangeland revegetation; and (8) water harvesting and runoff farming. Much of the research activity is focused on developing concepts and collecting data for use in modeling to extend the area of potential applicability of the research results.

Introduction

Major advances have been made in water resources research in arid and semi-arid regions in the past few decades, due in part to advances in computer technology, which permits the handling and analysis of many data. When matched with parallel development of sophisticated analytical models for various hydrologic processes, we are able to explain past events; but more importantly, we are now able to predict more accurately the hydrologic results, should various land- and water-management practices be implemented.

Research Facilities

The Southwest Rangeland Watershed Research Center is a facility of the U.S. Department of Agriculture, Agricultural Research Service. The main office and laboratory facilities are at Tucson, Arizona, with active experimental watersheds in southeastern Arizona, on the Walnut Gulch Watershed near Tombstone, and on the Santa Rita Experimental Range, U.S. Forest Service, south of Tucson. Watershed studies at Safford, Arizona, as well as Albuquerque, Santa Rosa, and Fort Stanton, New Mexico, are now terminated, the immediate research objectives having been achieved. The data obtained from these studies are used to complement ongoing research.

The major research area is the 150-km^2 Walnut Gulch watershed, an ephemeral tributary of the San Pedro river. The watershed is basically a high foothill alluvial fan with medium- to fine-textured soils that are gravelly or stony at the surface. The area is characterized by mild temperatures, limited rainfall (= 300 mm a^{-1}) and high evaporation (average pan evaporation of over 2600 mm a^{-1}). The climax vegetation is desert plains grasslands, with 60% of the watershed now supporting desert shrubs. Livestock grazing is the primary land use.

Stream-flow is measured with supercritical flumes (570 $m^3 s^{-1}$ capacity) at 11 gauging stations, three on the main channel, and eight on major tributaries. In addition, there are 12 subwatersheds (0.2-60 ha)

1. Southwest Rangeland, Watershed Research Center, Tucson, Arizona, USA.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502324, India: ICRISAT.

equipped with a smaller version flume (2.8 m^3 s^{-1} capacity) (Smith et al. 1982) and 11 subwatersheds (34 316 ha) where runoff and sediment yield are measured in earthen stockponds. Sediment transport is measured at most of the small flumes with solar batteries which power traversing slots or pump samplers. A network of 95 24-h weighing recording rain gauges distributed on the watershed are used for monitoring and recording precipitation amounts. Each small subwatershed has at least one recording rain gauge.

On the Santa Rita Experimental Range, eight small watersheds (1.1-4.0 ha) are equipped with small supercritical flumes (2.8 m^3 s^{-1} capacity) and solar-powered traversing-slot sediment samplers. Each watershed has a 24-h weighing-type rain gauge for monitoring precipitation.

Research Mission

The primary mission of the Center is to study the hydrologic characteristics of arid and semi-arid rangeland watersheds and the effects of changing land use and practices on the hydrologic cycle. Emphasis is on: (1) understanding and evaluating the effects of changing land use, including range renovations and conservation practices; and (2) developing the principles for such an understanding in order to apply the results and findings from research to areas where few or no research data are available.

Data from the experimental areas are used to study climate, soil, plant, chemical, and water relations from southwestern rangelands. Information obtained from the study watersheds is used for determining present and future water-resource potentials, developing water-management techniques for competing water users, providing design concepts and criteria for flood and sediment control, evaluating nonpoint source pollution, developing techniques for increasing and stabilizing forage production, and developing water-harvesting runoff-farming techniques for conserving and improving rangeland water supplies.

Recent Research Progress

Precipitation intensity and areal distribution studies

Precipitation at Walnut Gulch, representative of much of the southwestern United States, is highly variable in annual quantities, storm amounts and intensities, and storm frequency. The annual amounts are distributed between two seasons: summer and winter. The summer storms result from moisture originating in the Gulf of Mexico or from tropical storms in the Pacific Ocean off lower Baja, Mexico. These storms are basically high-intensity, short-duration, air-mass convective thunderstorms of limited areal extent (see example mapped in Fig. 1). Such intense summer thunderstorms produce most of the runoff from the Walnut Gulch Watershed. The winter storms are from Pacific Ocean storm systems moving into the area from the northwestern Pacific. These are characteristically of low intensity, long duration, and large areal extent. There is usually no runoff measured from these winter storms, but they do contribute to providing soil water for plant growth.

A significant factor contributing to the progress in understanding runoff processes on the arid and semi-arid watersheds of the southwestern United States has been the development of a better description of the thunderstorm processes that dominate the annual precipitation total and produce most of the runoff in the area.

Three elements are needed for an analytic description of thunderstorm rainfall: (1) distribution of rainfall events; (2) distribution of rainfall depths at a point; and (3) areal distribution patterns (Renard 1977). The physical processes that cause precipitation are complex and not completely understood. One simplifying procedure for characterizing precipitation is to use probabilistic descriptions for predicting properties of future precipitation events as an input in hydrologic models. The work at the Center has two major research objectives in this area: (1) to develop regional models of point and areal distributions of rainfall (primarily for Arizona and New Mexico); and (2) to develop models of intrastorm rainfall intensities, amounts, and frequencies.

Current results are the following. (1) A stochastic model of point precipitation, using a Markov Chain for daily occurrence (Smith and Schreiber 1973) and a mixed exponential distribution for the daily depths (Smith 1974), was found to reproduce most measured precipitation sequences at Walnut Gulch and other southern Arizona stations. (2) A convective storm model, including the areal pattern, has been developed. Depth-area curves generated by the model are being used by hydrologists and engineers for flood forecasting. And (3), a simulation program for modeling time and space distribution of rainfall

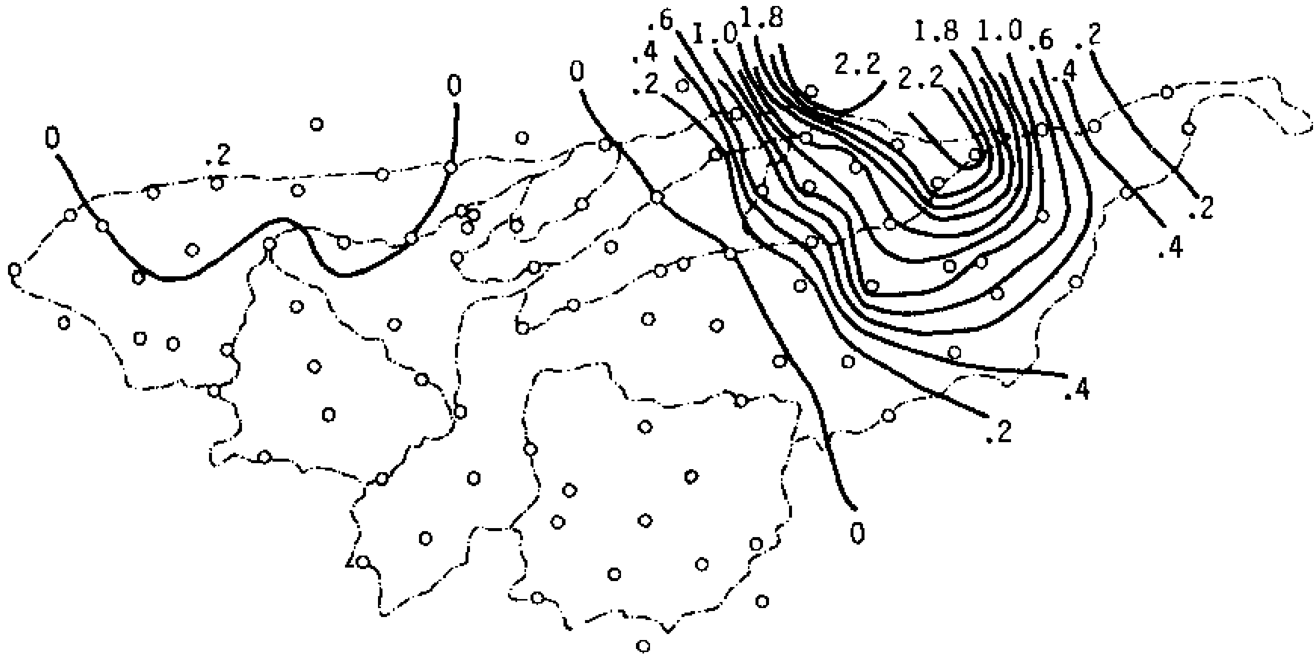


Figure 1. Isohyetal map of a storm on 30 Jul 1966 at Walnut Gulch watershed. (The small circles show the location of rain gauges.)

in Arizona and New Mexico has been developed (Osborn et al. 1980).

Infiltration and channel transmission loss studies

Stream channels in most arid and semi-arid areas are usually dry. Normally, channel flows occur only from intense rainfall events. During a runoff event, water infiltration into these normally dry alluvial streambeds is characteristically high, with dramatic effects on the resulting hydrograph. These losses of surface runoff as the flow moves through the channel are referred to as transmission losses; significant quantities of the infiltrating water may, however, eventually reach the regional groundwater. Much of the groundwater recharge in the semi-arid areas of the southwestern United States results from this infiltration into stream beds. The magnitude of this groundwater recharge is controlled by alluvial characteristics, geology beneath and adjacent to the channel, frequency of flow, and the type or quantity of vegetation along the channel which, if mesic, may use large quantities (for transpiration) of water when moisture is available.

Seven channel segments within the Walnut Gulch Watershed have been isolated so that the magnitude of transmission losses can be measured. These segments have widely different characteristics, and facilitate quantifying some of the factors controlling the magnitude of transmission losses. The actual magnitude of loss is determined by comparing hydrographs at upstream and downstream stations in a channel reach, for events where there is little or no runoff from intervening drainage points (a frequent occurrence with air-mass thunderstorms). Figure 2 illustrates these transmission losses for a 6.4-km reach of the Walnut Gulch for the storm of 30 Jul 1966. Results show that the magnitude of transmission losses for any flow event is variable and related to (1) flow duration, (2) channel length and width, (3) antecedent moisture conditions, (4) peak discharge, (5) flow sequences, (6) volumes and characteristics of the alluvium, and (7) amount of clay in suspension in the runoff. These studies led to the development of a design procedure for determining transmission losses (Lane 1982).

Hydrologic balance of a semi-arid rangeland watershed

The relative magnitudes of the various components of the hydrologic balance on Walnut Gulch watershed are shown in Figure 3. Over 80% of the annual precipitation leaves the watershed as evaporation and transpiration.

The various water losses from surface runoff have a marked effect on the response of a watershed to a

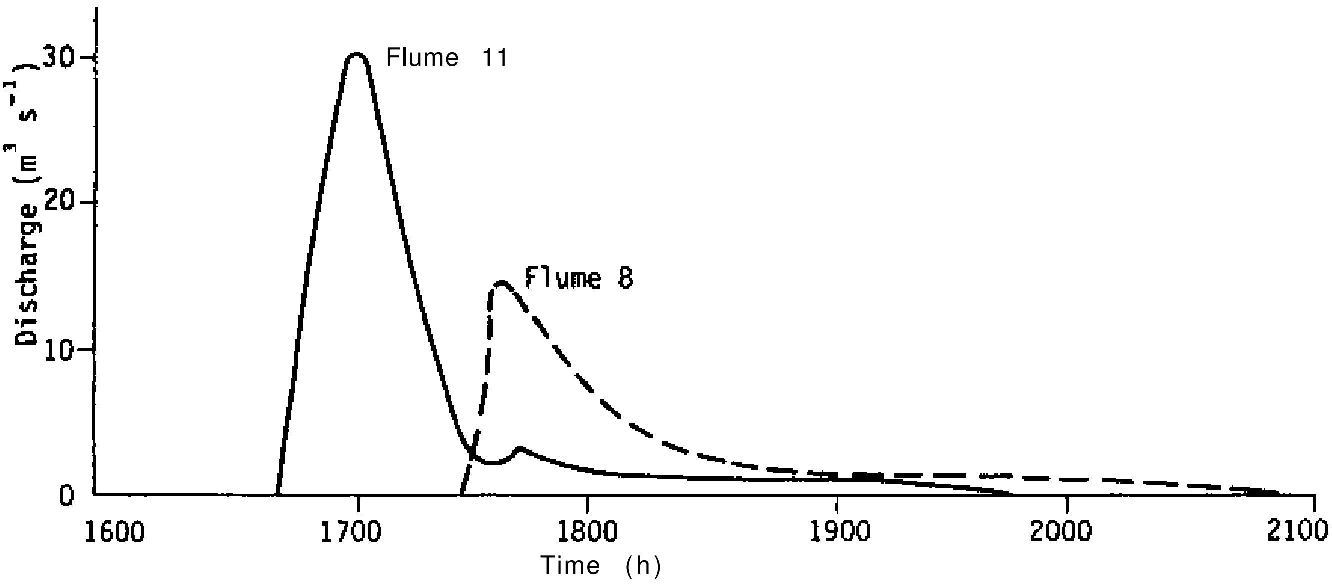


Figure 2. Hydrographs at two flumes for the storm on 30 July 1966, showing channel transmission losses. (Between flumes 11 and 8 there is a reach of 6.4 km.)

precipitation event. On semi-arid watersheds, annual water yield significantly decreases with increase in drainage area. In more humid areas, annual water yield per unit area may increase with drainage area (Fig. 4).

Runoff hydraulics and flood-water yield frequency studies

In arid and semi-arid environments, it is difficult to measure runoff and sample water quality because of high runoff velocities, large but infrequent flow occurrences, and rapid changes in flow depths (Renard 1982).

Stepwise multiple regression analysis of small plot data showed that the average runoff for any one location-year increased as the precipitation quantity increased; it decreased as the vegetative-crown spread increased, and increased as antecedent soil moisture increased (Schreiber and Kincaid 1967). Many models use precipitation data, which are usually more extensively available and of longer duration than runoff records, as the primary input

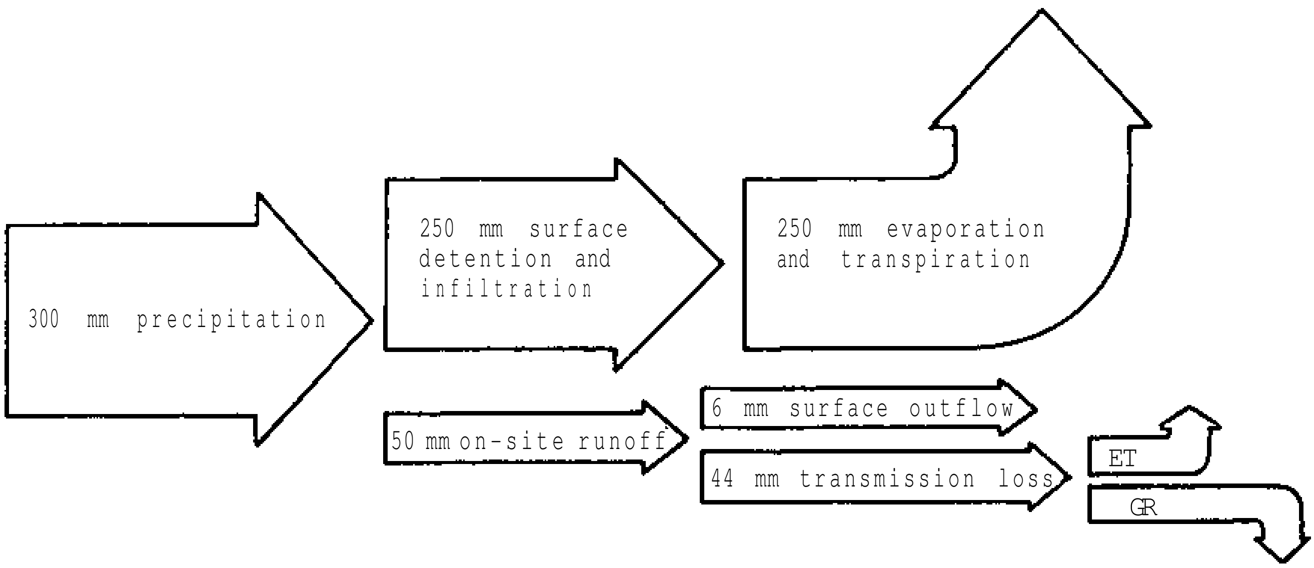


Figure 3. Hydrologic balance at Walnut Gulch. (ET - evaporation and transpiration; GR = groundwater recharge.)

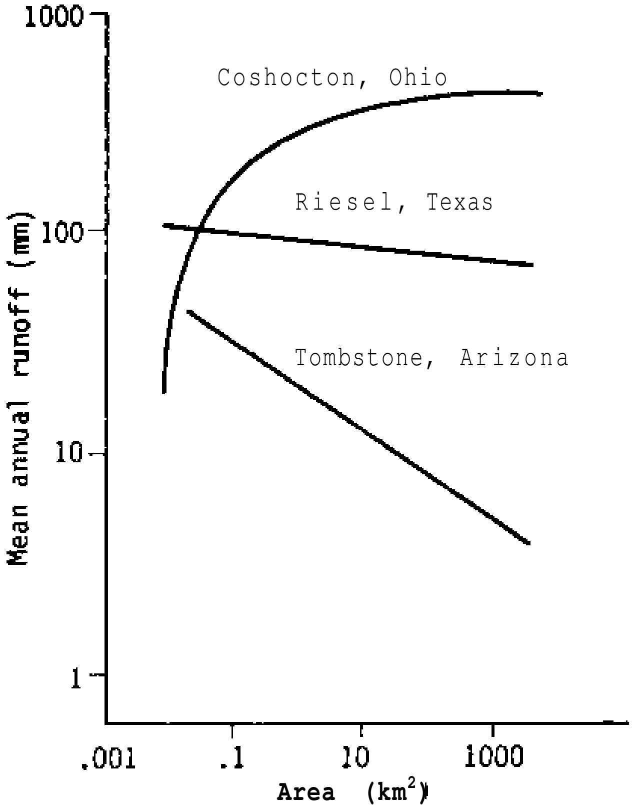


Figure 4. Mean annual runoff versus size of drainage area for several locations.

variable. These models can give only estimates, the accuracy of which depends upon the validity of the input data and the degree to which the model emulates the physical system.

