Beyond the Gene Horizon

Sustaining
agricultural productivity
and enhancing livelihoods
through optimization of crop and
crop-associated biodiversity with emphasis
on semi-arid tropical agroecosystems

Proceedings of a workshop

23 - 25 September 2002

Patancheru, India

Citation: **Waliyar F, Collette L,** and **Kenmore P E.** 2003. Beyond the gene horizon: sustaining agricultural productivity and enhancing livelihoods through optimization of crop and crop-associated biodiversity with emphasis on semi-arid tropical agroecosystems. Proceedings of a workshop, 23–25 September 2002, Patancheru, India. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and viale delle Terme di Caracalla, Rome 00100, Italy: Food and Agriculture Organization of the United Nations (FAO). 206 pp.
ICRISAT ISBN 92-9066-457-6 Order code CPE 146
FAO ISBN 92-5-104942-4

Sponsors

Food and Agriculture Organization of the United Nations (FAO) with partial financial support from the Government of The Netherlands

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)

Organizing Committee

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Acknowledgements

The Organizing Committee acknowledges the assistance of S D Hainsworth and T N G Sharma in the preparation of these proceedings.

Further copies of these proceedings and the summary proceedings (CPE 143) of the meeting are available from:

ICRISAT Patancheru 502 324 Andhra Pradesh, India	and	FAO viale delle Terme di Caracalla Rome 00100, Italy
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Beyond the Gene Horizon

Sustaining agricultural productivity and enhancing livelihoods through optimization of crop and crop-associated biodiversity with emphasis on semi-arid tropical agroecosystems

Proceedings of a workshop
23–25 September 2002, Patancheru, India

Editors

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2003

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Preface

W D Dar[1]

In welcoming participants to this workshop on sustaining agricultural productivity and enhancing livelihoods through optimization of crop and crop-associated biodiversity (C-CAB) with emphasis on semi-arid tropical (SAT) agro-ecosystems, that will run from 23–25 September, I would like first to thank the Food and Agricultural Organization of the United Nations (FAO) for its financial support and for working with ICRISAT staff to jointly organize the meeting.

As you all know, ICRISAT works on the improvement and integrated management of the five major crops grown by poor farmers in the SAT. This work is guided by our new vision which is the: Improved well-being of the poor of the SAT through agricultural research for impact. To attain this, ICRISAT is committed to: Help the poor of the SAT through 'science with a human face' and partnership-based research, and to increase agricultural productivity and food security, reduce poverty, and protect the environment in SAT production systems.

ICRISAT's vision is guided by the new Consultative Group on International Agricultural Research (CGIAR) vision and strategy. It is also anchored by our core competencies and thematic comparative advantages, by strategic analyses of opportunities in the SAT, and by potential impacts on the livelihoods of the poor. In order to pursue its vision and mission, ICRISAT has six global research themes that form the core of its research strategy. These are:

- Harnessing biotechnology for the poor
- Crop management and utilization for food security and health
- Water, soil and agro-biodiversity management for ecosystem health
- Sustainable seed supply systems for productivity
- Enhancing crop–livestock productivity and systems diversification
- SAT futures and development pathways

As can be seen, ICRISAT is highly involved in improving crops and managing natural resources, including their agro-biodiversity. In many ways, ICRISAT enhances agro-biodiversity through such action research programs as integrated watershed management and integrated pest management. In line with the objectives of this workshop, ICRISAT is fully committed to FAO's initiatives on C-CAB. The conservation and enhancement of biodiversity is vital to sustaining crop productivity and enhancing the livelihoods of farmers in the SAT. With over

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113,700 accessions assembled from 130 countries, ICRISAT's germplasm collection is the second largest in the CGIAR. This collection provides the necessary raw material with which to improve ICRISAT's mandate crops, and six other minor millets. About 98% of the collection is held in trust with the FAO to ensure the world community has unrestricted access to its treasures. Important morphological and agronomic traits in most of this assembled germplasm have been characterized and evaluated, and new genetic stocks and sources of resistance to important biotic and abiotic constraints have been identified.

Regional multiplication and evaluation of germplasm in partnership with national programs has resulted in the identification of locally adapted material and to the release of several superior genotypes as varieties. To enhance their use, core collections of all mandate crops representing the diversity in the global collection have been developed.

To date, the ICRISAT genebank has distributed over 650,000 seed samples to users in 140 countries. Such distribution remains the key genebank activity, and is highly necessary, since free access to genetic resources is becoming increasingly difficult in the era following the Convention on Biological Diversity. The demand for repatriation of native germplasm by donor countries is also increasing. ICRISAT's genebank is prepared to meet these challenges while contributing to the restoration of biodiversity and the sustainability of agricultural production systems in the SAT.

I am very happy to see a number of top-caliber experts from outside and within ICRISAT at this workshop and I am confident that the results of this meeting will significantly boost our initiatives in sustaining agricultural productivity and enhancing livelihoods in the SAT by optimizing C-CAB. But above all, the results should eventually reach the most marginalized, disadvantaged, and hungry. We must all therefore tailor our research efforts to meet real human needs by: reducing poverty, hunger, environmental degradation, and social inequity. This is at the heart of doing 'science with a human face'.

Introduction

Increasing international attention is being given to the role and productive value of biological diversity in agriculture. Recognizing the potential of agricultural biodiversity and the services it provides will be key to meeting future food needs while maintaining and enhancing other goods and services, such as clean air and clean water, provided by agricultural ecosystems. FAO and ICRISAT are joining forces to further the understanding of the contribution of crop and crop-associated biodiversity (C-CAB) in sustainable agriculture in the semi-arid tropics (SAT). In order to address some of the key components of C-CAB, FAO and ICRISAT organized a joint workshop in late September 2002.

The meeting was intended to generate animated exchanges between experts from different disciplines. Its outputs aim to provide a first step, not only in further understanding the role and value of main components of C-CAB for sustainable agriculture production intensification and livelihoods benefits, but also in identifying linkages and synergies between components of C-CAB in production systems for strategic interventions.

Workshop objectives

- Share knowledge and further understanding of the value and contribution of the main components of crop and crop-associated biodiversity (C-CAB) for sustainable production systems and agroecosystem health in the semi-arid tropics (SAT)
- Identify linkages and synergies between components of C-CAB in production systems
- Identify key limiting factors to better management of C-CAB to achieve sustainable agriculture and maintain agroecosystem health
- Explore how different components of C-CAB and management practices can be combined to optimize agroecosystem and livelihood benefits and support sustainable production
- Identify elements of frameworks for C-CAB with linkages between C-CAB components to facilitate strategic interventions
- Identify priorities for strategic intervention at policy, research, and farmer levels (in terms of assessment, adaptive management, capacity building, and mainstreaming).

An Ecosystem Approach for sustainable agriculture

L Collette[1] and P E Kenmore[1]

International instruments related to sustainable agriculture

The Conference of the Parties to the Convention on Biological Diversity (CBD) has adopted a Programme of Work on Agricultural Biodiversity (PWAB) and has requested the Executive Secretary to invite the Food and Agriculture Organization of the United Nations to support its development and implementation, and also to expand cooperation by inviting other relevant organizations [including the centers of the Consultative Group on International Agricultural Research (CGIAR)], to support the implementation of the PWAB, and to avoid duplication of activities. The PWAB makes provision for the further understanding of agricultural biodiversity in order to promote management practices, technologies and policies that promote the positive, and reduce and mitigate the negative impacts of agriculture on biodiversity, while enhancing productivity and the capacity to sustain livelihoods. It also contributes to the implementation of Chapter 14 of Agenda 21 (Sustainable agriculture and rural development).