Runoff modeling efforts at the Southwest Rangeland Watershed Research Center include the instantaneous unit hydrograph approach, a stochastic approach, and a physical-based kinematic cascade approach (involving planes-and-channels). A double triangle unit hydrograph approach has been demonstrated to be superior to the single triangle unit hydrograph (Diskin and Lane 1976). The stochastic model developed by Diskin and Lane (1972) has been found to be a good representation of the conditions encountered in thunderstorm-dominated runoff where each runoff event begins and ends with zero flow. This model was incorporated in a sediment-transport equation to estimate sediment yield as a function of watershed characteristics (Renard and Lane 1975).

Where the momentum equation can be approximated using only terms expressing bottom slope and friction slope, the flow is called kinematic. If the watershed geometry is represented by a series of planes and channels in cascade, and the overland flow and /or open channel flow are described by the kinematic-wave equations, the resulting mathematical model is called the "kinematic cascade model." Given rainfall, runoff, and topographic data for a small watershed, it is possible, during simulation, to define a kinematic cascade geometry that will preserve selected hydrograph characteristics (Lane and Woolhiser 1977).

These surface-water models have progressed from modeling subunits of a watershed to combining the subunits into more comprehensive models of entire watersheds. Such models have now been extended to include partial differential equations for sediment detachment and transport (Smith 1977). In the process, such models have become complex and relatively expensive to use (Renard 1977).

Erosion and sediment transport studies

Recent emphasis in the United States on water quality, as affected by soil loss/sediment yield, has created a need for nonpoint pollution data for conservation planning aimed at reducing soil erosion. In pursuit of this need, emphasis is placed on collecting data for a better understanding of the processes of sediment detachment, transport, and deposition. Suspended sediment samples are collected at runoff-measuring sites on two tributaries and the outlet to Walnut Gulch. Automatic sampling equipment is used on several small subwatersheds. Precise gully measurements are being made on selected small watersheds to determine direct and indirect gully contribution to watershed erosion and sediment transport. Data are used to calibrate a deterministic sediment-transport relationship. When used with a stochastic runoff model, the frequency distribution of sediment yield has been obtained (Renard and Laursen 1975, Renard and Lane 1975). The data are also used for estimating the parameters of the universal soil loss equation (USLE) (Wischmeier and Smith 1978).

Major research emphasis is currently on adapting and providing USLE parameter values for arid and semi-arid rangelands. A trailer-mounted rotating-boom rainfall simulator is being used to provide USLE parameter estimates for rangelands (Sirnanton and Renard 1982).

Surface and groundwater quality

Various studies are being conducted to develop improved procedures for evaluating the impact of land-use and watershed/river-basin management on runoff water quality. Runoff water quality samples, collected at selected small subwatersheds and at the watershed outlet, are used for determining the influence of soil type, land use, and vegetative cover on water quality (Schreiber and Renard 1978). Samples of precipitation are collected. Groundwater samples are collected from wells for assessing their variation in quality. These data are used as inputs for various models of nonpoint source pollution and erosion-productivity research. Some typical models are described below.

CREAMS (Chemical, Runoff, Erosion, and Agricultural Management Systems). This describes a mathematical model developed to evaluate nonpoint source pollution from field-sized areas. CREAMS consists of three components: hydrology, erosion/sedimentation, and chemistry. The general logic of the model is that the hydrologic processes provide the transport medium for sediment and agricultural chemicals. Thus the hydrology component is the major input to the other model components. The erosion/sediment yield component provides estimates of sediment yield and silt/clay/organic matter enrichment to be used in the chemical transport components where absorbed chemicals are involved (Knisei 1980).

SWAM (Small Watershed Model). SWAM is intended for use on watersheds composed of a number of field-sized areas. This model incorporates features that facilitate transition from field-sized areas to watersheds of larger size, where spatial rainfall variability as well as variations in topography, soils, crops, etc., affect the results. A major feature of the model is to route the outputs from CREAMS-derived elements to points downstream. This model, which is still being developed, will use a fully dynamic version of CREAMS.

EPIC (Erosion-Productivity Impact Calculator). This consists of physically-based components for simulating erosion, plant growth and related processes, and economic components for assessing the cost of erosion and determining optimal management strategies. Commonly-used EPIC input data (weather, crop, tillage, and soil parameters) are available from a computer-filing system assembled especially for applying EPIC throughout the USA. EPIC is generally applicable, computationally efficient (operates on a daily time step), and capable of computing the effects of management changes in outputs. The components of EPIC can be grouped into major categories that include hydrology, weather, erosion, nutrients, plant growth, soil temperature, tillage, and economics. The many potential uses of this model include its application in (a) national-level program planning and evaluation, (b) project-level planning and design, (c) field-level studies to aid technical assistance, and (d) as a research tool (Williams et al. 1983).

SPUR (Simulation of Production and Utilization of Rangelands). SPUR is a rangeland simulation model based on physical processes developed to aid resource managers and researchers. It can be applied to a wide range of conditions with a minimum of "tuning" or "fitting." As a management tool, it provides a basis for management decisions by predicting herbage yields, livestock production, runoff, and erosion. SPUR has five basic components: (1) climate, (2) hydrology, (3) plant, (4) animal (domestic and wildlife), and (5) economic (Wight 1983).

Vegetation manipulation and rangeland revegetation

Studies are being conducted to determine the influence of range renovation and grass seeding on runoff, erosion, cattle-grazing potential, and the hydrologic consequences of different range improvement practices. Typical results from two studies are presented in Table 1. Ripping reduced runoff for up to 5 years after treatment, but had little effect on reducing the density of the existing brush vegetation cover. Root-plowing and reseeding did not reduce runoff until 4 years after treatment, but was effective in converting the vegetation from brush to grass (Kincaid and Williams 1966, Simanton et al. 1978, and Tromble 1976).

Water harvesting and runoff farming

Water-harvesting techniques can be divided into five basic approaches: (1) vegetation management, (2) natural impervious surfaces, (3) land alternation, (4) chemical treatment of the soil, and (5) covering the ground with a membrane. The methods vary widely in terms of cost, performance, and durability (Frasier and Myers 1983). The major objectives of research on water harvesting are as follows.

1. To determine the feasibility of using water-harvesting methods for augmenting and conserv-

Table 1. Effects of two mechanical brush-control treatments on runoff and sediment yield from a semi-arid rangeland watershed.

Period	Average summer precipitation (mm)	Average summer runoff (mm)	Sediment yield (t ha^{-1} a^{-1})
Ripped			
Pretreatment (1955-64)	205	18	nm[1]
Posttreatment (1965-76)	185	4.7	nm
Posttreatment (1965-69)	191	0.5	nm
Posttreatment (1970-76)	180	7.8	nm
Root-plowed, reseeded			
Pretreatment (brush vegetation) (1966-70)	240	23	3.7
Transition (1971-73)	237	34	2.6
Posttreatment (grass vegetation) (1974-76)	174	3	0.3

1. nm = not measured.

ing water supplies to increase rangeland forage production.
2. To develop and evaluate catchment treatments and water-storage facilities for use on water-harvesting systems in remote areas.
3. To develop criteria relating to waterproofing efficiency and the durability of water-repellent treatments to soil and climatic parameters.

Water-harvesting systems for domestic supplies can employ many of the techniques used for harvesting water for livestock. These techniques are also adaptable to runoff-farming applications by increasing precipitation and concentrating runoff on adjacent strips of cropped land (Schreiber and Frasier 1978). At present, the cost of water-harvesting treatments developed for livestock is probably too high for many runoff-farming applications.

Information on the quality of water collected by water-harvesting systems is limited. With a few exceptions, precipitation is almost pure water; and contaminants contained are insufficient to harm animals and humans (Frasier 1983). Water-harvesting systems could be designed to furnish drinking water for both human beings and animals plus water for runoff-farming applications.

References

Diskin, M.H.,and Lane, L.J. 1972. A basin-wide stochastic model for ephemeral stream runoff in southeastern Arizona. Bulletin, International Association of Scientific Hydrology 17(l):61-76.

Diskin, M.H., and Lane, L.J. 1976. Application of a double triangle unit hydrograph to a small semiarid watershed. Pages 125-135 in Proceedings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science. Tucson, Arizona, USA: University of Arizona, Water Resources Research Center.

Frasier, G.W. 1983. Water quality from water-harvesting systems. Journal of Environmental Quality 12(2):225-231.

Frasier, G.W.,and Myers, L.E. 1983. Handbook of water harvesting. Agriculture Handbook no. 600. Washington, D.C., USA: U.S. Department of Agriculture, Agricultural Research Service.

Kincaid, D.R., and Williams, G. 1966. Rainfall effects on soil surface characteristics following range improvement treatments. Journal of Range Management 19(6):346-351.

Knisel, W.G. (ed.) 1980. CREAMS: a field-scale model for chemicals, runoff, and erosion from agricultural management systems. Conservation Research Report no.26. Washington, D C , USA: U.S. Department of Agriculture, Agricultural Research Service.

Lane, L.J. 1982. Transmission losses. Chapter 19 in National engineering handbook. Washington, D.C., USA: U.S. Department of Agriculture, Soil Conservation Service.

Lane, L.J., and Woolhiser, D.A. 1977. Simplifications of watershed geometry affecting simulation of surface runoff. Journal of Hydrology 35:173-190.

Osborn, H.B., Davis, D.R., Shirley, E.D., and Koehler, R.B. 1980. Model of time and space distribution of rainfall in Arizona and New Mexico. Agricultural Reviews and Manuals, ARM-W-14. Washington, D.C., USA: U.S. Department of Agriculture, Agricultural Research Service.

Renard, K.G. 1977. Past, present, and future water resources research in arid and semiarid areas of the southwestern United States. Pages 1-29 in Proceedings of the 1977 Hydrology Symposium, Sydney, Australia: Australian Institution of Engineers.

Renard, K.G. 1982. Report on quality of watershed and plot data from the Southwest Rangeland Watershed Research Center. Pages 1-10 in The quality of agriculture research service watershed and plot data. (Johnson, C.W., Farrell, D.A., and Blaisdell, F.W., eds.). Agricultural Reviews and Manuals no. ARM-W-31. Washington, D.C., USA: US Department of Agriculture, Agricultural Research Service.

Renard, K.G., and Lane, L.J. 1975. Sediment yield as related to a stochastic model of ephemeral runoff. Pages 253-263 in Present and prospective technology for predicting sediment yields and sources. Agricultural Reviews and Manuals no. ARS-S-40. Washington, D.C., USA: U.S. Department of Agriculture, Agricultural Research Service.

Renard, K.G.,and Laursen, E.M. 1975. Dynamic behavior model of ephemeral stream. Journal of the Hydraulics Division, American Society of Civil Engineers 101(HY5):511-528.

Schreiber, H.A.,and Frasier, G.W. 1978. Increasing rangeland forage production by water harvesting. Journal of Range Management 31(1):37-40.

Schreiber, H.A., and Kincaid, D.R. 1967. Regression models for predicting on-site runoff from short-duration convection storms. Water Resources Research 3(2):389-395.

Schreiber, H.A., and Renard, K.G. 1978. Runoff water quality from varying land uses in southeastern Arizona. Journal of Range Management 31(4):274-279.

Simanton, J.R., Osborn, H.B., and Renard, K.G. 1978. Hydrologic effects of rangeland renovations. Pages 331-334 in Proceedings of the First International Rangeland Congress. Denver, Colorado, USA: Society of Range Management.

Simanton, J.R., and Renard, K.G. 1982. Seasonal change in infiltration and erosion from USLE plots in southeastern Arizona. Hydrology and Water Resources in Arizona and the Southwest 12:37-46.

Smith, R.E. 1974. Point processes of seasonal thunderstorm rainfall. 3. Relation of point rainfall to storm areal properties. Water Resources Research 10(3):424-426.

Smith, R.E. 1977. Field test of a distributed watershed erosion/sedimentation model. Pages 201-209 in Soil erosion: prediction and control. SCSA Special Publication no. 21. Ankeney, Iowa, USA: Soil Conservation Society of America.

Smith, R.E., and Schreiber, H.A. 1973. Point processes of seasonal thunderstorm rainfall. 1. Distribution of rainfall events. Water Resources Research 9(4):871-884.

Smith, R.E., Chery, D.L., Renard, K.G., and Gwinn, W.R. 1982. Supercritical flow flumes for measuring sediment-laden flow. Technical Bulletin no. 1655. Washington, D.C., USA: U.S. Department of Agriculture, Agricultural Research Service. 70 pp.

Tromble, J.M. 1976. Semi-arid rangeland treatment and surface runoff. Journal of Range Management 29(3):251-255.

Wight, J.R. (ed.) 1983. SPUR—Simulation of production and utilization of rangelands: a rangeland model for management and research. Miscellaneous Publication no. 1431. Washington, D.C., USA: U.S. Department of Agriculture, Agricultural Research Service. 126 pp.

Williams, J.R., Renard, K.G., and Dyke, P.T. 1983. EPIC—a new method for assessing erosion's effect on soil productivity. Journal of Soil and Water Conservation 58(5):381-383.

Wischmeier, W.G., and Smith, D.D. 1978. Predicting rainfall erosion losses-a guide to conservation planning. Agriculture Handbook no. 537. Washington, D.C., USA: U.S. Department of Agriculture.

Cropping Alternatives

Conventional Cropping Systems for Alfisols and Some Implications for Agroforestry Systems

R.W. Willey, M.S. Reddy, and M. Natarajan[1]

Abstract

ICRISA Ts work on conventional annual cropping systems for Alfisols is summarized, and the implications for agroforestry systems examined. The importance of intercropping system is emphasized as a means of increasing cropping intensity above that of a sole crop. Data from sorghum / pigeonpea and millet / groundnut intercropping systems are presented to illustrate the concepts of "temporal" and "spatial" complementarity between crops. It is reasoned that both these concepts are equally applicable in agroforestry systems. Experiments on sorghum / groundnut are presented to indicate the possibilities of greater relative advantages of intercropping systems under conditions of moisture stress. But the dangers of increasing total plant populations under such conditions (e.g., by adding a tree species) are also highlighted. The limitations on nitrogen contributions from annual grain legumes used as intercrops are discussed, and it is suggested that there might be scope for much greater contributions from leguminous trees in agroforestry systems. The possibilities of improved pest or disease control, and of greater yield stability in intercropping systems are described, and again the implications for agroforestry systems are considered.

Introduction

Drawing largely on ICRISAT's work, this paper discusses cropping systems of conventional annual crops. The wider aim of the paper, however, is to consider the implications for alternative land-use systems, i.e., systems incorporating perennial shrub or tree species. Current interest in these agroforestry systems stems mainly from the fact that they place greater emphasis on the production of fuel and fodder-products that are becoming increasingly scarce in the developing world, but seldom seriously considered in the development of improved conventional systems. A further feature—potentially very important for Alfisols—is that these agroforestry systems can provide large amounts of crop material that can be used for various soil amelioration purposes, as a mulch, for instance, or incorporated into the soil for improvement of nutritional or physical properties.

ICRISAT has not made any studies, to date, on agroforestry systems. Hence, this paper does not directly focus on them. What is attempted here is an analysis of some aspects of conventional systems to examine how far the basic concepts can be extended to agroforestry systems. The paper also tries to highlight those areas in which agroforestry systems may have most to offer.

Sole-crop or Intercropping Systems

With any cropping system a major objective should be to provide a continuum of efficient crop growth for as long a cropping period as possible. On the SAT Alfisols, the potential cropping period is deter-

1. Farming Systems Research Program (now Resource Management Program), ICRISAT, Patancheru, A.P. 502 324, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

mined largely by moisture supply. The objective of a cropping system is, therefore, to start crop growth as early as feasible at the beginning of the rains and to continue it for as long after the rains as the limited soil moisture storage will allow. With conventional annual crops, this potential cropping period for most SAT Alfisols is about 120-150 days.

Traditional crops are usually well adapted to this cropping period, flowering towards the end of the rainy season and maturing on the stored soil moisture. But in agricultural terms, growth is not necessarily efficient: the traditional cereal genotypes of this growing period produce large amounts of vegetative material but little grain. Such slower-growing crops as pigeonpea and castor—which make very efficient use of residual moisture—make very inefficient use of resources in the early part of the season. Some of those inefficiencies have been reduced, and yields increased with improved early-maturing genotypes. In theory, these early genotypes also provide scope for further cropping, but, with the limited growing period on Alfisols, this becomes difficult. Sequential systems of two full crops are seldom possible unless at least one of them is a short-season catch crop and, thus, of low-yield potential. At ICRISAT, it has been possible to grow a catch crop of the hardy horse gram after an early pearl millet, or a very early mung bean before a castor crop. But in both these systems the additional returns, compared with that from the single crop, have been small (Table 1). Relay cropping, i.e., sowing of the second crop 2-3 weeks before harvest of the first one, may improve the probability of producing two crops. At ICRISAT both the previous examples of sequential systems were grown as relay systems as well (Table 1). However, relay systems can present considerable practical difficulties in terms of sowing the second crop in the standing first crop, and in harvesting the first crop while seedlings of the second crop are present. With some crops it is possible to harvest a shorter season ratoon crop after the main crop. One such crop—sorghum—however produced very poor and erratic ratoon yields on Alfisols at ICRISAT (Table 1), but pigeonpea may hold out better possibilities.

To summarize the difficulties with sole-crop systems for Alfisols, there may often be more than enough moisture to produce one crop but not enough to produce two. In this situation, intercropping systems can often provide the means of at least increasing the cropping intensity over that of a single crop. Three typical Alfisol intercropping combinations—sorghum /pigeonpea, millet/ groundnut, and pigeonpea/ground nut—averaged over 3 years, produced higher returns compared to sole-crop systems (Table 1). The mechanisms whereby these intercrops are able to achieve higher yields have considerable implications for agroforestry systems. A brief discussion on these mechanisms follows.

Intercropping Systems

Figure la shows the mean dry-matter accumulation and yields produced during a 2-year experiment at ICRISAT on sorghum/pigeonpea. The sorghum was an improved early hybrid of about 90 days, and the pigeonpea an improved genotype maturing in about 170 days on Alfisols. Fertilizer application was at a reasonably high level. Sorghum is usually regarded as the main crop in this system. The planting pattern was 2 rows sorghum to 1 row pigeonpea. The population of each crop was equivalent to its full sole-crop optimum. Growth and yield of the intercrop sorghum was a little less than that of sole sorghum, and the final grain yield averaged was 83% that of the sole crop. The slow growth of the pigeonpea in the early stages was further suppressed by the sorghum in the intercrop, but, at final harvest, it was still able to produce quite a large amount of dry matter—62% of the sole-crop dry matter. Moreover, because the early sorghum competition only reduced the vegetative growth, the harvest index of the intercrop pigeonpea was higher (30.1%) than that of the sole crop (25.9%). The net result was that the grain yield of intercrop pigeonpea was 72% of the sole-crop yield. Taking sorghum as the main crop, therefore, a sacrifice of 17% in yield of this crop allowed an additional 72% in pigeonpea yield. (The 5-year average for this combination over several agronomic experiments has been an 89% sorghum yield and a 59% pigeonpea yield.)

The use of resources in this combination is illustrated by the light interception pattern shown in Fig. 1 b. Again, compared with sole sorghum, light interception in the intercrop's early stages was only slightly reduced by the presence of pigeonpea rows; and, after sorghum was harvested, the intercrop pigeonpea ensured the interception of more light at the end of the season. Total dry-matter accumulation in the intercrop was directly proportional to the total amount of light energy intercepted. Therefore, the greater yield of the intercropping system could be wholly attributed to its interception of more light. Vertisol experiments with this combination have

Table 1. Cropping systems on Alfisols at ICRISAT Center (means of 1978, 1979, and 1980).

Cropping systems	Grain yield (kg ha^{-1})				Net monetary returns[1] (Rs ha^{-1})			
	1978	1979	1980	Mean	1978	1979	1980	Mean
Sole castor	1462	1144	1038	1215	2039	2814	2305	2386
Sole groundnut	1236	1173	1168	1192	1133	2211	3659	2334
Sole sorghum	2516	2241	2826	2528	1402	1406	3628	2145
Sole pearl millet	1940	2099	1875	1971	1158	1915	1781	1618
Sole pigeonpea	-	1221	1013	1117	-	2745	2578	2662
Sorghum/pigeonpea intercrop (2:1)	2169/417	1680/831	2391/634	2080/627	1873	2855	4648	3125
Millet/groundnut intercrop (1:3)	849/869	1063/881	1292/747	1068/832	1293	2681	3610	2528
Pigeonpea/groundnut intercrop (1:4)	-	844/841	769/926	807/884	-	3366	4826	4096
Mung bean + relay castor	634+885	603+737	570+292	602+638	2075	3393	2026	2498
Mung bean + sequential castor	593+672	569+613	-	581+643	1766	2928	-	2347
Millet + relay horse gram	1866+594	2099+536	-	1983+565	1412	2181	-	1797
Millet + sequential horse gram	1940+616	-	1875+376	1908+496	1583	-	2166	1875
Sorghum + ratoon sorghum	2516+505	-	2826+237	2671+371	1511	-	3689	2600
LSD (0.05)					304	399	430	
SE (mean)					103	135	146	
CV (%)					11.39	9.04	7.95	

1. These are gross returns, less the cost of seeds, fertilizers, and pesticides. Prevailing market prices (Rs/100 kg) 1 month after the harvest of the respective crops used for calculating gross returns for 1978-79, 1979-80 and 1980-81 were respectively: castor 170, 185, and 265; groundnut 150, 250, and 375; sorghum 80, 90, and 150; millet 80, 110, and 116; pigeonpea 230, 260, and 297; mung bean 200, 330, and 342; horsegram 100, 102, and 177.

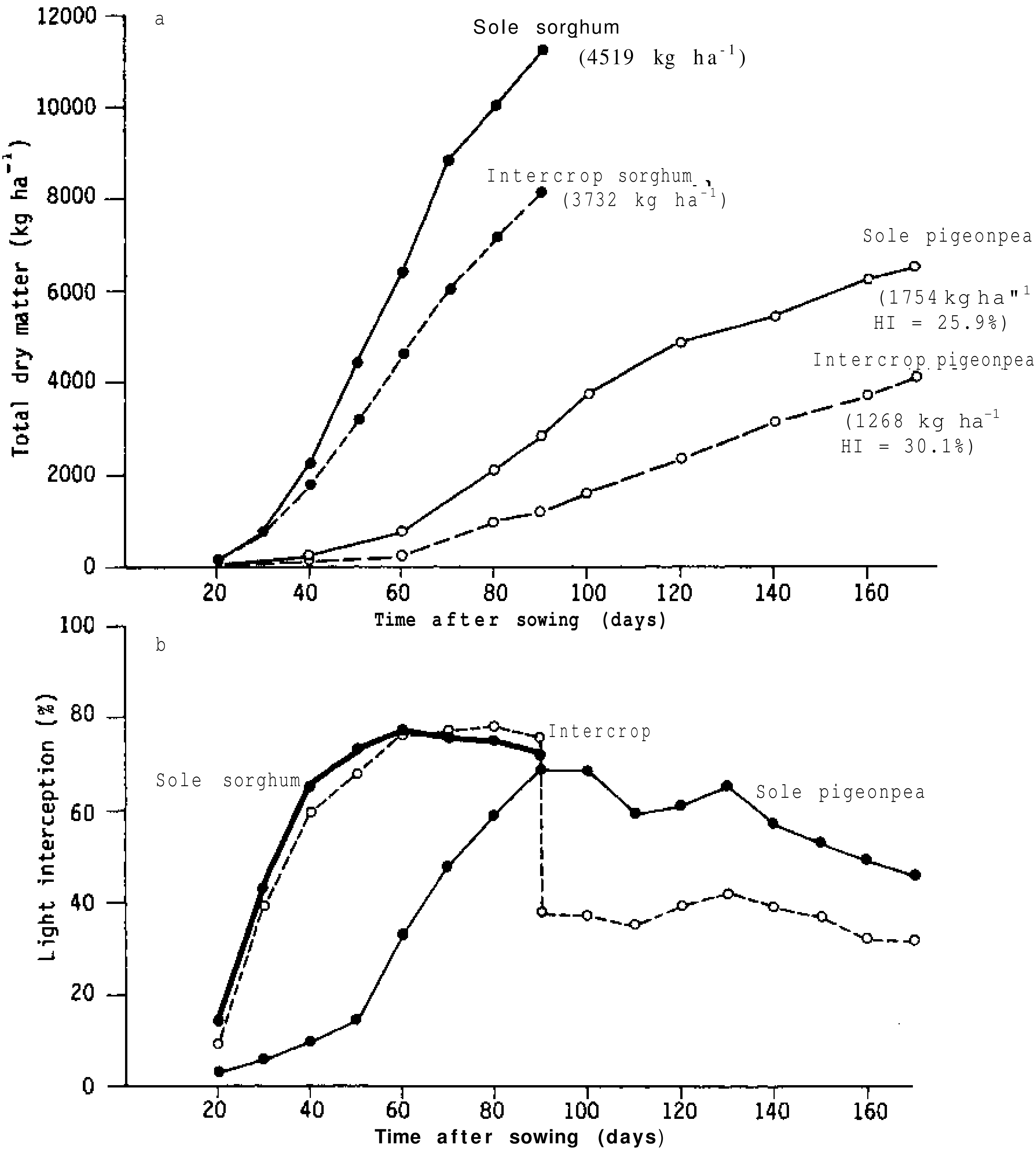


Figure 1. Dry-matter accumulation (a) and light-interception (b) patterns with sorghum and pigeonpea in sole and intercrop systems on Alfisols at ICRISAT Center (means of 1979 and 1981).

indicated similar effects for water use and nutrient uptake (Natarajan and Willey 1981).

In simple terms, therefore, this combination displays the classic "temporal" complementarity between an early, fast-growing component that ensures use of early resources, and a later-maturing component that ensures use of later resources. This complementarity has considerable implication for agroforestry systems because it emphasizes that, if the growing period can be extended still further, with deeper-rooting trees able to tap more moisture, there is scope for further increasing overall produc-

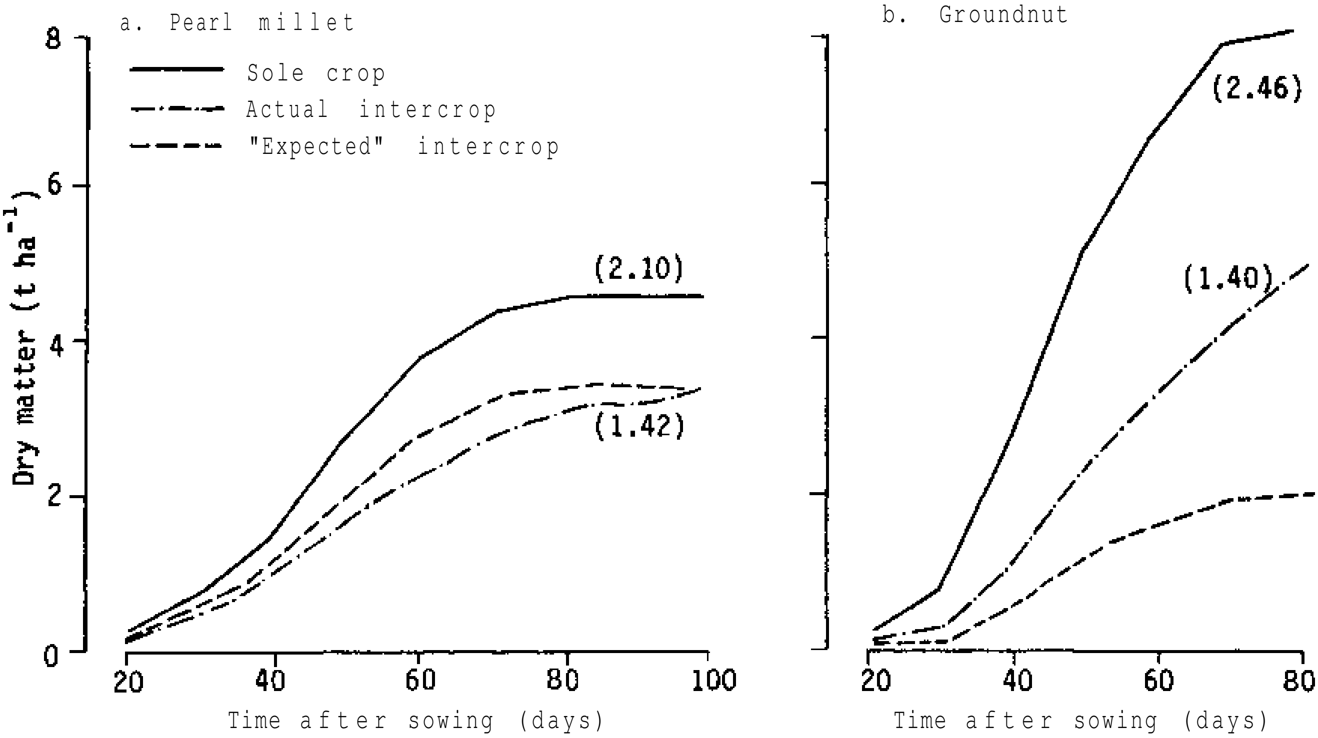


Figure 2. Dry-matter accumulation compared with sole crops in a 1:3-row combination of pearl millet and groundnut at ICRISAT Center (means of 1978, 1979, and 1980). Seed/pod yields (t ha^{-1}) are given in parentheses.

tivity. However, this simple concept of greater resource use due to temporal differences between crops gives no insight into the possible interactions that can occur at times of the season when two or more components are simultaneously making active demands on resources. Results with the millet/ groundnut combination illustrate some of these possible effects.

Figure 2 shows the dry-matter accumulation and yields, averaged over 3 years, of a 1:3-row combination of millet and groundnut in which the total population was equivalent to a full sole-crop population. The groundnut suffered some competition during the peak growth period of the millet, but the final yield per plant was very similar to that in sole cropping. Thus, yield per unit area was closer to the "expected" 75% sole-crop yield (Fig. 2b). In contrast, yield per plant of the highly competitive millet more than doubled in intercropping. Hence, yield per unit area was well above the "expected" 25% sole-crop yield (Fig. 2a). The overall yield advantage of intercropping was 35% for total dry matter, and 25% for grain. (The average grain yield advantage for this combination, as revealed by several agronomic experiments over a 5-year period, was 31%).

Unlike the temporal sorghum/pigeonpea combination that gives greater productivity simply by utilizing more resources, this millet/groundnut showed evidence of greater efficiency of resource use. This was especially so for light: each unit of intercepted light produced 26% more dry matter than expected from sole-crop efficiencies. There was also some evidence of improved water-use efficiency, partly because of reduced evaporation losses and partly because more dry matter was produced per unit of water transpired (Vorasoot 1982). Nutrient use, however, was similar to sorghum/pigeonpea in that the higher yield from intercropping was associated with a commensurately higher uptake of nutrients.

Insofar as these millet/groundnut results can be extrapolated to other crops, they provide some important pointers for agroforestry systems. They clearly show that a combination of different crop canopies may provide greater efficiency of light use. It is possible, of course, that the greater efficiency in millet/groundnut is due to the combination of a C4 and C3 species, in which case there might be no further improvement by adding a tree species. But it is also possible that the improved efficiency is simply due to better dispersion of the whole canopy, in which case an additional, taller species might confer additional benefits; indeed there is a general belief that more efficient use of light is one of the advantages of "multistorey" systems involving tree species (Nelliat et al. 1974).

There are similar implications for the water resource, although the millet/groundnut results suggest that, while there is some improvement in efficiency of water use, at the same time there may be greater demand for water in the soil profile. But whether this will necessarily result in increased stress on the crop components will depend on the extent to which one component may be able to utilize some water resource not available to another component. Clearly, where an additional tree species is able to utilize deeper profile water not accessible to conventional crops, a greater total water demand does not necessarily result in commensurately greater water stress. To some extent the same reasoning can be applied to the exploration of deeper nutrients by tree species; indeed, where some of the tree material is returned to the soil, as mulch or green manure, for instance, this can provide a beneficial recycling of some nutrients for shallower-rooting crops. But, where the greater productivity of intercropping or agroforestry systems results in greater removal of nutrients, it seems inevitable that, sooner or later, this greater productivity will only be maintainable by higher fertilizer inputs.