The PWAB contains four elements: 1. The assessment of the status and trends of agricultural biodiversity; 2. The identification and promotion of adaptive management practices, technologies and related policy and incentive mea-sures; 3. Promoting the participation and strengthening the capacities of farmers and other stakeholders in the sustainable management of agricultural biodiver-sity; and 4. Mainstreaming agricultural biodiversity in different sectors including agriculture. It includes the International Initiatives on Pollinators and on Soil Biodiversity. It also builds upon existing international plans of action, programs and strategies that have been agreed by countries, in particular, the Global Plan of Action for the Conservation and Sustainable Utilization of Plant Genetic Resources for Food and Agriculture, the Global Strategy for the Management of Farm Animal Genetic Resources, and the International Plant Protection Convention (IPPC). For instance, the Global Plan of Action for the Conservation and Sustainable Utilization of Plant Genetic Resources for Food and Agriculture promotes the conservation and sustainable use of genetic resources of actual and potential value for food and agriculture. One of its specific activities promotes sustainable agriculture through diversification of crop production and broader diversity in crops. Although targeted at crops, the requirement for diversification will, of

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necessity, impact on the biodiversity of agroecosystems including crop-associated biodiversity.

The goal of the recently adopted International Treaty on Plant Genetic Resources for Food and Agriculture is the achievement of sustainable agriculture and food security. The Treaty includes articles promoting an integrated approach to the conservation and sustainable use of plant genetic resources and the application of ecological principles.

The CBD PWAB highlights the lack of sufficient methods to assess and understand the larger role of biodiversity in agroecosystems, stressing that:

> '..Understanding of the underlying causes of the loss of agricultural biodiversity is limited, as is understanding of the consequences of such loss for the functioning of agricultural ecosystems. Moreover, the assessments of the various components are conducted separately; there is no integrated assessment of agricultural biodiversity as a whole. There is also lack of widely accepted indicators of agricultural biodiversity. The further development and application of such indicators, as well as assessment methodologies, are necessary to allow an analysis of the status and trends of agricultural biodiversity and its various components and to facilitate the identification of biodiversity-friendly agricultural practices...' (Decision V/5).

In its review of the implementation of the PWAB in 2002 the Conference of the Parties to the CBD emphasized further action on the wider understanding of the functions of biodiversity in agroecosystems, and the interactions between its various components, at different spatial scales (Decision VI/5).

An Ecosystem Approach for sustainable agriculture

Increasing productivity and food security to satisfy human needs while protecting and enhancing environmental quality and conserving natural resources for future generations is a major challenge. As populations grow and demand for food mounts, achieving sustainable agriculture is critical to food security and poverty alleviation. For this sustainability to be real, the use of agricultural biodiversity and particularly of crop and crop-associated biodiversity (C-CAB), must be optimized.

In their very first meeting (1992) member countries of the CBD defined 'ecosystem' as: 'a dynamic complex of plant, animal and micro-organism communities and their non-living environment acting as a functional unit'. In the decade since then these countries have worked actively to promote and apply the Ecosystem Approach so that the three objectives set out in the CBD are more balanced. While conservation of biodiversity still receives the lion's share of resources, the other two objectives, sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources, are now receiving more attention. The Conference of the Parties to the CBD (Nairobi, May 2000) formally adopted a decision elaborating and promoting the Ecosystem Approach and calling on all its member governments to support it in their programs and policies (Decision V/6).

The Ecosystem Approach is a strategy for the integrated management of land, water, and living resources that promotes conservation and especially sustainable use of resources, including agricultural biodiversity, in an equitable way. The Approach is based on the application of appropriate scientific methodologies focused on levels of biological organization including (but going beyond) genes to encompass the essential processes, functions, and interactions among organisms and their environments, all of which include human beings. It recognizes that humans, with their cultural, political, and social diversity, are integral components of ecosystems. C-CAB is an intrinsic and important part of agricultural ecosystems and includes such components as predators, herbivores (including pests, pathogens and weeds) as well as with soil biodiversity and pollinators.

The application of the Ecosystem Approach implies intersectoral cooperation, decentralization of management at the lowest appropriate level, equitable distribution of benefits, and the use of adaptive management practices that can deal with uncertainties by being modified in the light of experience and changing conditions. The implementation of the Ecosystem Approach will also build upon the knowledge, innovations and practices of local communities.

Role and value of C-CAB

C-CAB that includes such elements as pollinators, predators, soil biota and parasites can be either planned (managed) or un-planned – but both play important roles in maintaining ecosystem functions (such as pest regulation, decomposition, gene flow, nutrient cycling, soil structure, pollination, and disease suppression) (Figure 1). In turn, these ecosystem functions contribute to agricultural production.

Management decisions about farming systems have an impact on the components of crop-associated biodiversity (both planned and un-planned), for example, through adopting agroforestry interventions, rotations, cover crops, windbreaks, and so forth. Additionally, the targeted management of crop-associated biodiversity has an impact on farming practices (for example, on the rate of application of pesticides), and ultimately on ensuring sustainable livelihoods. Integrated pest management (IPM) is a very clear example of the management of crop-associated biodiversity as a means of sustainably utilizing external chemical inputs rather than their liberal application (at times also encouraged through perverse policies and such incentives as subsidies).

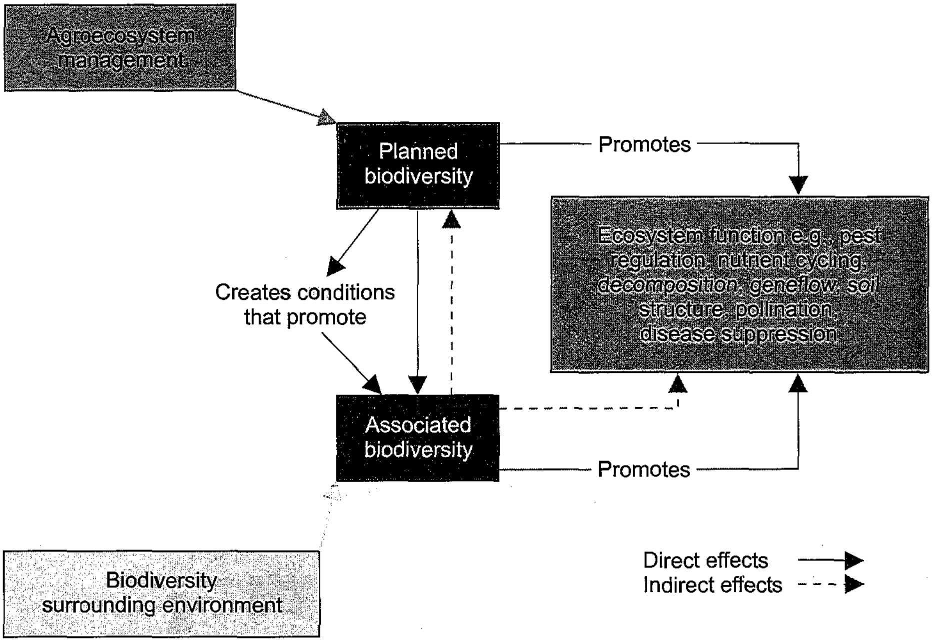

Figure 1. Planned and associated biodiversity

Source: Adapted from Vandermeer and Perfecto (1995)

At the policy level, in fact, in order to mainstream issues related to C-CAB vis-à-vis agricultural production, experience has shown that the most effective way to initiate policy reform (e.g., by removing such perverse incentives as subsidies) is to have the policy-makers themselves visit the field site.