These possibilities of greater demands for water and nutrients raise the question of how intercropping systems are likely to perform when water or nutrient supply is severely limited—conditions which commonly occur on the SAT Alfisols. The effects of moisture stress have been studied at ICRISAT over 3 summer seasons by arranging treatments at different distances from a "line source" of closely-spaced irrigation sprinklers. This technique allows a very wide range of moisture situations to be studied on a very small area. Results with a 1:2-row combination of sorghum and groundnut are shown in Figure 3. Under well-watered conditions yields were very high, but with increasing moisture stress they decreased to a level typical of many farms in the

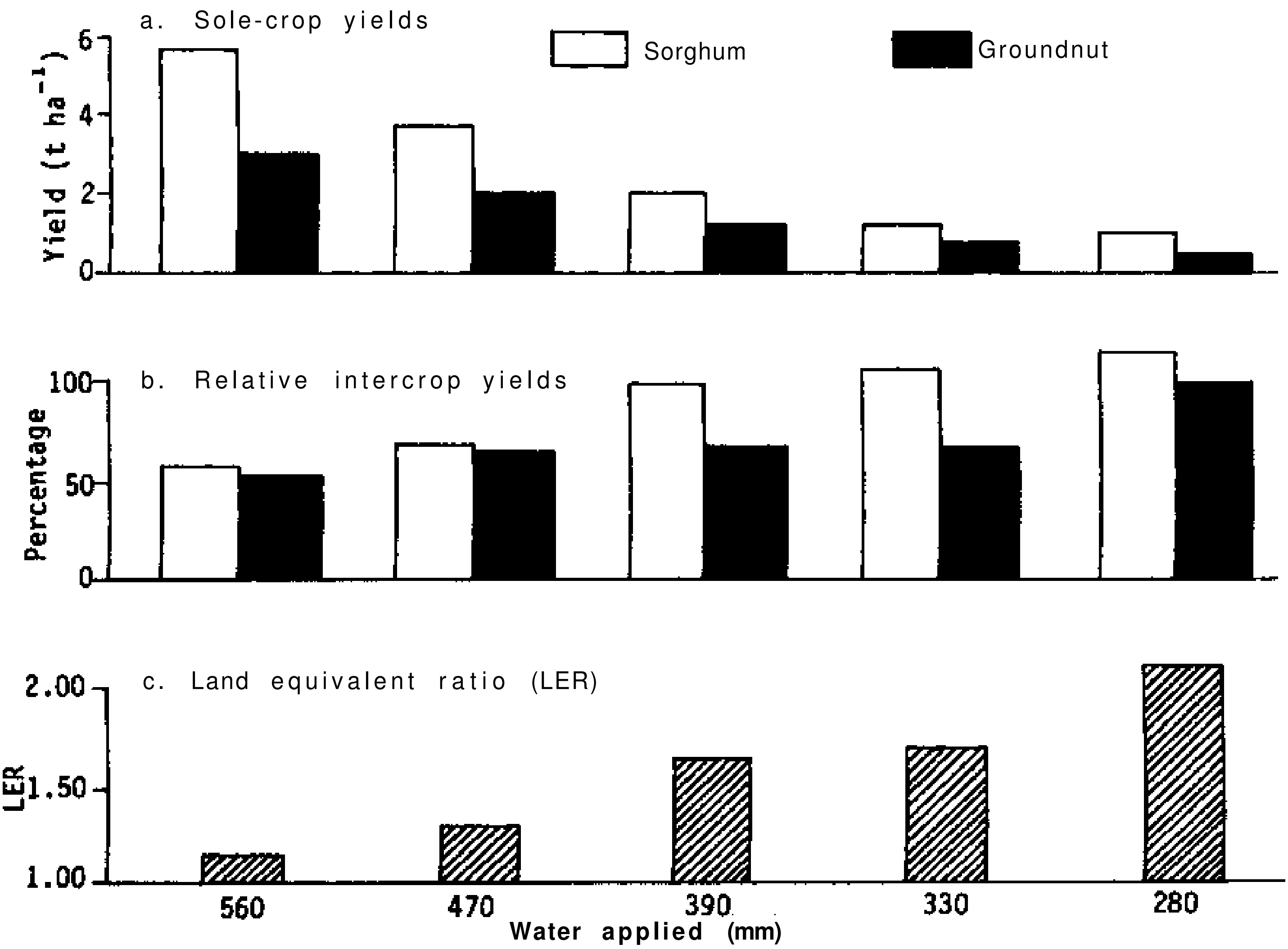


Figure 3. Effects of different moisture regimes on the yield advantages of a l:2-row sorghum/groundnut intercrop at ICRISAT Center (means of 3 dry seasons: 1980,1981, and 1982).

dry tropics. But for each crop the relative intercrop yield increased with increasing stress (Fig. 3b), and the overall relative advantage of intercropping thus also increased (Fig. 3c); where stress was greatest, the advantage was a sizeable 109%.

These results suggest that, under drought stress, even though yield levels are low the relative advantages of intercropping are even greater than when the moisture supply is good. However, it should be clear that the systems examined in these ICRISAT experiments were "replacement" systems where the total population of intercrops or sole crops was constant, so that each intercrop component was at a lower population than its sole crop. In such systems, the intercropping advantages can be conveniently explained in terms of complementary resource use, where each crop experiences less competition when growing in combination with the other crop than when growing alone as a sole crop. However, this reasoning is not so acceptable for "additive" systems (as agroforestry systems are likely to be), where additional crop components result in greater total populations and thus, probably, increased competition for water. Clearly, more research is necessary to determine how far the results obtained at ICRISAT with a sorghum/groundnut combination will apply to other systems.

Turning now to nutrient resources, there is similar evidence to show that the relative advantages of intercropping increase with increasing stress, although the effects reported (IRRI 1975, ICRISAT 1981, and Vorasoot 1982) were less marked than those described for drought stress. These results again suggest that intercropping systems may be particularly beneficial under conditions typical of SAT Alfisols, where inherent fertility and fertilizer applications are so often low. It is worth emphasizing, however, that this greater relative importance of intercropping under stress conditions should not be taken to mean that intercropping has no role to play at higher levels of nutrient and/or water availability. It has been pointed out elsewhere (Willey 1979) that, because of higher yields, absolute advantages of intercropping are often more under better conditions.

Legume Benefits

Legumes are common components of intercropping systems and it has often been assumed that they provide some nitrogen benefit. But showing benefits in the field has proved notoriously difficult, not least because nitrogen effects have so often been confounded by other intercropping effects. Nevertheless, there have been instances where a legume appears to have provided either a current benefit to a nonlegume growing in association (CIAT 1974, IARI 1976, Wein and Nangju 1976, and Eaglesham et al. 1981), or a residual benefit to a subsequent crop (Agboola and Fayemi 1972, Searle et al. 1981, and Yadav 1981).

Experiments at ICRISAT with maize/groundnut, sorghum/cowpea, and sorghum/pigeonpea intercrops have been undertaken to attempt to quantify these effects. In general there has been little evidence to show that there is much transfer of N to nonlegume crops actually growing with the legumes. In fact, under low levels of N, when growth of the nonlegumes is poor, the addition of legumes to the system has often resulted in a decrease in the nonlegume yield. But there is evidence of residual benefits on subsequent crops, especially after intercropped groundnut when the benefits were found to be equivalent to 15-20 kg ha^{-1} of applied N.

Some useful general findings have emerged from these experiments. The first is that the nitrogen contribution from many intercropped legumes in conventional intercropping combinations is necessarily very limited because the legumes are only partial crops in the system. Moreover, being usually grain legumes, much of the fixed N is removed in the seed. It is in this context that agroforestry systems may have much to offer: the incorporation of legume tree species may enable much larger qualities of material to be returned to the soil. Another finding of the ICRISAT experiments is that fixation rates may be reduced by shading, even when normal dry-matter growth is unaffected (Nambiar et al. 1983). This is unlikely to be important for the tree species themselves, except in the very early stages of establishment, but shading from the tree species could reduce the legume contribution from conventional crops in the system.

Pests and Diseases

At present there is considerable interest in the possibility that judicious manipulation of cropping systems may improve control over pests or diseases. In the developing areas of the world, in particular, there is obviously considerable merit in any control measure that does not have to depend on chemicals, which can be both costly and difficult to put into practice. Again, it is intercropping systems that seem to have the most to offer.

The commonest effect seems to be where one component crop in the intercropping system acts as a buffer or barrier against the spread of a pest or disease of another component crop. Some standard examples are the use of cereal intercrops to reduce insect attack on cowpeas and the insect-borne rosette disease of groundnut in Africa and bud necrosis disease of groundnut in India. It seems likely that intervening rows of tree species could have similar, or even greater effects; thus agroforestry systems could potentially be very important in this respect. More complex interaction can also occur; research at ICRISAT, for example, suggests that a sorghum intercrop reduces the soil-borne pigeonpea wilt disease by a more active interaction than a simple barrier effect, perhaps a root exudate. Obviously such interactions could also occur in agroforestry systems but, as in intercropping, they are likely to be specific to given crop combinations that will have to be identified. (In the case of pigeonpea wilt, for example, maize did not produce the same effect.) A further factor that should not be forgotten is that adverse as well as beneficial interactions can occur. The sorghum/pigeonpea intercrop serves as an example again (Bhatnagar and Davies 1981). In this combination Heliothis sp is a serious insect pest of both crops. It first builds up as a headworm on sorghum but is partially kept under control by some hymenopteran egg parasites. After the sorghum is harvested, the Heliothis sp transfers to the pigeonpea as a pod borer, but the hymenopteran parasites do not. The natural parasites on pigeonpea are mainly dipteran larval parasites that are less effective. The net effect of this build-up of the pest on sorghum and lack of transfer of effective parasites is that pigeonpea can suffer greater pod-borer damage as an intercop than as a sole crop. Agroforestry systems will usually be even more complex ecologically than systems with conventional crops and, clearly, similar adverse interactions are possible.

Yield Stability

Another advantage claimed for intercropping systems is that they can provide greater yield stability. The suggested mechanisms for this are better control over pests and diseases, greater relative yield advantages under stress conditions (which act as a buffer in bad years), and the compensation that is possible from another component crop if one crop fails or grows poorly. A survey of a large number of sorghum/pigeonpea experiments (Rao and Willey 1980) confirmed that, in terms of total monetary returns, intercropping "failed" (i.e., produced returns lower than the required level) much less often than comparable sole-crop systems (Fig. 4).

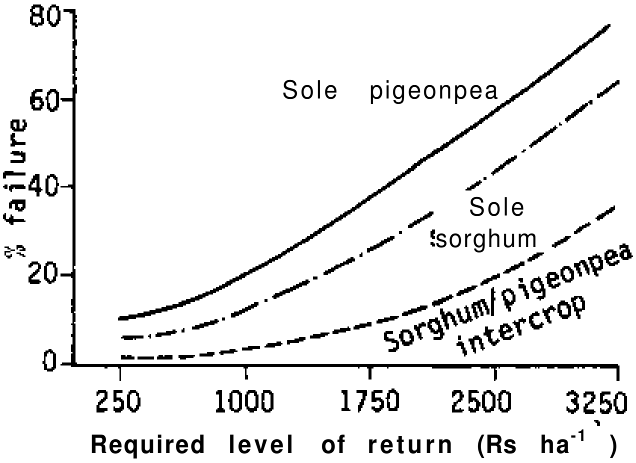


Figure 4. The probability of sole sorghum, sole pigeonpea, or a sorghum/pigeonpea intercrop failing to provide a given level of net monetary return (adapted from Rao and Willey 1980).

Not forgetting that adverse pest and disease situations may occur, or that systems with higher total populations might worsen environmental stresses, it seems likely that the greater diversity of crops in agroforestry systems could offer even greater overall stability. It is not difficult to imagine, for example, a situation where the conventional crop components might fail because of drought but the tree component would still produce something. This suggests a rather wider concept of stability, however, because any compensatory production from the tree species (e.g., fodder or fuel) is often likely to be very different from the products that have been lost (e.g., basic food crops). This might not matter where marketing is well developed and all products are saleable (and, thus, in theory interchangeable), but this particular kind of compensation may be viewed less advantageously in subsistence situations.

References

Agboola, A.A., and Fayemi, A.A. 1972. Fixation and excretion of nitrogen by tropical legumes. Agronomy Journal 64:409-412.

Bhatnagar, V.S., and Davies, J.C. 1981. Pest management in intercrop subsistence farming. Pages 249-257 in Proceedings of the International Workshop on Intercropping, 10-13 Jan 1979,1CRISAT, Hyderabad, India. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

CIAT (Centro Internacional de Agriculture Tropical). 1974. Multiple cropping. Pages 147-149 in Annual report for 1974. Cali, Colombia: CIAT.

Eagleaham, A.R.J., Ayanaba, A., Ranga Rao, V., and Eakew, D.L. 1981. Improving the nitrogen nutrition of maize by intercropping with cowpea. Soil Biology and Biochemistry 13:169-171.

IARI (Indian Agricultural Research Institute). 1976. Beneficial effects from the introduction of legumes in crop rotations and intercropping systems. Reporter 1 (1):1.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1981. Soil fertility and chemistry. Pages 178-185 in Annual report 1979/80. Patancheru, A.P. 502 324, India: ICRISAT.

IRRI (International Rice Research Institute). 1975. Cropping Systems Program report for 1975. Los Banos, Laguna, Philippines: IRRI.

Nambiar, P T C , Rao, M.R., Reddy, M.S., Floyd, C.N., Dart, P.J.,and Willey, R.W. 1983. Effect of intercropping on nodulation and N_2 fixation by groundnut. Experimental Agriculture 19:79-86.

Natarajan, M., and Willey, R.W. 1981. Sorghum-pigeonpea intercropping and the effects of plant population density. 2. Resource use. Journal of Agricultural Science (UK) 95:59-65.

Nelliat, E.V., Bavappa, K.V., and Nair, P.K.R. 1974. Multi-storeyed cropping: a new dimension in multiple cropping for coconut plantations. World Crops 26:262-266.

Rao, M.R., and Willey, R.W. 1980. Evaluation of yield stability in intercropping: studies on sorghum/pigeonpea. Experimental Agriculture 16:105-116.

Searle, P.G.E., Yuthapong Comudom, Shedoon, D.C., and Nance, R.A. 1981. Effect of maize and legume intercropping systems and fertiliser nitrogen on crop yields and residual nitrogen. Field Crops Research 4:133-145.

Vorasoot, N. 1982. A biological study of the benefits of intercropping in England and India. Ph.D. thesis, University of Reading, Reading, UK.

Wlen, H.C., and Nangju, D. 1976. The cowpea as an intercrop under cereals. Page 32 in Intercropping in semi-arid areas: report of a symposium, 10-12 May 1976, Morogoro, Tanzania (Monyo, J.H., Ker, A.D.R., and Campbell, M., eds.). Ottawa, Canada: International Development Research Centre.

Willey, R.W. 1979. Intercropping—its importance and research needs. II. Agronomy and research approaches. Field Crop Abstracts 32(2):73-85.

Yadav, R.L. 1981. Intercropping pigeonpea to conserve fertiliser nitrogen in maize and produce residual effects on sugarcane. Experimental Agriculture 17:311-315.

Cropping Systems and Agroforestry in Alfisols and Related Soils in Dryland Areas of Karnataka

S.V. Patil[1]

Abstract

*Alfisols and related soils occur extensively in southern dryland regions of Karnataka. Finger millet (*Eleusine coracana*) is the main crop in the area. Frequent dry spells make good crop yields uncertain. With proper soil and water management and fertilizer application, yields can be improved. Cowpea or other crops (grown for fodder), followed sequentially by finger millet, enables farmers to get a higher income. Establishment of mulberry for rearing silkworms, and casuarina and eucalyptus for wood, gives farmers a more assured income than the cultivation of annual crops year after year. Alternative cropping systems such as agroforestry, agrohorticulture, and agro-silvi-horticulture may provide greater security of income. In these systems, one to four rows of perennial plant species are planted in strips with an interstrip space of 15-30 m, and annual crops are grown between the strips. Growing bamboo as a crop in low-lying areas may also provide more secured incomes.*

Introduction

In Karnataka, about 60% of the geographical area is covered by Alfisols and related soils (Fig. 1). Karnataka is divided into 10 agroclimatic zones of which 6 are dry-farming zones. Alfisols and related soils occur in all the 6 zones. Moisture is the main factor limiting crop production in these areas under rainfed conditions.

Soil Characteristics

Alfisols and related soils that occur in the southern zones of Karnataka are characterized by low clay content (mostly kaolinitic) and nutrient-retention capacity. They contain low levels of decomposed organic matter, and there is accumulation of clay in their lower horizons. The soils are derived mostly from granite gneiss. The depth of these soils varies with the topographic sequence. Their maximum water-holding capacity is about 30-40%; the field capacity is about 14-18%; and the permanent wilting point ranges between 7 and 13%. The soils are acidic, with a pH of about 5.5-6.5, and they have a high infiltration rate of 4-6 cm h^{-1}. The cation-exchange capacity is about 3-5 meq 100 g^{-1}. The soils are very low in nitrogen and available phosphorus (AICRPDA 1981a, AICRPDA 1981b, and Murali 1982).

The soils set hard when they dry. Thus only a short time is available for soil preparation and interculti-vation after rainfall. Proper crop establishment is a problem because of poor germination and the high mortality of seedlings. Crop growth is affected by dry spells. The soils pose a problem in terms of timely control of weeds by mechanical methods. In undulating drylands topography, continuous neg-lect has led to erosion of the topsoil, and gulley formation is common. Crop yields are, therefore, very low in these areas.

1. University of Agricultural Sciences, Bangalore, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

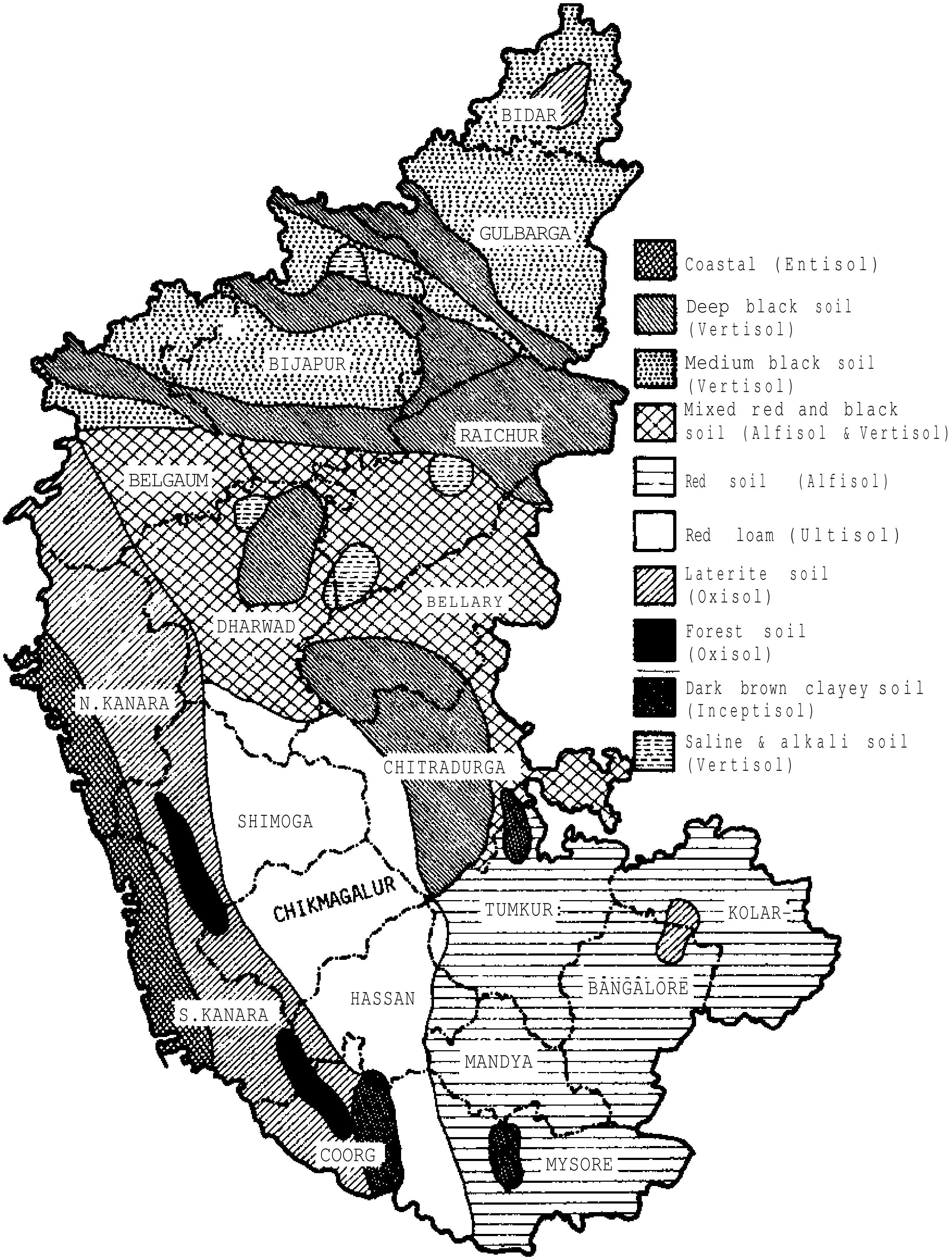


Figure 1. Soils of Karnataka (Perur et al. 1973).