An example of the interactions and linkages between planned and unplanned C-CAB interventions on agricultural production systems can be found in rice. In tropical irrigated rice systems, soil organic matter feeds an aquatic food web whose top consumers (chironomid midges), together with arthropod detritivores feeding directly on the organic matter (principally collembolans and ephydrid flies) are available as an abundant source of food to omnivorous predators in the plant canopy. This early-season boost of energy ensures abundant and well distributed populations of predators throughout the season, and greatly increases the effectiveness of biological control of crop pests. This example comes from tropical irrigated rice, but is probably a more general phenomenon than has been previously suspected, and is another fruitful avenue for research. Further research tested and found a strong correlation between inputs of organic matter (crop residues) and the abundance of important predator populations (Figure 2).

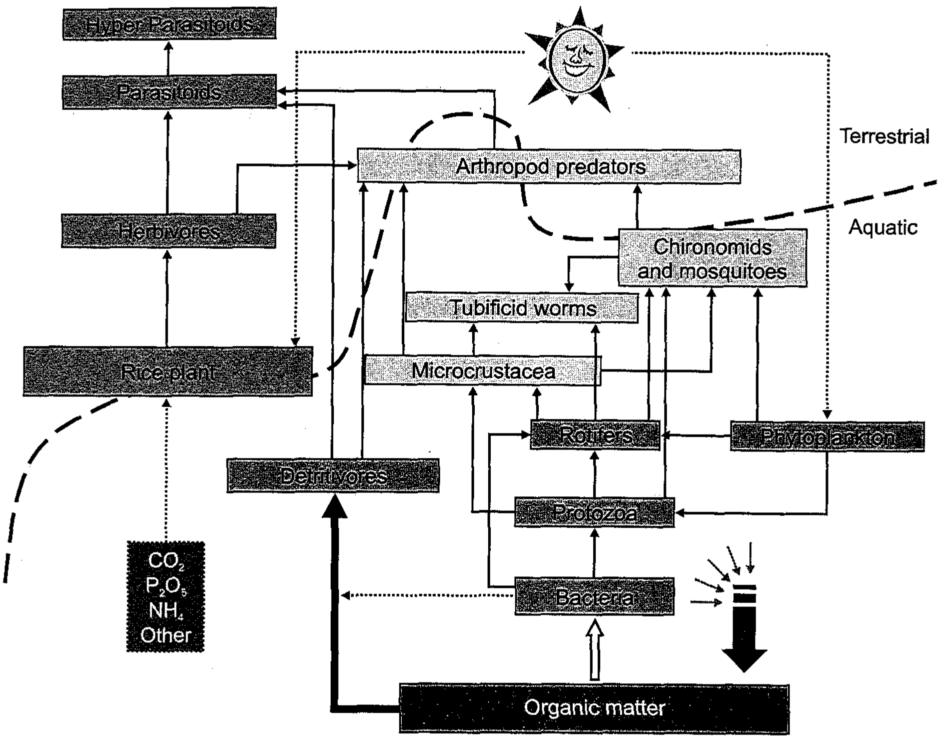

Figure 2. Tropical irrigated rice foodweb showing pathways from organic matter to terrestrial arthropod predators that support strong biological control of rice pests

Source: Settle 2001

Studying C-CAB will be a new challenge for traditional agricultural researchers. Conventional methods of holding all factors constant and varying the one of interest in a controlled manner may be appropriate in some instances, but not as a general approach. One approach might be to follow the example of field ecologists who try to look at elements and processes across a transect of a particular ecosystem, or even across a transect of ecosystems within a certain classification level. For agricultural systems, we might look at a particular class of agro-ecosystem (e.g., tropical irrigated rice, or rice–wheat cropping systems, etc.), by taking measurements across a transect of a particular cropping dimensions (e.g., crop heterogeneity, input intensification, soil amendment practices, water control regimes, within-crop genetic heterogeneity, etc). The following are several points that could be useful to interested researchers:

- Sample agricultural systems within-crop and across a continuum of landscapes and management intensities
- Seek to understand the range of mechanisms (both in terms of nutrient-flow and community dynamics) that support the 'service' in question
- Seek to understand how these mechanisms are affected by large-scale factors that underlie ecosystem function (the 'ecological context')
- What are the implications at management and policy levels?
- Build capacity in countries
- Take responsibility for educating people in an effective and practical manner.

For further discussion on C-CAB, the reader should refer to the draft background document prepared for the meeting and presented as Appendix 1.

Workshop process

The process designed for the workshop by the organizing committee was intended to be open, participatory, flexible, and conducive to the generation of contributions from experts from multiple disciplines.

Prior to the meeting, in addition to a draft background paper on possible elements for consideration in the development of frameworks for C-CAB (Appendix 1), individual papers on components of C-CAB and on SAT environments were circulated to participants, and are included in these proceedings.

The workshop was attended by more than 35 delegates, representing a range of research and development agencies and national and international research institutions.

On the first day, following a welcome by ICRISAT's Director General, Dr W D Dar, in which he stressed the importance of the topic and of working in partnership to achieve impacts, FAO's views and objectives of the meeting were presented and plenary presentations on the role and linkages of components of C-CAB and on SAT environments were made by selected experts on the following topics:

- Strategic assessments of agriculture in the semi-arid tropics: understanding change
- Soil and water: the flesh and blood of semi-arid agriculture in Africa
- Genetic diversity, arthropod response, and pest management
- Effect of organic resources management on soil biodiversity and crop performance under semi-arid conditions in West Africa
- Managing and harnessing soil flora–fauna biodiversity in the tropics for sustainable crop production
- Improving agricultural productivity and livelihoods through pollination: some issues and challenges
- Seed sense: strengthening crop biodiversity through targeted seed interventions
- Sustaining agricultural productivity and enhancing the livelihoods of rural communities through the promotion of neglected crops and their associated biodiversity in semi-arid agroecosystems
- Improving productivity and livelihood benefits of crop–livestock systems through sustainable management of agricultural biodiversity in the semi-arid tropics.

On the second day, participants were divided into two working groups representing the interests of Asia and Africa. Experiences were shared collectively and captured in a 9 by 7 matrix that guided the discussions. The results are presented in Appendix 2. The main aim was to identify cross linkages and synergies of the potential contributions of C-CAB to sustainable agricultural intensification and to propose frameworks for strategic C-CAB interventions. Similarities between the two regional matrices were also evident, and can been seen, for example, in the C-CAB components relating to seeds, neglected or underutilized crops, and in some aspects IPM as well (bearing in mind those differences relating to country specifics). Other similarities were seen when dealing with strengthening local capacities. The discussion that followed the development of the regional matrices allowed frameworks to be elaborated. The frameworks for strategic C-CAB interventions that emerged from both groups were complementary across continents, and were sufficiently robust to accommodate stakeholders from farmers to policy-makers.

The groups then identified and prepared suggested research priorities that took into account six key criteria [partnership, demand-driven, scale of analysis, participatory, communication, conservation (sustainable use/preservation)]. Detailed results were presented in plenary, and the workshop ended by participants endorsing a final statement.

These proceedings present the context within which the workshop was held, i.e., the Ecosystem Approach for sustainable agriculture, the workshop process, outcomes, final statement, and the presentations on SAT environments and C-CAB components.

These are followed by Appendix 1, a draft background document on crop and crop associated biodiversity, and Appendix 2, the outcomes of working groups for Africa and Asia discussions.

Outcomes

In order to better understanding the interactions between components of C-CAB each working group filled in a matrix that highlights the interaction between C-CAB components. The results of the working group discussions are presented in Appendix 2.

Both working groups identified common measures (technical, political, institutional, etc.) that would have positive impacts on C-CAB.

Outcome of working group discussions (Asia)

The Asia Group illustrated linkages between components of C-CAB and particularly explored how targeted interventions focusing on one component of planned C-CAB can have direct or indirect effects on other components of non-planned C-CAB.

With the on-going shift in the focus of agriculture from subsistence systems to commercial farming in many developing countries, new challenges for improving and maintaining productivity are emerging. Among these challenges are crop failures due to inadequate pollination caused by several factors – most important among which is the lack of adequate number of pollinators. Consequently the need to ensure pollination particularly by conserving pollinators and incorporating managed crop pollinators into the system has increased. This calls for a more intensive focus on the issue from the perspectives of policy, research, development and extension.

The outcomes of the discussions on the linkages between pollination and different components of C-CAB are shown in Figure 1. The discussions revealed that pollination has positive linkages to almost all components of C-CAB except water. Direct positive linkages were found with crops and seeds since pollination increases crop productivity (yield) and seed quality.

Better pollination means higher yields and better quality produce. Pollination also has positive but indirect linkages to such components of C-CAB as better crop health through the use of better quality seeds that result from better pollination, and healthy crops are less prone to attack from pests and diseases. Pollination also has positive indirect linkages to soil. It results in better and improved soil nutrition and helps to conserve soil by adding the extra biomass that result from better crop health. Such biomass has a positive impact on soil micro- and macro-fauna.

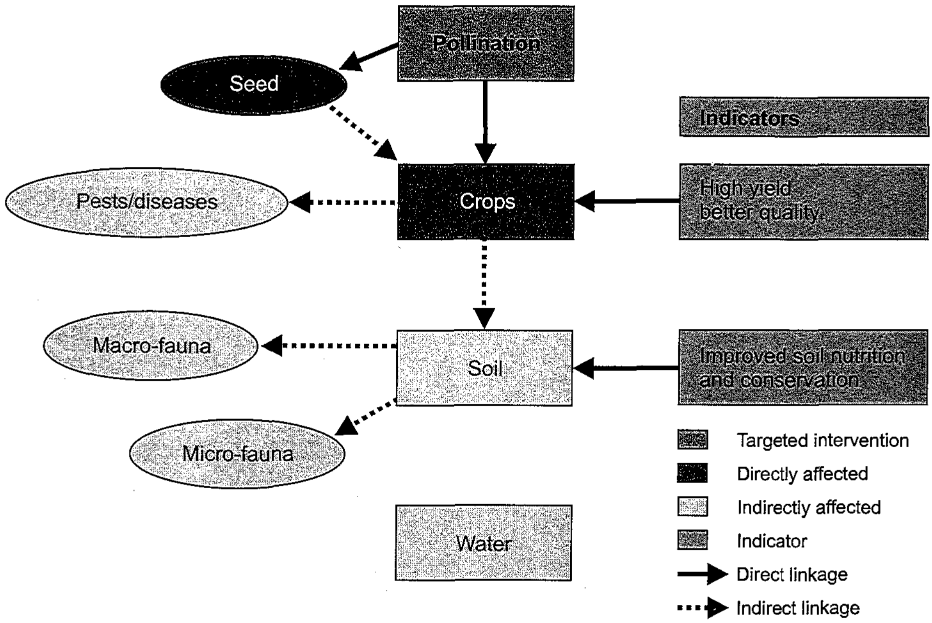

Figure 1. Pollination linkages to components of C-CAB (Asia working group output)

The excessive and indiscriminate use of pesticides on several crops has led to the extermination of both populations and the diversity of pollinators and such other beneficial insects such as predators. Integrated pest management (IPM) is being promoted to control pests and diseases of crops as a way to avoid these problems. The group also considered the impact of IPM (as an intervention) to the linkages between different components of C-CAB (see Figure 2).

The use of IPM was positively linked to all components of C-CAB including water. IPM helps to control pests and diseases and results in better quality seed. It has both direct and indirect positive linkages with pollination, crops, and different components of soil (soil micro- and macro-fauna) and water. The indicators of this also include higher yield, better quality and less pesticide residues in fruits and seed. Indicators at soil level were less pollution and improved fertility through the increase in micro- and macro-fauna and reduced water pollution.

Releasing the strong positive linkages of pollination to all components of C-CAB, the group felt that there is a strong need to make efforts at research, extension, and policy levels to promote conservation and sustainable use of pollinators.

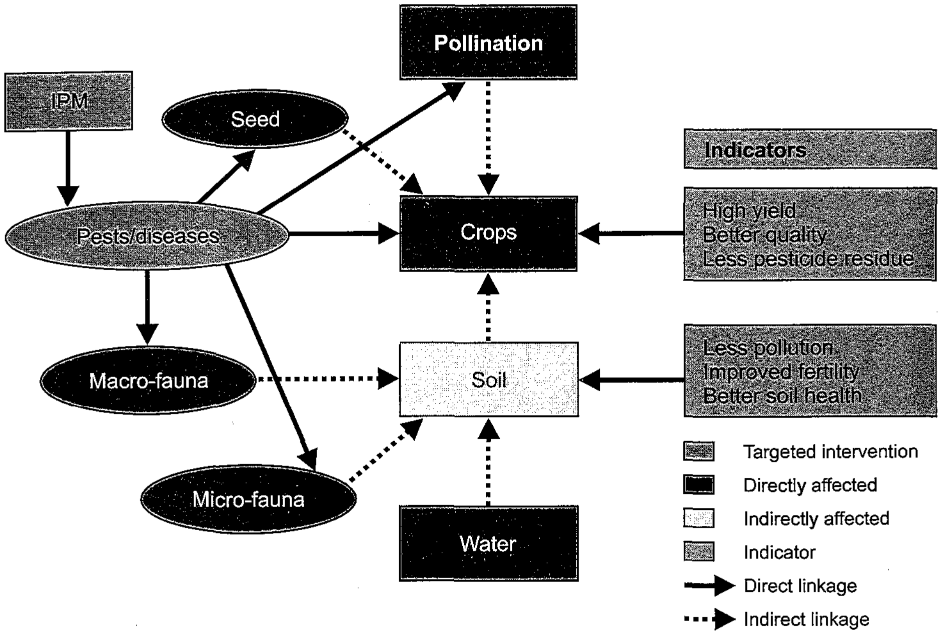

Figure 2. Integrated pest management linkages to pollination and other components of C-CAB (Asia working group output)

Outcome of working group discussions (Africa)

The Africa Group produced a diagram (Figure 3) illustrating a timeframe of interventions and bioindicators of C-CAB. The nature of the interventions determines when their impact could occur. Early bioindicators that monitor the impact of the interaction were identified. For instance, the effect of an IPM intervention could be seen in the field within the first year and could be monitored by predator density indicators, while tillage and organic matter interventions would have impacts 2 years after their initiation, and their impact could be monitored by measuring water infiltration rates and/or populations of termites, ants, and earthworms.

The complementary frameworks developed in both working groups considered six key criteria, i.e., partnership, demand driven, scale of analysis, participation, communication, and conservation (sustainable use/preservation) to identify priority areas for research (Figures 1, 2, 3). These priority areas have been clustered and are presented in the final statement.