Climatic Conditions

The annual rainfall ranges from 500 to 900 mm. The mean monthly distribution of rainfall at selected stations is given in Table 1. There are two peak periods in the year: one in May and the other in September-October. Representative additional meteorological observations for Bangalore are given in Table 2. The frequency of dry spells of 14 and 21 days at different locations is shown (Table 3) in percentages. Although rainfall is received from April onwards, it is not dependable in May, June, July and the greater part of August. Rainfall in September and October is more assured, when there are monthly totals of over 100 mm.

Table 1. Mean monthly annual rainfall (rr(mm) at selected stations in the southern dryland region of Karnataka (1931-60).

Month	Bangalore	Kolar	Tumkur	Chitradurga
Jan	6.1	7.4	2.8	6.3
Feb	6.6	4.1	6.1	2.8
Mar	10.2	10.2	7.4	4.3
Apr	40.9	34.5	36.1	24.6
May	105.7	85.1	96.0	74.7
Jun	72.6	60.2	85.9	65.6
Jul	111.0	68.6	107.2	72.9
Aug	136.3	98.0	135.1	85.9
Sep	156.1	133.6	174.0	111.0
Oct	155.4	121.2	51.6	120.9
Nov	59.1	86.9	57.9	60.2
Dec	11.2	16.5	7.6	13.2
	871.2	726.3	867.7	642.4

Source: Rama Rao and Havanagi 1979.

Moisture-conservation Practices

High runoff and soil erosion is a serious problem in dryland farming. For effective soil and water conservation, graded bunds of 0.5-m^2 cross section at a vertical interval of 1 m and a grade of 0.2-0.4% are

Table 3. Percentage frequencies of occurrence of dry spells of at least 14 and 21 days during June to October at Bangalore, Kolar, Tumkur, and Chitradurga (1921-70).

	Bangialore		Kolar		Tumkur		Chitradurga	
Month	14d	21d	14d	21d	14d	21d	14d	21d
Jun	52	24	na[1]	na	50	26	74	54
Jul	50	16	80	32	40	14	54	28
Aug	30	12	58	30	36	16	52	26
Sep	54	14	64	28	42	18	68	34
Oct	48	16	50	14	38	18	58	28

1. na = not available.
Source: Rama Rao and Havanagi 1979.

Table 2. Meteorological data for Bangalore.

Month	Mean daily max. temp. (°C)	Mean daily min. temp. (°C)	Wind speed (km h^{-1})	Mean daily duration of sun-shine (h)	Mean daily evapo-ration (mm d^{-1})	Potential evapo-transpi-ration (mm mo^{-1})	Mean daily soil temperature at 5 cm depth (°C)	
							At 0720	At 1420
Jan	26.9	15.0	10.4	9.3	5.2	117.4	18.4	34.7
Feb	29.7	16.5	9.7	10.1	7.4	130.0	20.3	37.8
Mar	32.3	19.0	9.4	9.9	8.6	166.2	22.3	41.1
Apr	33.4	21.2	9.0	9.3	8.4	158.2	26.0	42.8
May	32.7	21.1	11.3	8.6	7.5	158.2	25.2	37.6
Jun	28.9	19.7	17.1	5.7	6.8	156.5	23.9	34.9
Jul	27.2	19.2	17.5	4.0	5.7	126.5	22.4	32.4
Aug	27.3	19.2	15.2	5.0	5.4	115.7	21.5	30.6
Sep	27.6	18.9	12.1	5.8	4.8	114.2	22.2	32.4
Oct	27.5	18.9	8.2	6.6	4.3	108.9	21.5	31.9
Nov	26.3	17.2	8.5	7.7	4.3	105.1	20.1	33.1
Dec	25.7	15.3	9.6	7.8	3.9	98.3	19.9	31.4

Source: Rama Rao and Havanagi 1979.

recommended for land having a slope of about 2-5%. In deep Alfisols, however, border strips of 0.2-0.4% slope, with not more than 15-cm cutting, are more effective for soil and water conservation. Provision of protected waterways is necessary in order to check gully formation, and for draining off the surplus water. Interterrace management is essential for in-situ moisture conservation. Practices such as furrowing or ridging across the slope at 3.0-4.5 m intervals for closely-spaced crops (e.g., finger millet), and broadbeds and furrows on a grade of 0.3-0.4% for widely-spaced crops (e.g., maize) are suggested.

On deep Alfisols runoff equals about 25-30% of annual rainfall, and the soil loss about 3-4 t ha^{-1} a^{-1}. For harvesting runoff from 3-5 ha of land, a tank or reservoir of 1000-2000 m^3 capacity is useful. About 25% of the catchment area can be given one or two protective irrigations, and the crop yields increased by 1.5-2 times (Havanagi 1983).

Cropping Systems with Annual Crops

The success of a cropping system depends on how effectively the environmental resources such as soil, rainfall, and solar energy are utilized. The crops that can make the best use of rainwater, and give more economic returns over a period of years, are the ones suitable for inclusion in a cropping system.

Finger millet is a crop extensively grown under rainfed conditions in the dryland regions of southern Karnataka. Data on the areas under different crops are given in Table 4. Pulses, groundnut, and sorghum are the other important crops grown in the area. The crop yields obtained over a period of years under good management at the Agricultural University Farm, Gandhi Krishi Vignana Kendra(GKVK), Bangalore, are given in Table 5. Maize, finger millet, groundnut, and chilli give fairly good yields on well-developed land under good management in years when the rainfall distribution was favorable. In drought years maize, groundnut, and chilli give very low yields. Finger millet can grow well in poor shallow soils, and even under drought conditions. Its straw is the main fodder for cattle in the area.

Double-cropping

About 30% of annual rainfall is received during the period May to July. Farmers carry out repeated plowing or cultivation during this time to keep the land loose and the weeds in check. Investigations carried out at GKVK, Bangalore, indicated that cowpea (C 152) can be sown in May, followed by drilled or transplanted finger millet in August-September. An average grain yield of about 0.7 t ha^{-1}

Table 4. Percentage areas under different crops in dry-zone districts in southern Karnataka.

Districts	Net cultivated area in the state (%)[1]	Irrigated area in the districts (%)	Annual rainfall (mm)	% of major dryland cropping area of the gross area of the zone	
Chitradurga and Tumkur	9.58	18.7	455-717	Finger millet	16.9
				Pulses	14.2
				Sorghum	12.0
				Groundnut	6.0
Bangalore and Kolar	8.19	27.6	679-889	Finger millet	42.9
				Pulses	11.3
				Groundnut	9.7
Mysore and Mandya	7.16	30.0	671-889	Finger millet	27.1
				Pulses	22.3
				Sorghum	10.8
Parts of Hassan, Shimoga, and Mysore	6.60	25.0	708-1054	Finger millet	20.1
				Pulses	6.3
				Sorghum	3.7

1. The total net cultivated area in Karnataka is 10.4 million ha.
Source: Kulkarni 1983.

Table 5. Crop yields under rainfed conditions during 1977, 1978, and 1979 at Agricultural University Farm, GKVK, Bangalore.

Crop	1977	1978	1979	Mean
	Grain yield (t ha^{-1})			
Finger millet (Indaf 5) (110 days to maturity)	4.1	4.1	2.1	3.4
Maize (EH 4207) (115 days)	6.5	5.0	6.0	5.9
Groundnut (Spanish Improved) (100 to 110 days)	1.8	1.9	1.6	1.8
Cowpea (C 152) (90 to 100 days)	1.5	0.7	0.5	0.9
Pigeonpea (HY 3C) (135 days)	1.9	0.8	1.1	1.3
Dry chilli (Byadgi) (150 days)	1.6	1.8	0.3	1.2
Annual rainfall (mm)	924	1086	1168	1059

Source: AICRPDA 1981a

for cowpea, and 2.4 t ha^{-1} for finger millet were obtained (1974-79), as against 2.5 t ha^{-1} for a single crop of finger millet. Sorghum, cowpea, maize, and pearl millet for fodder were also grown in place of cowpea for grain. These crops gave about 1-2 t ha^{-1} of green fodder. Additionally, studies were carried out to establish whether finger millet as a second crop can be replaced by other crops. The average grain yields obtained for the following crops, sown in September, were: soybean (EC 3984) 0.65 t ha^{-1} horse gram (PLKU 32) 0.73 t ha^{-1}, sunflower (EC 101495) 0.46 t ha^{-1}, and setaria (S 701) 0.74 t ha^{-1}. Finger millet (PR 202), by comparison, gave 1.55 t ha^{-1}. This suggests that other crops are not better substitutes for finger millet (AICRPDA 1981a).

Double-cropping is labor-intensive, and requires that operations for preparing the land, and sowing the crop should be done on time. Farmers in the area face considerable shortage of bullock power. Cowpea requires one or two plant-protection sprays. These are the main constraints in the adoption of double-cropping by the farmers.

Intercropping

Intercropping finger millet with dolichos (Dolichos lablab), fodder sorghum, niger (Guizotia abyssinica), and castor is common among farmers in the area. The yield of finger millet however, is reduced by intercropping with these crops, particularly when high-yielding cultivars are used. The intercropping of finger millet (PR 202) with soybean (Hardee) was tried in alternate rows spaced 25 cm apart. The grain yield of finger millet was about 2.03 t ha^{-1} and that of soybean about 0.27 t ha^{1} as against 2.58 t ha^{-1} for finger millet as a sole crop. Intercropping groundnut with pigeonpea in a proportion of 3:1 gave 0.95 t ha^{-1} of groundnut pods and 0.67 t ha^{-1} of pigeonpea grain, while the sole groundnut gave a pod yield of 1.3 t ha^{-1}. Monetary returns were higher from intercropping groundnut with pigeonpea, compared with sole groundnut. Several other fodder crops, such as sorghum (J. Set. 3), pearl millet (BJ 104), lucerne, and maize (Ganga 5) were tried as intercrops in the proportion of 3:1 and 7:1. The indications were that intercropping finger millet with fodder pearl millet in the proportion of 7:1 was more economical (AICRPDA 1981b).

In years of favorable rainfall, an income of about Rs 3000-4000 ha^{-1} is obtained from annual crops in a year. The cost of cultivation may come to about Rs 1500-2000 ha^{-1} a^{-1}. In years when the season is unfavorable there is a drastic reduction of both crop yields and income.

Perennial Crops in the Region

Mulberry

Mulberry (Bombyx mori) is another important crop grown under rainfed conditions. It is cultivated for rearing silkworm. Of the total area of 0.17 million ha under mulberry in India, Karnataka accounts for nearly 0.118 million ha. In about 80% of that area, mulberry is grown as a rainfed crop. The rainfed crop is pruned at the bottom or individual leaves are harvested by plucking. With proper crop management and adequate fertilizer application (100 N: 50 P: 50 K) it is possible to obtain yield of 10-15 t ha^{-1} of green leaf, as against 25-30 t ha^{-1} under irrigation. Planting is done at a spacing of 60 x 22.5 cm for bottom pruning, and with a spacing of 90 * 90 cm for individual-leaf harvesting. The crop, once planted, is maintained in the field for about 12-15 years. Every year, soon after the beginning of the rainy season in June, the plants are pruned to a height of 8-10 cm above the ground. About 3-6 harvests are taken—depending upon the rainfall—for 1000-2000 layings ha^{-1} a^{-1}. The cost of leaf production comes to about Rs 4000-4500 ha^{-1} a^{-1}. The net income comes to about Rs 5000 ha^{-1} a^{-1} (Jolly 1982). Mulberry cultivation is labor-intensive. Since mulberry is a perennial crop, a high degree of soil moisture utilization is achieved.

Casuarina

Casuarina (Casuarina equisetifolia) is generally grown under rainfed conditions. Seedlings 6-8 months old are planted at a spacing of 1 x 1 m, or 1 x 2 m, or 2 x 2 m. The plants are hardy, and grow well even in poor soils because they can fix atmospheric nitrogen. After establishment, compartment bunds are constructed to conserve rainwater in situ. The plants are cut after about 6-8 years and 100-200 t ha^{-1} of wood is obtained. This produces an income of about Rs. 20000-30000 ha^{-1}, or about Rs 3000- 4000 ha^{-1} a^{-1}. Sometimes, one or two ratoon crops are also obtained.

Casuarina once occupied a large percentage of the cultivated land in the Alfisol region. The main advantage of the crop is that casuarina, being a perennial plant, offers good financial security. Also, cultivation is less costly and labor-intensive in comparison with annual crops.

Eucalyptus

From 1979 or 1980 a large area of cultivated Alfisols has been used for planting eucalyptus. The seedlings are planted at 1.5 x 1.5 m or 2 x 2 m spacing. Eucalyptus is a hardy plant, and grows fast. However, it needs fertilizer for good growth. The plants are cut in the 8th year. About 120-250 t ha^{-1} of wood is obtained and this provides an income of Rs 35000-50000 ha^{-1}, which may work out to Rs 4000-6000 ha^{-1} a^{-1}. There is a ready market for wood from polyfibre and paper mills. Eucalyptus forms a coppice quickly; three or four ratoon crops may therefore be harvested. The yield from the first ratoon crop is generally higher than that of the plant crop.

Cropping Alternatives

In low-rainfall Alfisol regions of southern Karnataka the cultivation of annual crops under rainfed conditions is beset with a number of problems. Crusts form on the soil soon after spells of rain. The expenditure on preparatory tillage and weeding is therefore comparatively high. And, because the rainfall is low and erratic, it is difficult to establish a good crop stand. Also, crop growth is affected by sustained dry spells during the growing season. There is therefore always an element of uncertainty about getting good returns for the expenditure incurred. Many enterprising farmers have thus planted mulberry, casuarina, and eucalyptus trees, lasting 15-20 years as perennial crops, instead of cultivating annual crops.

Alternative systems of cropping, capable of wide application in Alfisol regions, need to be evolved to make the best use of land and water resources for higher and more assured incomes, and to enhance soil productivity so that high levels of food and fodder production are obtained. A few alternative cropping systems involving both annual and perennial plants are suggested and briefly outlined. More detailed investigations are necessary, however, before suitable techniques can be evolved.

Agroforestry system

In this system, both annual crops and perennial trees are grown together on cultivated land. The perennial plants are planted in two to four rows in a strip along the contour line with an interstrip space of 15-30 m. This space between two strips of perennial trees is utilized for growing annual crops such as finger millet, groundnut, and pigeonpea. Casuarina, dalbergia (Dalbergia sissoo), and subabul (Leucaena leucocephala) are three perennial plants that suit this system. These plants are hardy and easy to establish, grow fast, fix nitrogen, and have a deep-rooting system. Dalbergia and subabul are leguminous plants and yield fodder as well as wood. Casuarina and dalbergia are planted in strips at the close spacing of 1 * 1 m. Subabul, however, can be established by planting seedlings or by sowing seeds in lines at 0.5-m spacing. These perennial plants utilize soil moisture and nutrients from the deeper soil layers, and their year-round growth results in a high level of biomass production, thereby providing security of income. The perennial plants act as a windbreak, and with proper canopy management, excessive shading can be reduced. Perennial plants play an important role in soil and water conservation. One-side-open compartments, or crescent-shaped bunds, are provided in the perennial plantation strip to hold runoff water and silt. The leaf fall and tree loppings provide some organic material for incorporation into the adjoining cultivated land (Itnal and Patil 1983). A suggested layout for such an agroforestry system is shown in Fig. 2.

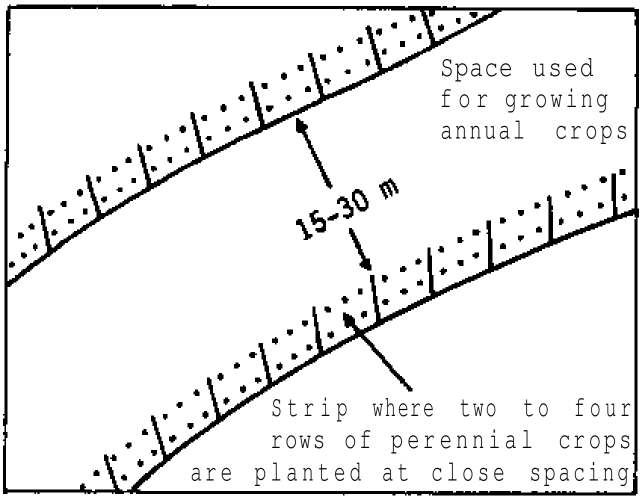


Figure 2. Suggested layout for an agroforestry system.