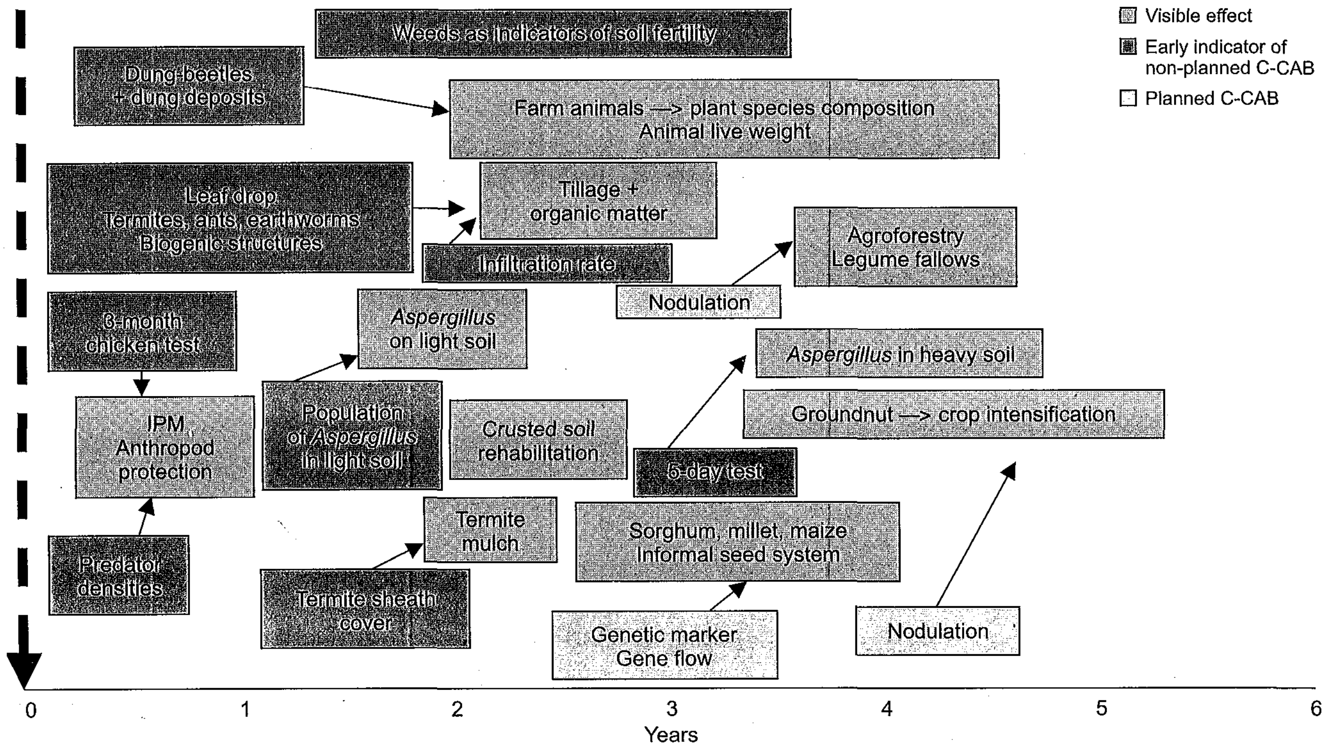

Figure 3. Timeframe of intevention and bioindicators of non-planned C-CAB (Africa working group output)

Final statement

Prepared during the workshop and agreed by all participants, this final statement is the result of all presentations and deliberations and presents research priorities that relate to FAO's Global Programme on Biological Diversity for Food and Agriculture.

The Workshop was designed to ensure that the agreed objectives were fully addressed in an iterative manner. Following the plenary presentations on specific topics, nine components of C-CAB were identified. These were combined with seven elements of a generic process for operationalizing C-CAB in SAT ecosystems to form a matrix. Two working groups representing the interests of Asia and Africa shared their collective experience across the resulting matrix.

This culminated in the identification of cross linkages, synergies, and indicators of the potential contributions of C-CAB to sustainable agricultural intensification. During the discussions it was noteworthy that key processes leading to those contributions emerged, along with practical biological indicators. Those indicators could be used by farmers to manage their agroecosystems more adaptively quite soon after they initiate interventions.

From the group discussions evolved frameworks for strategic C-CAB interventions that were remarkably complementary across continents. These frameworks were sufficiently robust to be drawn upon by communities of farmers, researchers, and policy-makers when considering potential C-CAB interventions. The groups then used the frameworks to suggest research priorities that took six key criteria into account. These research priorities were regrouped into clusters (12 for Asia and 8 for Africa) and are shown in the following table. They correspond well to the elements of FAO's Global Programme on Biological Diversity for Food and Agriculture.

Elements of FAO's Biodiversity Programme	Working group research area priorities: Asia	Working group research area priorities: Africa
Assessment	• Agroecosystem biodiversity • Marketing intelligence for under-utilized crops	• Agroecosystem biodiversity • Potential interventions
Adaptive management	• Dual-purpose crop varieties • Improvement and value addition of crops including under-utilized crops • Improved breed of animals • Seed production and processing technologies • Sustainable eco-friendly agricultural practices	• Trade-off analysis: preservation or conservation (sustainable use) • Case studies of C-CAB costs and benefits • Creating demand for products through marketing
Local capacity building	• Knowledge sharing • Farmer-friendly media • Farmers' field schools	• Participatory needs assessment[1] • Knowledge transfer pathway to make it demand driven[1]
Mainstreaming (especially policy)	• Policy reforms • Incentives for eco-friendly agriculture	• Policy reform, market failure, and public–private partnerships

1. All proposed research under this cluster will strengthen the local capacity to intervene in any activities related to assessment, adaptive management and mainstreaming.

Presentations on SAT environments and C-CAB components

Strategic assessments of agriculture in the semi-arid tropics: ICRISAT's approach to understanding change

M C S Bantilan[1] and R Padmaja[1]

Introduction

Despite the remarkable advances made by agricultural research in recent decades, poverty, food insecurity, and malnutrition still remain as the most critical challenges facing the semi-arid tropics (SAT) (ICRISAT 2001). The SAT is a harsh, risk-prone, fragile environment (Figure 1). Drought is a constant threat; water scarcity is a growing problem; soils are poor; and land degradation is increasing. Risks are pervasive and greater than in any other important food production system. Poor infrastructure and inadequate policy contribute to the lag in transformation into vibrant diversification and commercialisation.

Agriculture remains the backbone of SAT economies. Research should therefore be directed at developing appropriate technologies for sustainable intensification of agriculture in risk-prone SAT areas for the benefit of the hundreds of millions of poor people who live there. In particular, improved integrated genetic, soil and water management strategies are increasingly needed to maintain/enhance productivity and reverse degradation in the SAT.

There is a growing recognition of the special challenges and opportunities available in the SAT. First of all, it offers the hope of redressing the imbalance that has been evident in research and development (R&D) investments in the past. Environmental considerations are being increasingly integrated into international development policy. Moreover, publicly funded agricultural research which has declined by over 50% during the past 15 years is increasingly augmented by the private sector's growing share of agricultural research and ownership of new technologies.

The International Crops Research Institute for the Semi-Arid Tropics' (ICRISAT's) global theme on SAT Futures seeks to examine the changes taking place in the SAT. The region has changed significantly in the past three decades and some conditions, pervading when the Institute began, no longer hold true. This theme seeks to identify major changes, emerging trends, and their implications for ICRISAT's research priorities, in order to ensure that the Institute remains focused on key issues influencing agricultural development and poverty reduction. The theme aims to inform and guide ICRISAT's future research direction and strategy.

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In this regard, the completion of 'Future challenges and opportunities for agricultural R&D in the semi-arid tropics' by Ryan and Spencer (2001) was an important contribution as it highlighted priority research directions for SAT research that led to the reorientation of ICRISAT's vision and strategy.

The major findings from the literature survey, data analyses and stakeholder consultations, conducted by ICRISAT as a part of exercise to monitor changes highlight a number of implications for agricultural R&D strategies and priorities. A synthesis is presented below.

Synthesis of past activities on challenges and opportunities for agricultural R&D in the SAT

This section is mainly derived from key results of recent global theme reports, e.g., Ryan and Spencer (2001) on the future potential of SAT agriculture.

Poverty in the SAT

It is estimated that the incidence and depth of rural poverty is often higher in semi-arid regions. In 1996 the arid and SAT regions of Asia, sub-Saharan Africa (SSA), and Latin America jointly accounted for about 38% (380 million) of the 995 million rural poor in developing countries. South Asia (SA) alone accounted for almost all (236 of the 237 million) of the rural poor in SAT Asia and about 63% of the rural poor in the SAT worldwide. These figures indicate that about 50% of the abject poverty in SA is concentrated in the SAT areas.

Income sources of the poor

Significant changes are occurring in the income patterns of poor people living in the SAT (Figure 2). Documenting and understanding these, along with changes in consumption patterns, help in redesigning R&D strategies and priorities. In SA, the poor have less land; rely heavily on labor income on and off the farm; are less educated; belong to the lower castes; have larger families; have more children; and have higher dependency ratios than the more-affluent. In this region, labor-intensive technological change and the increased demand for non-farm labor from rural industries with high labor/capital ratios seem to favor the poor. The more-affluent are inclined to gain more from available labor-saving technological change.

In SSA, income from sale of crops is a more significant source of income for the poor than the more-affluent, as is income from livestock and remittances from emigrants. Crop production is viewed primarily as a sub-sistence activity and not a source of cash income. Commercial crops and live-stock are seen as sources of income growth and drivers of the investment strategies of SSA farmers. Non-farm income is important to the non-poor in SSA; increased opportunities to earn non-farm income enables diversification; and labor-saving technological change have become even more critical as the HIV/AIDS epidemic more seriously affects the young and middle-aged than the old. The increasing feminization of agriculture, especially in SSA, as a result of the migration of men to urban areas implies that particular attention must be given to the needs of women who now have added opportunities provided by their extra cash incomes from remittances.

Dynamics of SAT agriculture

Semi-arid areas house a vulnerable labor force because the limited opportunities to earn cash income lead to high levels of mobility and migration in search of better opportunities. This poses new challenges for agricultural research and development strategies in these areas. In SSA, the most immediate impact of HIV/AIDS at the household level is on the availability and allocation of labor. Labor available for agriculture declines as people fall sick, and ultimately die. At the same time the labor services of other household members are diverted from productive activities to care for HIV/AIDS patients. Studies from southern and eastern Africa (SEA) show how HIV/AIDS affected households shift from the cultivation of labor-intensive crops to activities that require less labor. Crop production has subsequently declined as a result of the reduction in areas cultivated, and adoption of less labor-intensive farming practices.

The share of merchandise exports and imports has been observed to be declining in all SAT regions, except for SEA where it has been relatively steady. It appears from analysis of trends that agriculture in the SAT will largely be import-substituting rather than led by growth in export industry. A decline in the share of the ICRISAT mandate crops is seen in the agricultural gross domestic product (GDP) in SAT regions with the exception of West and Central Africa. In contrast, commodities including commercial crops, livestock, and fish have increasing GDP shares.

In the Indian SAT (1970–94), there was a marked shift in cropping patterns away from coarse grains, in favor of wheat, rice, and oilseeds. The share of pulses in the gross cropped area was steady during the same period, whereas the oilseed share rose. Vegetables, fruits and spices also grew rapidly in relative importance. These changes all reflect the parallel changes in consumption patterns.

Trends indicate that some 76% of the projected growth in cereal production in developing countries is estimated to come from yield growth in the next 20 years. Yield growth will be a far more significant contributor in SA than in SSA.

The demand for meat in developing countries is projected to rise by 2.8% per annum until 2020, this is about half the rate of its demand growth (1982–94). The demand for milk will grow at 3.3% per annum, i.e., at a slightly lower rate (3.75%) than in the recent past (1982–94). The demand for feed grains will grow at a rate of 2.4% per annum. The predominance of smallholder crop–livestock systems in the SAT and the environmental difficulties of sourcing the required increase in meat production from intensive peri-urban livestock systems, provide good scope for the former to capitalize on the projected dynamic growth in the demand for animal products in developing countries in the coming decades.

The further liberalization of international trade and the rationalization of subsidies in agriculture will potentially change the comparative advantages in SAT agriculture. Studies in India, for example, suggest that such trends may favor rice, wheat and cotton but not pulses and oilseeds. If fertilizer and power subsidies are removed in the process, ICRISAT mandate crops could gain an advantage as they use little fertilizer and irrigation water at present, relative to rice and wheat. But, the implications for agricultural R&D priorities are not clear.

Changes are also reflected in the capacity for R&D in the agricultural sector. In SSA and SA the numbers of agricultural scientists have increased substantially in the last 20 years. Expenditure per scientist on the other hand has fallen in SSA and marginally risen in SA. This highlights the need to enhance partnerships among national agricultural research systems (NARSs) and international agricul-tural research centers (IARCs) to better exploit synergies and improve cost-effectiveness.

The role of the private sector in agricultural research in South Asia is small but growing, and there is still less private-sector involvement in SSA. Biotechnology and genetic improvement seem to be the private-sector growth areas. While there are opportunities for public–private partnerships, the commercial, biosafety, and associated public liabilities may prevent close collaboration from being fully consummated. It seems intellectual property rights (IPR), not only on genes but also on transformation processes, will continue to constrain access by the IARCs and NARSs to proprietary technology.

It should be noted that the global statistics do not reflect the fact that women are becoming increasingly responsible for overall farm management, especially in circumstances of male migration, e.g., in the SEA SAT. This is because the increasing feminization of agriculture in some regions is mainly the result of seasonal or non-permanent out-migration from rural areas by males (Figure 3). In countries where feminization of agriculture is an important factor, agricultural policies, including those for technology development, need to take a-priori consideration of the special needs of women. Such policies must take full cognizance of the possibility that female-headed households may have higher incomes than the male-headed rural households because of the increased remittances they receive from their migrant family members. The increased incomes that women control may have a significantly positive effect on the human development of children in such communities. The phenomenon is therefore most likely an economically viable response to non-farm opportunities in the changing dynamics in the SAT and the other parts of the developing world.