Agrohorticulture system

In this system horticultural plants are planted instead of perennial tree plants. These plants are planted in an arrangement of one to two rows in a strip along the contour line with an interstrip space of 15-30 m (Fig. 3). More hardy horticultural plants such as mango, sapota (Manilkhara achras), guava (Psidium guajava), tamarind, cashew, ber(Zizyphus jujube), and jack fruit are appropriate for this system under rainfed conditions (Sulladmath 1983). Coconut is planted in areas receiving higher annual rainfall (900-1000 mm). Underneath the horticultural plants one-side-open compartments or crescent-shaped bunds are provided to hold runoff from the interstrip space. Canopy management is necessary to regulate shade and light interception. Other species, such as date palm and oil palm, are also worth trying. The interstrip space is utilized for raising annual crops in the same way as in the agroforestry system.

Agro-silvi-horticulture system

In this system one to two rows of horticultural plants are planted in a strip along the contour line at a distance of 15-30 m. The distance between two horticultural plants within the strip is greater than in the above systems, so that the interstrip space can be utilized for planting quick-growing tree species such as casuarina, subabul, and dalbergia. The tree plants are cut for wood after 3-4 years, or even earlier for fodder or green manure. The interstrip space is utilized for growing annual crops. Here, also, one-side-open compartment bunds are provided for holding runoff and silt. The idea behind planting tree species as an intercrop with horticultural plants is to obtain biomass production before horticultural plants achieve full growth, and later to obtain fodder or green manure material by frequent cutting, and create thicker vegetation for better soil and water conservation. A suggested system layout is shown in Figure 4.

Bamboo cultivation

Bamboo (Dendrocalamus strict us) is another crop that grows well under rainfed conditions. Seedlings

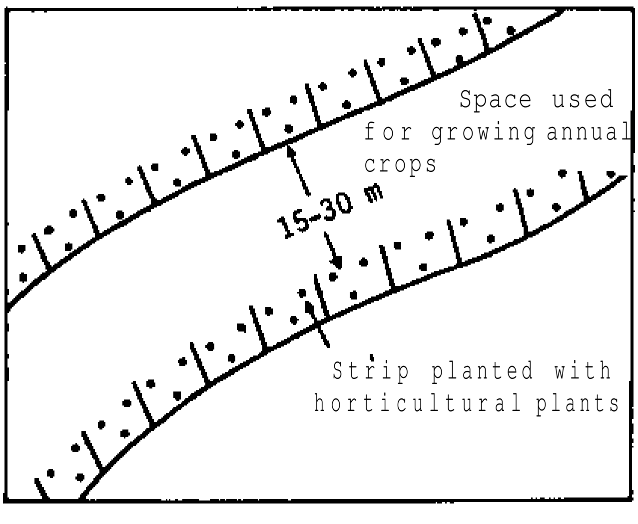


Figure 3. Suggested layout for an agrohorticulture system.

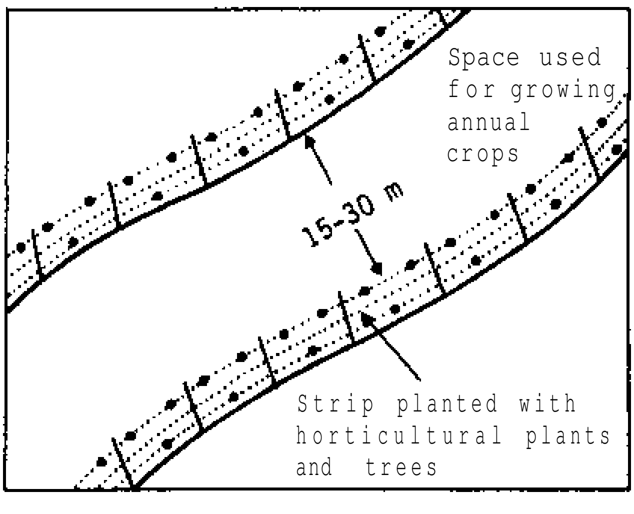


Figure 4. Suggested layout for an agro-silvi-horticulture system.

1-2 years old are planted at 1 x 1 m or 1.5 x 1.5 m spacings. If grown with care in its initial stages of establishment, and with adequate fertilizer (100 N: 50 P: 50 K kg ha^{-1} a^{-1}) bamboo grows quickly and gives good biomass production. The closer spacing of 1 * 1 m helps suppress weeds in the initial stages. Where the spacing is 1.5 x 1.5 m, casuarina is planted diagonally in the interstrip space (Patil 1979). Casuarina is cut after 4-5 years. Bamboo shoots are cut selectively to regulate spacing, and the shoots are sold for eating. Well-grown bamboo culms are selectively felled periodically, to harvest the crop.

Bamboo is planted in a contiguous low-lying area, as shown in Figure 5. On the higher cultivated land graded bunds are established and waterways provided to lead the runoff down to the area where the bamboo is planted. The bunds help to retain silt and runoff in the field itself. Bamboo, once established, lasts many years, providing a regular income from 3-4 years after its establishment.

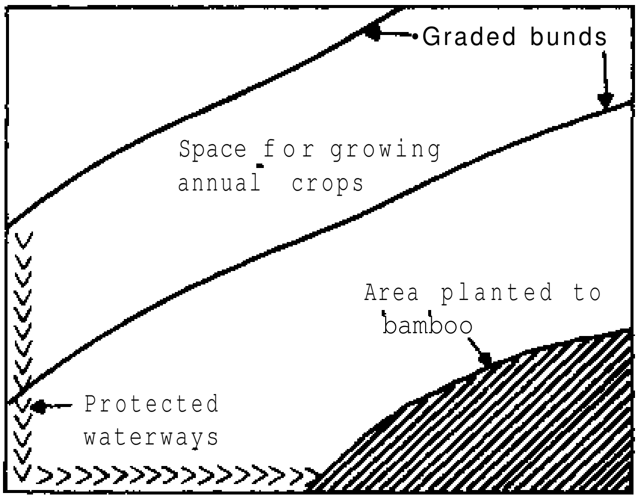


Figure 5. Suggested topographic location for growing bamboo with annual crops.

Conclusions

Because of their inherent characteristics, Alfisols and related soils occurring in the southern region of Karnataka pose problems in terms of establishment of annual crops, and in obtaining sustained yields year after year underdryland conditions. At present, this region is undercultivated because of farmers' aversion to take risks. If the annual and perennial plants are grown together, using suitable sowing and planting techniques, it may be possible to obtain an overall increase in farm income and improve the security of income as well. Alternative approaches, such as systems of agroforestry, agrohorticulture, agro-silvi-horticulture, and bamboo cultivation are suggested as ways of achieving maximum soil and water conservation, and of using soil and rainfall resources effectively to obtain an assured and higher income.

A systems approach, i.e., integrating agriculture, horticulture, and forestry in cropping systems may also help to improve the ecological conditions of the region. Such cropping systems may additionally help to bring marginal, waste, and fallow lands into cultivation, for higher economic returns. Inclusion of fodder-yielding plants in perennial plantation strips may help to increase the number of milch animals and the production of farmyard manure. Further detailed studies are needed as part of an effort to improve the natural resource base; and to use Alfisols and related soils in dryland areas for sustainable, profitable agriculture.

References

AICRPDA (All India Coordinated Research Project for Dryland Agriculture). 1981a. Salient findings of research 1971-80. Bangalore, Karnataka, India: University of Agricultural Sciences.

AICRPDA (All India Coordinated Research Project for Dryland Agriculture). 1981b. Progress report. Bangalore, Karnataka, India: University of Agricultural Sciences.

Havanagi, G.V. 1983. Land management practices in dryland regions of Karnataka. Presented at the Seminar-cum-Workshop on Dryland Development, 29-30 Oct 1983, Karnataka State Department of Agriculture, and University of Agricultural Sciences, Bangalore, Karnataka, India.

Itnal, C J., and Patil, S.V. 1983. Scope of agro-forestry in drylands. Presented at the Seminar-cum-Workshop on Dryland Development, 29-30 Oct 1983, Karnataka State Department of Agriculture, and University of Agricultural Sciences, Bangalore, Karnataka, India.

Jolly, M.S. 1982. Economics of sericulture under rainfed conditions. Mysore, Karnataka, India: Central Sericulture Research and Training Institute.

Kulkarni, K.R. 1983. Crop production in drylands of Karnataka. Presented at the Seminar-cum-Workshop on Dryland Development, 29-30 Oct 1983, Karnataka State Department of Agriculture, and University of Agricultural Sciences, Bangalore, Karnataka, India.

Murali, N.K. 1982. Genesis and classification of red soils of Tumkur district, Karnataka state. M.Sc. thesis, University of Agricultural Sciences, Bangalore, Karnataka, India.

Patil, V.C. 1979. Agronomic investigations on bamboo (Dendrocalmus strictus). Ph.D. thesis, University of Agricultural Sciences, Bangalore, Karnataka, India.

Perur, N.G., Subramanian, C.K., Muhr, G.R., and Ray, H.E. 1973. Soil fertility evaluation to serve Indian farmers. Bangalore, Karnataka, India: Department of Agriculture, and University of Agricultural Sciences.

Rama Rao, B.V.,and Havanagi, G.V. 1979. Meteorology in the service of agriculture. Agroclimatology of Bangalore, Tumkur, Kolar and Chitradurga districts. Research reports 1 to 4. Bangalore, Karnataka, India: University of Agricultural Sciences.

Sulladmath, U.V. 1983. Fruit crops of dryland agriculture. Presented at the Seminar-cum-Workshop on Dryland Development, 29-30 Oct 1983, Karnataka State Department of Agriculture, and University of Agricultural Sciences, Bangalore, Karnataka, India.

An Agroecological Approach to Management of SAT Alfisols

R.L. McCown[1]

Abstract

Crop production in the semi-arid tropics (SA T) is predominantly on Alfisols and without irrigation. Crop yields are low, and soils are being degraded rapidly due to a complex of climatic, edaphic, and management factors. Green Revolution technology does not alleviate the serious problems of managing the soil surface; it calls additionally for capital and energy requirements that are incompatible with economic circumstances of farmers in this environment. Certain approaches to land use that are in sympathy with the limitations of both the climate and soils may offer better prospects of improved production systems. Research that provides a first approximation of the suitability of such systems as (a) no-tillage/mulch farming, (b) legume alley farming, and (c) legume-ley farming for various physical and socioeconomic conditions in the SA T is urgently needed. Preliminary results of a no-tillage legume-ley strategy at an Australian SAT location show substantial benefits of the legume to both crop and animal production and of no-tillage /mulch to improved soil environment and crop yields. The need for a research approach in developing countries that evaluates such strategies in a relevant cost/benefit framework, and the problems of capital availability as a constraint to adoption, are discussed.

Introduction

Alfisols are agriculturally important soils throughout much of the SAT, in spite of serious chemical and physical limitations. The diversity within the group and the lack of a simple, agriculturally meaningful classification greatly hinders interregional communication pertaining to their management. Nevertheless, such communication is urgently needed to facilitate sharing of any new progress and coordination of new research effort. In general, agriculture on these soils suffers from nutrient impoverishment, soil erosion, and unfavorable surface physical conditions that result in reduced infiltration and poor crop establishment (Jones and Wild 1975, Lal 1979). In Africa and India, opportunities for using traditional practices of land rotation, or bush fallow, to counter these forms of degradation have declined rapidly with increase in human population. Replacement of fallow with land-saving technologies is rare because of the general scarcity of farmer capital. A promising approach to improved agriculture on these soils is the use of agricultural practices that capture many of the benefits of natural and traditional agricultural systems and require less capital than Green Revolution technology.

This paper examines the problems of Alfisols and the management requirements for improved systems, the agroecological concept (and an example of a research program that has been testing the feasibility of one strategy), and discusses the prospects for success of this approach in the developing countries of the SAT.

The Problems of Alfisols as a Resource for Crop Production

The problems of agriculture on Alfisols in the SAT are numerous and their causes complex. The main

1. Tropical Crops and Pastures, CSIRO, PMB P.O. Aitkenvale, Queensland 4814, Australia.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1987. Alfisols in the semi-arid tropics. Proceedings of the Consultants' Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils, 1-3 December 1983, ICRISAT Center, India. Patancheru, A. P. 502 324, India: ICRISAT.

problems are set out hierarchically at the top of Figure 1, and direct contributions to these problems by various climatic, edaphic, and management factors are indicated. Multiple entries in "problem" columns show the complexity of causes, often involving all three main factors.

Good crop establishment is jeopardized by a high risk of rapid surface soil drying because of erratic rainfall and very high radiation in the early wet season. On light-textured soils, high temperature of this dry zone causes injury to emerging seedlings (McCown et al. 1980); on heavy-textured Alfisols, mechanical impedance of this dry zone to emerging seedlings is the main problem (Arndt 1965).

The effects of unreliability of rainfall, especially early in the wet season, are exacerbated by the low moisture-storage capacity of Alfisols. Reliability of water supply for growth is reduced by impaired infiltration, in turn caused by lowered conductivity of pore systems when cover is not present to dissipate raindrop energy (Bridge et al. 1983). Cultivation increases infiltration initially, but, in the longer term, porosity and infiltration rates are usually lower than in unfilled soil with mulch cover (Osuji and Babalola 1982).

These soils are very poor in supplying nitrogen and phosphorus (Nye and Greenland 1960, Jones and Wild 1975, Jones et al. in press)—deficiencies that have probably dominated management systems more than other problems. The total amount of P in Alfisols is generally very low, and, while they do not "fix" or absorb large amounts of P (Mokwunge 1977, Probert 1978), they are not well buffered against removals of P from the system. Inherently low concentrations of organic matter and rapid leaching act to keep N supply low. While long periods of bush fallow tended to replenish nutrients, increased cropping intensity has resulted in widespread "mining" of nutrients on these soils, with drastic loss of productivity (Ruthenberg 1980).

In the long term, the most serious problem in Alfisols is soil erosion (Sanchez 1976, Lal 1977). Under the natural vegetation, erosion on SAT Alfisols is very low (Roose 1977, Kowal 1970). But, when these soils are denuded, and especially if they are cultivated, high rainfall intensities cause particle detachment and degeneration of infiltration capacity. This results in high runoff and soil loss.

Alfisols in the SAT are frequently described as structureless or massive, with the implication that hydraulic conductivity is low. These soils are more correctly described as "apedal" and, when undisturbed and well vegetated, they behave hydraulically as "well structured" (Wilkinson and Aina 1976). This state is fragile, however, and destroyed by tillage and/or denudation. Its maintenance depends strongly on macrofaunal activity, which in turn is dependent on amelioration of a hostile water and temperature environment by organic mulch (Lal 1975).

In general these soils are especially sensitive to mismanagement, i.e., by denudation, cultivation, and nutrient mining (Fig. 1). Historically, low population pressures and long fallow periods with vegetative growth have together diluted the deleterious effect of man's activities on these soils. In present demographic circumstances there is an urgent need for technologies that are more sympathetic to the ecological tolerances of Alfisols in SAT farming systems.

Improvement of Alfisol Management

The prospects for applying high-input Green Revolution technology to solve these problems are poor. Few small farmers have the capital required, or access to credit (Greenland 1975). There are, however, a number of strategies that are conceptually appealing both ecologically and economically and whose performances have yet to be adequately tested in the SAT.

How can innovative strategies worthy of high research priority be identified? In 1973, Janzen called attention to the degree of misconception and distortion of the reasons for the lack of contemporary sustained-yield tropical agroecosystems. In recent years, considerable progress has been made in elucidating the ecology of existing systems and quantifying various constraints. At the same time there has been a growing tendency to look to natural ecosystems and traditional agricultural ecosystems as a source of concepts for improved agricultural systems. The aim is to mimic strategies that confer yield stability, and efficient use of energy and nonrenewable resources, and result in minimum ecosystem degradation (Altieri 1983). Although it is inescapable that innovative systems that substantially increase land productivity will require greater capital inputs than either traditional systems or current involutionary ones (Ruthenberg 1980), modest capital and energy demands are important criteria in selecting prospective technology.

What agroecological concepts are available that might contribute to improved Alfisol management

Heirarchy of problems of cultivated SAT Alfisols / Factors contributing to problems		Poor crop stands		Poor crop growth					Declining land productivity	
		Poor emergence		Unreliable soil water supply			Low soil fertility		Accelerated erosion	
		High soil temper-atures	High mech-anical imped-ance	Drought spells	Low infilt-ration	Low water storage	Inade-quate nutrient supply	Rapid leach-ing	High runoff	Ready particle detachment
CLIMATIC	Unreliable rainfall	X	X	X						
	High-intensity, high-energy rainfall		X		X				X	X
	High radiation, E_o, in early rainy season	X	X	X						
	Rainfall excess for days or weeks							X	X	
EDAPHIC	Structurally unstable surface soil		X		X				X	X
	Narrow available water range	X		X		X		X		
	Low rates of mineral supply						X			
	Low organic matter		X		X		X			X
MANAGEMENT	Denudation	X	X		X				X	X
	Cultivation		X		X				X	X
	Net nutrient removal						X			

Figure 1. Summary of problems in agriculture on Alfisols in the semi-arid tropics.

in the SAT? There are a number of key concepts that are sufficiently well understood to point the way in research for the development of feasible technologies.