Important implications for agricultural R&D strategies in the SAT emerge from the SAT Futures foresight studies, the key messages for ICRISAT are:

- Water will likely be the primary constraint throughout the SAT in the coming years (Figure 4). Research could focus on: identifying genes that can improve water-use efficiency and drought tolerance; crop and systems modeling; watershed management; water policy; integrated soil–water–nutrient management, including improvements in plant nutrient-use efficiency; and the extent and nature of land degradation
- Understanding the dynamics and determinants of poverty in the SAT and how ICRISAT can intervene
- ICRISAT's mandate cereals are becoming less important in household food budgets in Asia, but will remain staple foods of the poor in the driest areas, especially in SSA. It may therefore be worth considering a shift in focus towards feed (as opposed to only food) uses, particularly in view of the continuing and increasing importance of livestock in SAT farming systems, and the anticipated growth in demand for livestock feed grains
- Limiting the mandate to the current five crops may reduce ICRISAT's future ability to impact on the welfare of the SAT poor
- Future research and policy agendas must account for regional differences, e.g., in resource endowments, infrastructure, etc. For example, labor-intensive technologies would be appropriate for the poor in South Asia, and labor-saving ones for SSA. HIV/AIDS is a serious constraint to labor availability in SEA, and must receive explicit attention in R&D strategies. A thematic, problem-driven agenda would be more appropriate
- There are inherent differences in the characteristics of the SAT countries of SSA and South Asia that are important when defining agricultural R&D strategies. These include differences in resource endowments, infrastructure, capacities of the NARSs, the nature and extent of poverty and malnutrition, the role of livestock in production and consumption, and land degradation. Such factors suggest the need for separate agricultural R&D strategies for these two major SAT regions.

Emerging challenges

Persistent poverty. Despite the surplus reserve of grains, food insecurity and child malnutrition in SA remain at unacceptably high levels, in both favored and less-favored areas. Owing to the high levels of population growth and unequal access to productive assets, the gains from productivity growth in agriculture are not sufficient to bring down the levels of poverty. India alone contributes over 70% of the absolute poor in SA and about one-third of the absolute poor in all developing countries. About 75% of the poor in the SA region concentrated in rural areas. There is paucity of data on spatial distribution of poverty according to the potential of agricultural lands. More-detailed poverty mapping needs to be carried out if to to achieve a more complete understanding of the concentration of poverty, its spatial distribution, and the associated socioeconomic and biophysical factors that may explain its distribution.

Human wellbeing in the rural areas of SA remains highly dependent on agriculture and related employment possibilities. Access to productive assets (e.g., land) and new technologies is crucial for equitable growth and sustainable food security. As a consequence of population growth and stagnation of the non-agricultural sector, land : person ratios have been progressively declining. Intensification of crop production and transformation of subsistence-oriented agriculture into more viable family farms through the adoption of Green Revolution technologies has counteracted this process of land scarcity in several more-favored regions. In the SAT and many less-favored regions, such transformation of subsistence agriculture has not occurred. This means that the rate of productivity growth in agriculture has been much lower than in irrigated regions. Although poor net food buyers in these regions have also benefited from the low food prices resulting from increased surplus in more-favored regions, small-scale farmers in the less-favored regions, where crop yields are low and costs of production are high, have been adversely affected. Lack of competitiveness in major crops leads to further marginalization and withdrawal from market participation. As land becomes scarce, some workers migrate to cities and high-potential regions in search of employment. Increasing mechanization of production and adoption of less labor-intensive technologies in Green Revolution areas, however, limits the absorption of migrants from the marginal regions. Hence, under increasing population growth and limited productivity-enhancing intensification in less-favored regions, the trickle-down effects from agricultural transformation in more-favored regions have not been sufficient to alleviate poverty in the less-favored SAT regions. Marginalization and poverty in less-favored SAT regions is also asso-ciated with increasing scarcity of water, incidence of drought, and degradation of the productive resource base.

Water scarcity and resource degradation. Agriculture and livelihoods in the SAT evolved under the influence of biotic (pest and disease) and abiotic constraints. The most binding abiotic constraints are related to water scarcity and poor soil fertility. The availability of limited fresh water and particularly the seasonal variation and unreliability of rainfall make agriculture in the semi-arid regions inherently risky. In SAT rainfed systems, the constant risk of drought increases the vulnerability of livelihoods and decreases human security. Since water is vital for crop growth, the low and unreliable rainfall for rainfed agriculture makes drought management a key strategy for agricultural development in SAT regions (Ryan and Spencer 2001). Future projections indicate that water availability in the semi-arid regions is expected to decline further mainly due to population growth, depletion of aquifers, and the competition for non-agricultural water use associated with increased urbanization and industrial development. Some one billion people (among the poorest in the world) living in the arid and semi-arid lands will be affected (Seckler et al. 1998). Hence, in the coming decades, many of the SAT countries are likely to be among the worst affected by water scarcity and shortages. The high costs of new water development and policy and market failures that encourage overuse of water resources in irrigated zones accentuate water problems in dry areas where supply is limited.

Apart from the tightening water scarcity constraint, degradation of soil resources (due to salinization, waterlogging, soil erosion, and nutrient depletion) threatens livelihoods and sustainability of food production across SA (Figure 5). The impressive productivity gains in cereal production achieved in the more-favored Green Revolution areas are now showing declining or stagnating signs in productivity growth. Adverse policies or declining policy support and slackening in R&D investments may explain some of this slow-down in productivity growth. However, emerging empirical evidence shows that in intensive rice–wheat monoculture systems, it is difficult to sustain productivity over a long term. Lowland intensification under the Green Revolution has been associated with build up of salinity in drier areas and waterlogging in wetter areas, depletion of groundwater reserves, formation of hardpan (sub-soil compaction), soil nutrient imbalance and increased pest build up (Pingali and Rosegrant 2001).[2]

Along with widespread poverty, water scarcity and soil degradation in the SAT, the tradeoffs and intensification-induced resource degradation problems and associated productivity decline in more-favored regions, justify a strategy for improving the productivity of agriculture in the less-favored regions. This

2. Although these external environmental impacts were associated with the Green Revolution, as many would agree, intensification of land use and productivity growth has perhaps reduced expansion of agriculture into forests and marginal and ecologically vulnerable areas.