The enormous importance of vegetative cover in the management of soils in the tropics is well documented. The main problems are how to get enough of it at the right time, and at an acceptable cost. Increase in crop canopy density (Hudson 1971), additional interrow vegetation, e.g., intercrops or "live mulch" (Akobundu 1982), and dead mulch all benefit soil physical properties and soil and water conservation. The retention of organic residues and replacement of tillage with the chemical killing of weeds at, or just prior to, planting has been shown to be a practical way of providing mulch in the humid tropics (Lal 1975) and providing it at the time when the crop canopy is least effective (Wilkinson 1975a and b). Although less research has been conducted in the SAT, results indicate that benefits from mulch here are similar with respect to soil conservation (Roose 1977) and are even greater with regard to crop establishment (McCown et al. in press).

Rotating tropical legumes with nitrophilous crops is an effective means of supplying N to the crop (Henzell and Vallis 1977). Although in Africa and India grain and oilseed legumes have traditionally been grown in rotation with cereals and as intercrops, recent developments in forage legume technology for the SAT have opened up prospects for enhancement of this N-supply strategy. Pasture and browse legumes that produce high yields of N are now available (Vallis and Gardener in press) and knowledge on their ecology is growing. There has, however, been virtually no evaluation of these legumes in cropping systems.

The concept of mixtures of crops possessing different morphological and agronomic attributes is well established as a means of more fully utilizing scarce resources both above and below ground. This is one of the advantages of the traditional practice of intercropping (Willey 1979). Recently, there has been increased interest in mixing annual crops with perennial species, a strategy that maximizes differences in utilization of both above- and below-ground resources in space and time (Willey et al. 1987). Agroforestry (King 1979) and alley cropping (Kang et al. 1981), both of which capitalize on these principles, deserve comprehensive evaluation in the SAT.

The benefits of integration of livestock and cropping are well established and widely appreciated. Of the several types of possible linkages, the one that holds the most unexplored promise is that of enhanced production of legume fodder in the cropping enterprise (McCown et al. 1979). The future contribution of improved integration of livestock and cropping in this zone is controlled largely by nontechnical factors, e.g., the effects of cultural traditions of crop and livestock husbandry on current farmer attitudes and skills. Where the likelihood of integration under one ownership is low, but where herders and cultivators co-exist, there is the possibility of greater market transaction of legume fodders produced in the crop lands. Although integration of livestock with cropping does not directly benefit soil management, and at times is detrimental (Bayer and Otchere 1984), it is crucial to the economics of increased use of legumes to provide increased soil N. Forage legumes in cropping systems are profitable only when additional substantial benefits to an animal enterprise can be realized (McCown et al. 1979).

While there are promising ways of substituting N-fixing plants for N fertilizer, there appears to be no escaping the purchase of other nutrients, most commonly P. Deficiencies of nutrients other than N will limit both the growth and fixation of N by the legume and the growth of the succeeding nitrophilous crop. To capitalize on a biological supply of N, relief of these nutrient deficiencies is necessary. Substantial progress has been made in recent years in understanding the complexities of phosphate fertilizer-soil-water-plant relationships. This has enabled the development of models for predicting responses to applied phosphate (Barrow and Carter 1978). This has potential for improving the management tools for determining optimum use of P fertilizer on the SAT Alfisols.

What sort of research is needed? In general, the priority need is to examine the economic feasibility of practices that are promising conceptually. Analyses need to be conducted for a range of cost-price-capital availability scenarios that include, but extend well beyond, those which farmers now face. To do this will require a large biotechnical research effort, but it must be orientated toward this economic goal. Table 1 provides an example of such a research framework for no-tillage/mulch farming. In spite of the fact that, (a) research by R. Lal in the humid tropics in the early 1970's showed enormous benefits, and (b) benefits should theoretically be greater in the SAT, very little research on no-tillage/mulch farming has been conducted. It is often argued that mulching with crop residues is not practical in the SAT because they are utilized for

Table 1. Research on the economic feasibility of no-tillage/mulch farming.

Information needs	Research activities
Costs	
Opportunity costs of using plant materials suitable for:	Documentation of:
Fodder	a. existing system and
Building materials	b. innovative systems with increased
Fuel (instead of mulch)	production of mulch and/ or timber
Herbicides and application equipment	Verification of optimum application methods and rates of "best-bet" herbicides
Benefits	
Effects on crop yields via:	Quantification of the effect of different types and amounts of mulch on:
Soil water	
Soil temperature	a. seedbed environment, crop establishment,
Soil surface seal impedance	and yield
	b. soil hydraulic properties, infiltration, soil-water regime, and crop yield
Effects on water and soil conservation:	c. soil detachment, runoff, and sediment transport
Infiltration/runoff	
Soil erosion	
Effects on labor economy:	Documentation of existing and alternative systems
Reduction of plowing labor and time	
Reduction in weeding labor and time	
Effects on farm draft requirements of reduction in tillage	Documentation of fodder requirements of system and effects on herd size and structure

fodder, fuel, or as building materials. But, considering the rate at which land degradation is taking place, there are good grounds for asking the question: can the farmer (or society) afford not to leave residues for mulch? Answering the question would call for quantitative understanding of the performance of innovative farming systems. If the farmer had greater on-farm production of timber and fuel wood, he could well afford to leave residues for mulch. If he brought down N and P deficiencies, increases in yields might allow him to remove the usual amount of residues and leave a substantial amount.

This example illustrates a second attribute of the kind of research that is needed, i.e., a production system scope. One of the lessons of past research is that innovations need to be evaluated in the context of the larger system or subsystem. As Figure 1 indicates, the problems form a matrix of complex interactions. Evaluation in too narrow a biotechnical field risks missing other crucial biotechnical implications. For example, the finding that grass leys can greatly improve aggregate stability upon cultivation is viewed very differently when the strong yield-depressing effects due to nitrogen immobilization are considered as well (Fig. 2). Similarly, tied ridges have been shown to effectively reduce runoff in the SAT, but maximum yield benefits will not be realized where high soil temperatures are a problem, since this is exacerbated by ridging (Lal 1973).

Too exclusive a biotechnical approach to soil management risks missing opportunities for addressing those economic issues on which success or failure of this technology most depends. Improved soil management involves costs, and, in general, the farm system has to bear them. Although improved soil management is the key to technically improved farming systems, improved soil management is sustainable only within economically improved farming systems.

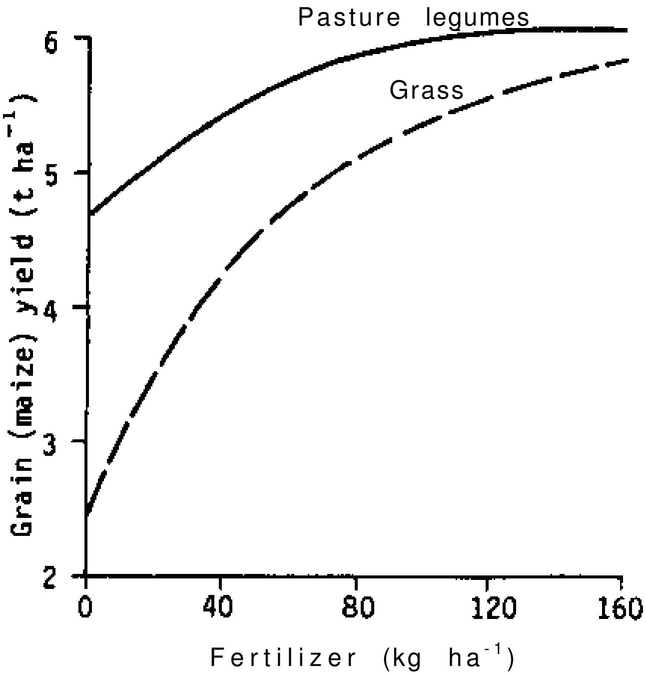


Figure 2. Maize grain yield responses to nitrogen fertilizer in the first crop following 1 year of legume or grass-leys on a loamy Alfisol.

An Innovative Agroecological Strategy for the SAT

Problems of Australian SAT agriculture

The Australian SAT is used almost exclusively for cattle and sheep grazing. Periodic attempts have been made to establish dryland cropping industries, but all have failed due in part to high costs of production and use of inappropriate technology. A feature of this area is that land that is potentially arable tends not to occur in large, contiguous areas, but is rather interspersed with large areas of land suitable only for grazing. One possible means of more efficient utilization of these land resources is the integration of livestock grazing and cropping. The concept of legume-ley farming, so important in the integration of wheat and wool production in Australia's Mediterranean and warm climates, has been suggested as a promising model for West African savanna zones (Jones and Wild 1975), but to date there has been no substantial evaluation of the strategy anywhere in the SAT.

Past research has set the stage for this test. The technology for growing leguminous pastures is well-developed for the Australian SAT, but has not proved economic because of the high costs of improvement relative to beef prices, as well as serious marketing uncertainties. Crop research on the Alfisols has shown the need for high inputs of both nitrogen and phosphorus (Jones et al. in press) and revealed other problems (Fig. 1) associated with conventional tillage practices.

The research strategy

The strategy is expressed as a hypothetical farming system that combines the concepts of legume-ley farming and no-tillage with the existing system of grazed native pastures. The key feature (Table 2) is the rotation of a self-regenerating legume pasture and a maize or sorghum crop, where the legume supplies all or most of the N fertilizer required by the crop.

The second feature (Table 2) concerns the integration of cropping with the existing system in which cattle graze on native pastures. In areas with long dry seasons, the strategy of having cattle on native grass pastures during the green season, when they are at their best, and on sown leguminous pastures in the dry season, is attractive (Norman 1968). However, the test of this strategy in the late 1960s and early 1970s failed because of the inability of the legume, Townsville stylo, to compete satisfactorily with annual grasses and, ultimately, to its susceptibility to the fungal disease anthracnose. The availability of several "new" legumes with superior competitive ability and resistance to anthracnose makes a new attempt at implementing this strategy feasible. (The growing of a nitrophilous crop every 1-3 years should further contribute to maintaining legume dominance by regularly depleting soil N.)

The third feature of this system (Table 2) is the retention of surface mulch by use of no-tillage planting technology. In this system, the main source of mulch is killed pasture vegetation rather than crop residues.

Table 2. Features of a hypothetical farming system.

1. Self-regenerating legume-ley pasture of 1-3 years duration are grown in rotation with maize or sorghum.
2. Cattle graze native-grass pasture in the green season and leguminous pastures and crop residues in the dry season.
3. Crops are planted directly into the pasture that is chemically killed at, or shortly before, sowing.
4. The legume sward, which volunteers from hard seed after the pasture is killed, is allowed to form an understory (live mulch) in the main crop.

The fourth feature of our hypothetical system concerns a form of intercropping (Table 2). The herbaceous pasture legumes that are well adapted to this climate invariably produce a proportion of seed that is still "hard" when the re-established pasture is killed with herbicide and a crop planted early in the next rainy season. However, newly germinable seed from the "hard-seed" pool produces a new stand of legume of the same age as the sown crop. [This is an important difference from the "live mulch" situation in which the legume sward is never killed (Akobundu 1982)]. Although re-establishment can be prevented by use of a pre-emergent herbicide, this legume intercrop offers several potential benefits: it does not cost anything to establish; it provides a more long-lasting protective cover for the soil than the dead mulch; it provides high-protein forage to complement the low-protein stover available for grazing in the following dry season; and it provides an additional source of seed for pasture re-establishment in the following season. The main potential detriment is that the understory of pasture legume may depress the yield of the grain crop. In this particular version of intercropping, this would be a very undesirable outcome because the grain crop has a much higher monetary value than the forage intercrop and, therefore, only small reductions in grain yield can be tolerated. Although recent results from the humid tropics of West Africa have shown that yields of crops sown into legume swards killed only on the row zones can compare favorably with those of crops grown without this live mulch (Akobundu 1982), the degree to which competition for water or nutrients during the growing season jeopardizes the success of this forage intercropping strategy in the SAT is unknown.

Research Progress

Subsystem 1: Effect of legume-ley/crop rotation on crop production

In studying this subsystem, the prime objectives are to quantify the N contribution to the following grain crops by leys of various legumes grown for between 1 and 4 years. Objectives of a lower order are quantification of the amount of N fixed by various legumes and elucidation of the relative importance of losses from litter, urine, and dung. It is to be expected that soil type will strongly influence N transfer processes, so studies of this subsystem are being conducted on two Paleustalfs— one heavy-textured (Tippera clay loam) and the second very sandy (Blain sand).

A direct experimental approach is used to estimate the N contribution by legumes, whereby a crop of maize or sorghum is used in a bioassay. Rates of fertilizer N are superimposed on the crop so that its responses to N, additional to that supplied by the preceding legume or grass (control) swards, can be measured and compared. Supporting information includes soil N prior to cropping, and N yield of both the ley and the crop.

Salient results from six experiments—most of which are still in progress—include the following.

1. On the loamy soil, maize grain yield with no N fertilizer, following 1-year leys of various pasture legumes, was equivalent to that on plots receiving at least 50 kg ha^{-1} N following 1 year of grass. (Fig. 2 shows data from one experiment). Legume leys of longer duration had greater effects in the first crop and a greater residual effect on the second crop.
2. For a given level of dry-matter production by a short ley of Caribbean stylo (*Stylosanthes hamata* cv Verano), the apparent N contribution to the following crop is much less on the sandy soil than on the loamy one.
3. Legume species do not differ greatly in N contribution after 1-year leys, but large differences occur following 4-year leys.

Subsystem 2: Effect of no-tillage technology on crop production

The first objective here was to quantify the advantages/disadvantages of sowing crops with no tillage in relation to conventional tillage. The reason for focusing on this practice is that, wherever comparisons have been made throughout the world, the inherent benefit of no-tillage/mulch retention in conserving soil has been demonstrated. The pressing questions were those of the effects of this technology on yields and of comparative costs.

On both light-textured and heavy-textured Alfisols, stands were better and yields higher under the no-tillage system. On the sandy soil, mulch retention resulted in an average increase in maize yields of 33% (from 1.8 to 2.4 t ha^{-1}) in two crops. This was on account of the soil temperature reduction by the mulch (McCown et al. 1980). On loamy soil, injurious soil temperatures are less frequent than on the sandy one, but, without mulch, they are still too high for optimum seedling growth. This soil poses an additional problem: on drying, it forms a strong surface crust that impedes seedling emergence (Arndt 1965). Mulch reduces this problem by protecting the soil surface from raindrop impact and slowing the drying of the soil. In four crops, mulch retention resulted in an average yield advantage of 20% (from 4.8 to 5.8 t ha^{-1}) in maize.

Having confirmed that mulch retention and no-tillage had beneficial effects on establishment and yields, we turned our attention to the following questions: what constitutes a minimum effective mulch? How do we get an effective mulch economically? How do we plant into such a mulch efficiently? (In most years, the pasture mulch at planting time consists of a mixture of dead pasture residue—mainly stems—from the previous growing season and recently-killed regrowth and seedlings resulting from rainfall received early in the current wet season. The relative proportions of these components varies with the intensity of grazing during the dry season and with the amount and distribution of rainfall in the early part of the wet season.)

Work to date has been on the loamy soil only and we can make the following observations:

a. As little as 700 kg ha^{-1} of mulch—in this case standing Caribbean stylo which had been killed with herbicide—reduces soil temperatures enough to dramatically improve emergence.
b. Analysis of the radiation balance has shown that mulch retards the rise in soil temperature and soil strength by retarding drying. This is due primarily to the interception of radiation by mulch.
c. Pasture mulch is quite efficient in radiation interception; 1900 kg ha^{-1} of dead standing Caribbean stylo intercepted 80%, and 700 kg ha^{-1} 55%, of direct beam radiation.
d. Tropical grasses and weeds, in general, are killed by dosages of the herbicide glyphosate similar to those used in temperate regions (1.5 to 2 t ha^{-1}).
e. The most successful planter has been a narrow tyne preceded by a rolling coulter to cut surface mulch, and followed by a narrow in-furrow press wheel.

Research has recently commenced on planting on the sandy soil where there appear to be fewer technical problems than on the loamy soil.

Considering the overall results of the various studies in this subsystems, our tentative conclusion is that no-tillage technology for this farming system is feasible in all major aspects, and that further progress will most likely be made in on-farm research and development that is now under way.

Subsystem 3: The effects of competition from pasture/legume intercropping on crop production

Two early studies were conducted to assess the effect of Caribbean stylo, Alysicarpus vaginalis, and Centrosema pascuorum intercrops on maize yield. In one, intercropped maize yielded 15% more than sole maize, but in the other it yielded 30% less. Data on yield, chemical composition, and weather only were collected, and these are inadequate to explain the results. Work at present is focused on the competition between the crop and the pasture/legume intercrop for the two resources most likely to be deficient in this system: water and nitrogen.

Preliminary results indicate the following.

a. With an ample supply of water and N, maize yields are high (>5 t ha^{-1}) and little reduced by the legume intercrop, despite a yield of dry matter up to 4 t ha^{-1}.
b. At low nitrogen levels, a legume understory reduced yields 10-50%, depending on the species of the legume.
c. When water deficits occurred, a legume understory exacerbated the stress effect on maize yield, but the effects were moderate and dependent on the timing of the stress.
d. In a year of very high rainfall and low radiation, legume yields were low.

The question of whether it is economically desirable to have a legume understory at a given location has a weather-related probabilistic answer. The only feasible way to answer this question is by numerical simulation of the effects of the legume for a long period of weather records.

Subsystem 4: The effect of cattle-ley rotations on animal and crop production

Study of this subsystem is being conducted within one "whole-system" experiment. Its objectives are the following.

a. To quantify the N contribution to a succeeding crop by various legumes under realistic dry-season grazing management.
b. To compare liveweight performance in the legume-ley system with that on continuously grazed native pastures and on improved pastures.
c. To document the ecological stability of pastures of Caribbean stylo, A. vaginalis, and C. pascuorum, particularly in relation to re-establishment and the ability to resist invasion by annual grasses.

d. To document the trends in weed abundance in the crop and the pasture and to identify possible weed-management strategies.
e. To quantify costs of production and yields of maize under realistic operational conditions with respect to planting and harvesting.

The cropland component of this study consists of three paddocks in which the legume-ley is Caribbean stylo, A. vaginalis or C. pascuorum. Within each paddock there are three areas of equal size. This allows a 1-year maize: 2-year legume-ley rotation, with a maize crop every year. Adjacent is a large area of unimproved native pasture under eucalypt woodland.

The native pasture area is stocked during the green season at an appropriate density (0.2 beasts per ha) with equal numbers of weaners and yearling steers. After crop harvest, three groups of four cattle (2 weaners + 2 yearlings) are moved into the cropland paddocks; an equal number remain on the native pasture. At the end of the dry season, yearlings are turned off and weaners return to native pasture; the latter return in the following year to their respective legume paddocks for finishing.

Maize is planted by no-tillage after spraying the regenerating pasture with glyphosate. In half of the crop area, the legume understory is allowed to develop; in the other half this is prevented by the application of a pre-emergent herbicide. A range of N rates is superimposed on parts of the maize to assess response to N above that contributed by the 2-year leys.

Botanical composition of ley pastures is measured annually near the end of the green season. Pasture on offer, and the proportions and chemical composition of leaf, stem, and seed are measured periodically through the dry season in conjunction with diet sampling with oesophageal-fistulated cattle.

This experiment was sown only in January 1982, so time trends in pasture production and ecology, as influenced by crop-pasture rotation, are not yet available. Animal production, however, is not as dependent on crop-ley sequences, and results from the first two dry seasons should be as informative as those to come. In 1982 the liveweight gain on legume ley/ stover, averaged over legume species, was 75 kg per head greater than on native pasture for the 4-month period mid-July to mid-November. In the cropland, during the first 7 weeks, 10-20% of time spent grazing was in the stover and, after that, virtually all grazing was on legume. There was virtually no effect of legume species on liveweight performance.

Discussion

From an agroecological standpoint, a no-tillage legume-ley system appears promising for SAT Alfisols in northern Australia. Of the problems in Figure 1, all those involving a management factor are alleviated, i.e., high soil temperatures, surface crusting seals, low infiltration, high erosion, and poor nutrient supply. Although there are still numerous technical questions to be answered, the most pressing questions concern the economics of the system. At this preliminary stage there are at least some indicators. On the positive side, there are high grain yields, savings in fertilizer, only modest herbicide demands, (and willingness of the government to subsidize a fledgling industry if the technology is appropriate). On the negative side, there are unfavorable trends in Australia's export markets for coarse grains and beef. In response to the latter, particularly, our research scope is expanding to include systems that allow continuous cropping and which use high-value grain legumes in addition to pursuing further research on the ley system.

There is ample evidence of a general nature to indicate that a no-tillage legume-ley system can contribute to improved management of Alfisols in other SAT regions. The main questions concern adaptation to economic and sociocultural environments; the issues of land and capital availability are especially pertinent.

In the evolution of agricultural systems in the SAT (Ruthenberg 1980), grass fallow systems occur when pressure on land increases to a level at which insufficient time is allowed in the fallow period for woody vegetation to regenerate. The substitution of sown legumes for naturally-regenerated native grass in fallows is a possible means of increasing the effectiveness of this phase of the rotation in terms of both animal and crop production. Thus land requirements for a legume-ley system can be satisfied where fallow systems are used, and substitution of pasture legumes provides a potential means of maintaining production as shorter fallows are forced. Under circumstances where land must be used even more intensively, other agroecological options become relatively more attractive. No-tillage/ mulch farming combined with alley cropping or with a living mulch system offer possibilities of retaining benefits of legumes to soil, crop, and animals, while cropping continuously.

Ruthenberg (1980) argued that implementation of a ley system, although less capital-intensive than modern permanent cultivation, still requires considerable investment in clearing, livestock, fences, implements, carts, tracks, and buildings. He viewed these costs as prohibitively high. I suggest that a no-tillage legume-ley system, in contrast to Ruthenberg's traditional European model, requires an initial investment only in pasture legume seed and annual capital inputs of phosphate fertilizer and herbicide. Vis-a-vis Ruthernberg's model, this system offers (a) greater N fertilizer-saving and animal production benefits as a result of recently-domesticated legumes better suited to the SAT, and (b) capital and labor reductions associated with no-tillage. Substitution of chemical land preparation for mechanical preparation eliminates or reduces the need for stump clearing, traction, and implements. Realization of the latter requires a low-cost herbicide with the broad-spectrum, nonresidual, and low-mammalian-toxicity properties of glyphosate (Roundup®). With the expiry of the original patent of this product in many countries in 1987, substantial price reductions are expected as other producers enter the market. The simple nature of the compound and its inherently low cost of production offer prospects of much reduced prices in the longer term. The demonstration of technological and ecological successes of no-tillage/mulch farming by small farmers in the SAT could favorably influence the future cost and supply aspects of a suitable chemical.

Even assuming a much cheaper herbicide, the capital requirements of the most ecologically sound and capital-conserving farming strategies are still too high for most farmers working on Alfisols in the SAT, who have a largely subsistence economy. However, it is most important that these potential innovations are not dismissed as inappropriate on these grounds. If a given strategy can be shown to have large ecological and economic advantages over that currently used in a given environment, governments have the means to alter the farmer's economic environment to favor adoption by changing policies that affect markets, the cost of inputs, product prices credit, etc.

In the African SAT, deficits in urban food supply and expenditure of foreign exchange on food imports have been increasing at alarming rates. These problems of great political and economic urgency may provide the needed incentives for national food production reforms. If so, the urgency extends to the research evaluation of innovations that offer the best promise of stable, profitable agriculture.

It cannot be assumed that it is economically feasible to check the degradation of SAT Alfisols and the accompanying impoverishment of those who subsist on them. Fyfe et al. (1983) suggest that no form of improved management using conventional technology is cost-effective on such soils. It remains to be seen if management strategies designed for maximum ecological and economic efficiencies greatly alter this conclusion.

Acknowledgments

The research program at Katherine has been a joint program of R.K. Jones, the late D.C.I. Peake, W.H. Winter, R.J. Chamberlin, and the author.

References

Akobundu, I.O. 1982. Live mulch crop production in the tropics. World Crops 34(4): 125-126, 144-145.

Altieri, M.A. 1983. The question of small farmer development: who teaches whom? Agriculture, Ecosystems, and Environment 9:401-405.

Arndt, W. 1965. The nature of the mechanical impedance to seedlings by soil surface seals. Australian Journal of Soil Research 3:45-54.

Barrow, N.J., and Carter, E.D. 1978. A modified model for evaluating residual phosphate in soil. Australian Journal of Agricultural Research 29:1011-1021.

Bayer, W., and Otchere, E.O. 1984. Effect of livestock-crop integration on grazing time of cattle in a subhumid African savanna. Presented at the International Savanna Symposium,-28-31 May 1984, Commonwealth Scientific and Industrial Research Organization, Brisbane, Australia.

Bridge, B.J., Mott, J.J., and Hartigan, R.J. 1983. The formation of degraded areas in the dry savanna woodlands of northern Australia. Australian Journal of Soil Research 21:91-104.

Fyfe, W.S., Kronberg, B.I., Leonardos, O.H., and Olorunfemi, N. 1983. Global tectonics and agriculture: a geochemical perspective. Agriculture, Ecosystems, and Environment 9:383-399.

Greenland, D J. 1975. Bringing the green revolution to the shifting cultivator. Science 190:841-844.

Greenland, D J. 1981. Soil management and soil degradation. Journal of Soil Science 32:301-322.

Henzell, E.F., and Vallis, I. 1977. Transfer of nitrogen between legumes and other crops. Pages 73-88 in Biological nitrogen fixation in farming systems of the tropics (Ayanaba, A., and Dart, P.J., eds.). Chichester, UK: John Wiley.

Hudson, N. 1971. Soil conservation. London, UK: Batsford.

Janzen, D.H. 1973. Tropical agroecosystems. Science 182: 1212-1219.

Jones, M.J., and Wild, A. 1975. Soils of the West African savanna. Commonwealth Bureau of Soils Technical Communication no. 55. Farnham Royal, Slough, UK: Commonwealth Agricultural Bureaux.

Jones, R.K., Myers, R.J.K., Wright, G.C., Day, K.J.,and Mayers, B.A. (In press.) Research for improved crop management—fertilizers. In Agro-research for Australia's semi-arid tropics (Muchow, R.C., ed.). Brisbane, Australia: University of Queensland Press.

Kang, B.T., Wilson, G.F., and Sipkens, I. 1981. Alley cropping maize (Zea mays) and Leuceana leucocephala Lam) in southern Nigeria. Plant and Soil 63:165-179.

King, K.F.S. 1979. Agroforestry and the utilization of fragile ecosystems. Forest Ecology and Management 2:161-168.

Kowal,J. 1970. The hydrology of a small catchment basin at Samaru, Nigeria. IV. Assessment of soil erosion under varied land management and vegetation cover. Nigerian Agricultural Journal 7:134-147.

Lal, R. 1973. Effects of seed bed preparation and time of planting on maize {Zea mays) in western Nigeria. Experimental Agriculture 9:303-313.

Lal, R. 1975. Role of mulching techniques in tropical soil and water management. Technical Bulletin no. 1. Ibadan, Nigeria: International Institute of Tropical Agriculture.

Lal, R. 1977. The soil and water conservation problem in Africa: ecological differences and management problems. Pages 143-149 in Soil conservation and management in the humid tropics (Greenland, D.J., and Lal, R., eds.). New York, USA: John Wiley.

Lal, R. 1979. The role of physical properties in maintaining productivity of soils in the tropics. Pages 3-5 in Soil physical properties and crop production in the tropics (Greenland, D.J., and Lal, R., eds.). Chichester, UK: John Wiley.

McCown, R.L.,Haaland,G., and deHaan,C. 1979. The interaction between cultivation and livestock production in semi-arid Africa. Pages 297-332 in Agriculture in semi-arid environments (Hall, A.E., Cannell, G,H., and Lawton, H.W., eds.). Ecological Studies no. 34. Berlin, Federal Republic of Germany: Springer-Verlag.

McCown, R.L., Jones, R.K., and Peake, D.C.I. 1980. Short-term benefits of zero-tillage in tropical grain production. Page 220 in Proceedings of the Australian Agronomy Conference, April 1980, Queensland Agricultural College, April 1980, Lawes, Queensland, Australia.

McCown, R.L., Jones, R.K., and Peake, D.C.I. (In press.) Evaluation of a no-till, tropical legume ley farming strategy. In Agro-research for Australia's semi-arid tropics (Muchow, R.C., ed.). Brisbane, Australia: University of Queensland Press.

Mokwunge, V. 1977. Phosphorus fertilizers in Nigerian savanna soils. I. Use of phosphorus sorption isotherms to estimate phosphorus requirement of maize at Samaru. Tropical Agriculture (Trinidad) 54:265-271.

Norman, M.J.T. 1968. The performance of beef cattle on different sequences of Townsville lucerne and native pasture at Katherine, N.T. Australian Journal of Experimental Agriculture and Animal Husbandry 8:21-25.

Nye, P.H., and Greenland, D.J. 1960. The soil under shifting cultivation. Commonwealth Bureau of Soils Technical Communication no. 51. Farnham Royal, Slough, UK: Commonwealth Agricultural Bureaux.

Osuji, G.E.,and Babalola,0. 1982. Tillage practices on a tropical soil. I. Effects on soil physical and chemical properties. Journal of Environmental Management 14:343-358.

Probert, M.E. 1978. Availability of phosphorus and sulphur in tropical soils in relation to legume growth. Pages 347-360 in Mineral nutrition of legumes in tropical and subtropical soils: proceedings of a workshop, 16-21 Jan 1978, Brisbane, Australia (Andrew, C.S., and Kamprath, E.J., eds.). Melbourne, Australia: Commonwealth Scientific and Industrial Research Organization.

Roose, E.J. 1977. Adaptation des methodes de conservation des sols aux conditions ecologiques et socio-economiques de l'Afrique de 1'Ouest. Agronomie Tropicale 32(2): 132-140.

Ruthenberg, H. 1980. Farming sytems in the tropics. 3rd edn. Oxford, UK: Clarendon Press. 424 pp.

Sanchez, A. 1976. Properties and management of soils in the tropics. New York, USA: John Wiley.

Vallis, I., and Gardener C.J, (In press.) Nitrogen inputs into agricultural systems by Stylosanthes. In The biology and agronomy of Stylosanthes (Stace, H.M., and Edye, L.A., eds.). Sydney, Australia: Academic Press.

Wilkinson, G.E. 1975a. Effect of grass fallow rotations on the infiltration of water into a savanna zone soil of northern Nigeria. Tropical Agriculture (Trinidad) 52:97-103.

Wilkinson, G.E. 1975b. Canopy characteristics of maize and the effect on soil erosion in western Nigeria. Tropical Agriculture (Trinidad) 52:289-297.

Wilkinson, G.E., and Aina, P.O. 1976. Infiltration of water into two Nigerian soils under secondary forest and subsequent arable cropping. Geoderma 15:51-59.

Willey, R.W. 1979. Intercropping—its importance and research needs. Field Crop Abstracts 32:2-10.

Willey, R.W., Reddy, M.S., and Natarajan, M. 1987. Conventional cropping systems for Alfisols and some implications for agroforestry systems. (In this volume.)

Participants

R.N. Athavale
Assistant Director
National Geophysical Research Institute
Hyderabad 500 007
India

R. Chambers
Program Officer
The Ford Foundation
55 Lodi Estate
New Delhi 110 003
India

T. Englehardt
Research Scholar
University of Hohenheim
Institut 490
Postfach 700565
D-7000 Stuttgart
Federal Republic of Germany

G.W. Frasier
Research Hydraulic Engineer
Southwest Rangeland
Watershed Research Center
442 East 7th St.
Tucson
Arizona 85703
USA

B.P. Ghildyal
Program Officer
The Ford Foundation
55 Lodi Estate
New Delhi 110 003
India

B.R. Hegde
Agronomist
Dry Farming Project
Gandhi Krishi Vignana Kendra Campus
Bangalore 560 065
India

W.B. Hoogmoed
Lecturer
Tillage Laboratory
Agricultural University
Wageningen
The Netherlands

R.L. McCown
Principal Research Scientist
Division of Tropical Crops and Pastures
Davies Laboratory
University Road
Douglas
Towns ville
Qld. 4814
Australia

S.R. Naga Bhushana
Head of the Regional Centre
National Bureau of Soil Survey
and Land Use Planning
Regional Centre
Hebbal
Bangalore 560 065
India

S.V. Patil
Dean
College of Agriculture
University of Agricultural Sciences
Bangalore 560 024
India

R.L. Schafer
Director
National Tillage Machinery Laboratory
USDA-ARD-AR
P.O. Box 792
Auburn
Alabama 368-0792
USA

J. Sinclair
Soil Physicist
Dryland Farming Research Scheme
Agricultural Research Station
Private Bag 0033
Gaborone
Botswana

J. Venkateswarlu
Project Coordinator
All India Coordinated Research Project
for Dryland Agriculture (now CRIDA)
Santhoshnagar
Saidabad P.O.
Hyderabad 500 659
India

K. Vijayalakshmi
Chief Scientist
All India Coordinated Research Project
for Dryland Agriculture (now CRIDA)
Santhoshnagar
Saidabad P.O.
Hyderabad 500 659
India.

Participants from ICRISAT

R.K. Banaal
Agricultural Engineer
J.R. Burford
Principal Soil Scientist
R. Busch
Principal Soil Scientist
S.A. El-Swatfy
Principal Soil Scientist
G. Gunasekera
Principal Soil & Water Scientist
R.T. Hardiman

C.W. Hong
Principal Soil Scientist
A.K.S. Huda
Agroclimatologist
J.S. Kanwar
Director of Research
(now Deputy Director General)
N.A. Naidu
FSRP Consultant
M. Natarajan
Agronomist
P. Pathak
Agricultural Engineer
J.M. Peacock
Principal Plant Physiologist
E.R. Ptrrtar
Principal Agronomist
Soil & Water Management
Burkina Faso
N.Raghavan
Editor
M.S. Reddy
Agronomist
T.J. Rego
Soil Scientist
R.C. Sachan
Agricultural Engineer
S.K. Sharma
Sr. Research Associate
Piara Singh
Soil Scientist
Sardar Singh
Soil Scientist

M.V.K. Sivakumar
Principal Agroclimatologist
P. Soman
Plant Physiologist
K.L. Srivastava
Agricultural Engineer
L.D. Swindale
Director General
T. Takenaga
Principal Agricultural Engineer
G.E. Thierttein
Principal Agricultural Engineer
S.M. Virmani
Principal Agroclimatologist
K.P.R. Vittal
Soil Scientist
M. von Oppen
Principal Economist
T.S. Walker
Principal Economist
R.W. Willey
Principal Agronomist
J.H. Williams
Principal Plant Physiologist

RA-00112

ICRISAT

International Crops Research Institute for the Semi-Arid Tropics
Patancheru, Andhra Pradesh 502 324, India

ISBN 92-9066-103-8

ICR 86-0007