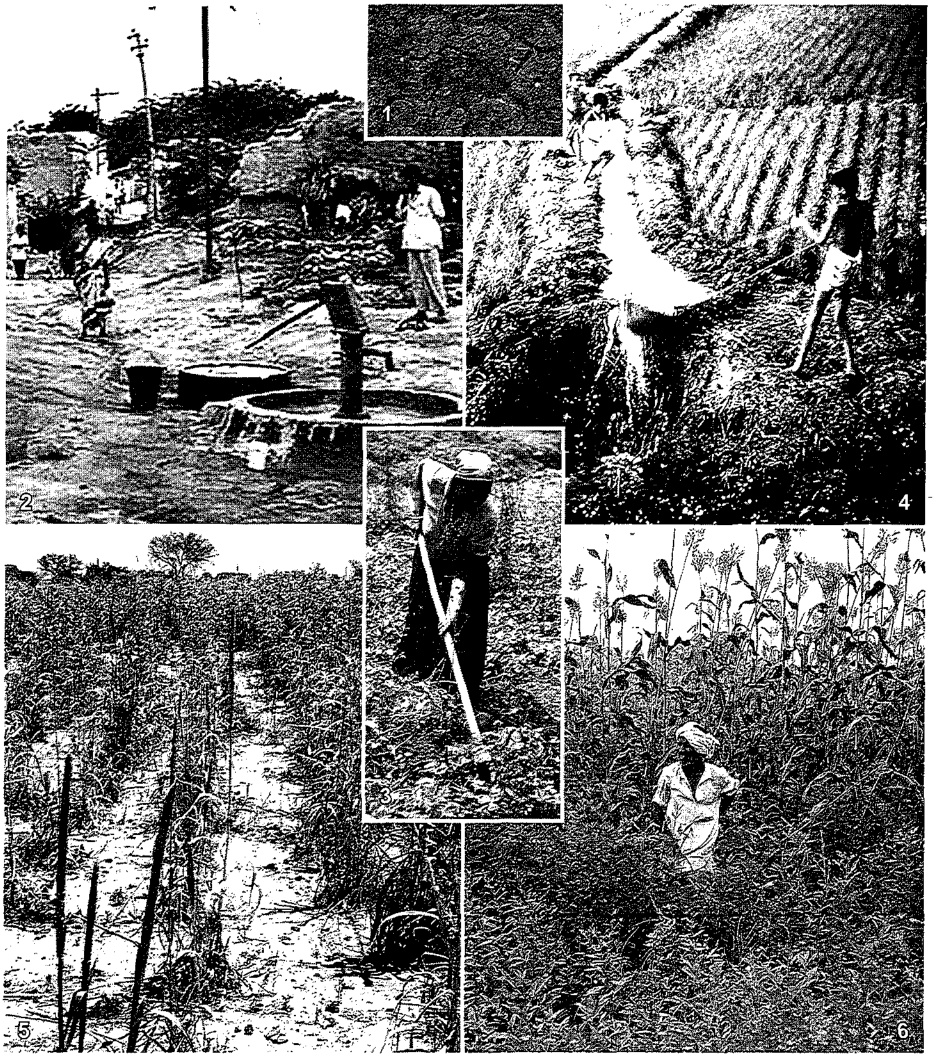

Figure 1. The harsh soils of the SAT

Figure 2. Understanding the development dynamics of the poor is an important priority

Figure 3. Male out-migration is resulting in the increasing feminization of agriculture

Figure 4. Water will become an overarching constraint in SAT

Figure 5. Degradation of soil resources is a binding constraint in the SAT

Figure 6. The transformation from vulnerabilities to opportunities requires development strategies made more complex by the need to adapt to globalization

suggests a development strategy for the less-favored areas that differs from the intensive monoculture systems of the Green Revolution, and takes into account environmental externalities, and is compatible with the expressed aspirations for more equitable and sustained productivity growth in agriculture. This task becomes more complex given the demands of adapting to globalization (Figure 6).

Globalization and marginalization. With increasing strides towards globalization of markets through domestic market reforms that encourage integration and liberalization of import and export markets, production efficiency and competitiveness of agricultural products within the domestic market and international markets are becoming important policy issues in the agricultural sector. In the past, macro-economic policies and R&D investments in many developing countries targeted food security and self-sufficiency in major food products. With increasing openness in the global economy, national self-sufficiency may not be a viable development strategy, as certain food products may be cheaper to import than produce domestically. However, considering agriculture's role as a means of livelihoods for millions of poor people in SA, enhancing its competitiveness through cutting average costs of production is critical for the survival of many smallholder farmers.

Accessing domestic and global markets requires investment in new cost-reducing or yield-enhancing technologies in addition to the basic marketing infrastructure. Investments in irrigation to boost yields and reduce production risk, extension services, supply of credit facilities the required inputs at the right time to supply the desired high quality and competitive products are all essential for production to be competitive. Identifying niche markets and comparative competitive advantages and harnessing such niches are challenges to many poor nations lacking the requisite human, organizational, and technological skills. For countries lagging behind in terms of technological advances and development of efficient market structures there is a risk that globalization may lead to further marginalization and poverty (World Bank 2002). Similarly, without adequate investment in productivity-enhancing technologies and basic infrastructure and human resources, less-favored areas poorly serviced in the past in terms of these investments, may loose out even further as agricultural markets become more liberalized and competitive. This means that globalization and increased market liberalization could further marginalize these areas, potentially leading to worsening poverty and environmental degradation.

Past empirical evidence in agricultural technology development and infrastructural investments in SA lends support to this process of marginalization in less-favored regions, especially the rainfed SAT. In the case of India, Fan and Hazell (1999) show that adoption of improved varieties, road density, market access (number of rural markets 1000 km^{-2}), and intensity of fertilizer use are consistently lower in rainfed than in more-favored irrigated districts. The high transaction costs and low productivity of agriculture in the rainfed SAT will affect the relative competitiveness of smallholder crop–livestock production activities in these areas. It will also influence farm-household decision behavior in terms of crop and technology choice and ability to hedge risk, both from the market and from the adverse biophysical environment.

There is also empirical evidence in India that under the influence of access to irrigation investment, changing consumption patterns and market opportu-nities, the composition and mix of crop–livestock production activities in the SAT has been changing. Comparing 1968–70 to 1992–94, Gulati and Kelly (1999) found falling shares in gross cropped area in the Indian SAT for sorghum, pearl millet, cotton and groundnut in marginal areas and rising shares for such tradables as sunflower, soybean, mustard, and chickpea. In more-favorable areas of the SAT, they found rising shares for wheat, rice, cotton, and oilseeds and declining shares for chickpea, millets, sorghum, and barley. There is a clear overall trend in cropping patterns away from the traditional SAT crops (like sorghum and pearl millet) towards high-value and tradable commodities. When technological options exist, small-scale farmers often capture market opportunities through diversification into new products. Rainfed agriculture in SA is evidently diversifying in favor of such high-value tradables as fruits, vegetables, and livestock and fish products. Such changes and patterns of diversification, unlike supply-driven food grains promoted through the Green Revolution, are market- and demand-driven. The basic question is how SAT agriculture in SA can be organized or diversified to overcome complex challenges and capture emerging opportunities in such a way that the forces of globalization, and technology, policy and institutional innovations can be harnessed to reduce poverty and resource degradation rather than lead to further marginalization in these less-favored areas (Global Theme on SAT Futures and Development Pathways 2002a).

ICRISAT's response. ICRISAT's new mandate is to 'Enhance the livelihoods of poor in semi-arid farming systems through integrated genetic and natural resource management strategies'. ICRISAT will:

- Make major food crops more productive, nutritious, and affordable to the poor
- Diversify utilization options for staple food crops
- Develop tools and techniques to manage risk and more sustainably utilize the natural resource base of SAT systems
- Develop options to diversify income generation
- Strengthen delivery systems to key clients. Partnership-based research for impact, gender sensitivity, capacity building and enhanced knowledge and technology flows are integral to this mandate (ICRISAT 2002).

ICRISAT's research strategy is founded on six global research themes, addressed through problem-based and impact-driven regional and local projects. These projects reflect specific strategic priorities for SA and SSA. ICRISAT's strategy has a dual focus on scientific excellence and impact. It targets key opportunities for improving the wellbeing of the poor, with food security being fundamental. Above all, it recognizes greater integration and diversification of partnerships as a core methodology for engaging science and technology development. This also ensures that its deliverables improve the wellbeing of the poor. Functional linkages between research, extension, farmers and markets and participatory approaches will enhance the impact of knowledge and technologies generated through research on reducing food insecurity and poverty. Priority setting, impact assessment and conserving and strategically using biodiversity are mainstreamed in this strategy.

Global theme on SAT Futures and Development Pathways

The global theme on SAT Futures and Development Pathways (SAT Futures) has evolved to respond to the strategic needs of the Institute and to provide an essential social science context for ICRISAT research (Figure 7). The SAT is continually changing, and changes will impact on the relevance of ICRISAT's research agenda. Strategic assessments for agriculture and economic growth in the SAT–the dynamics of rural livelihoods, nature and determinants of poverty together with commodity and market trends in increasingly globalized markets, and input supply and access constraints – are vital to inform and direct future investments in the SAT. These assessments are aimed at stimulating the identification of technological/policy/institutional alternatives and development pathways to enhance livelihoods in the SAT. They include identifying constraints to the

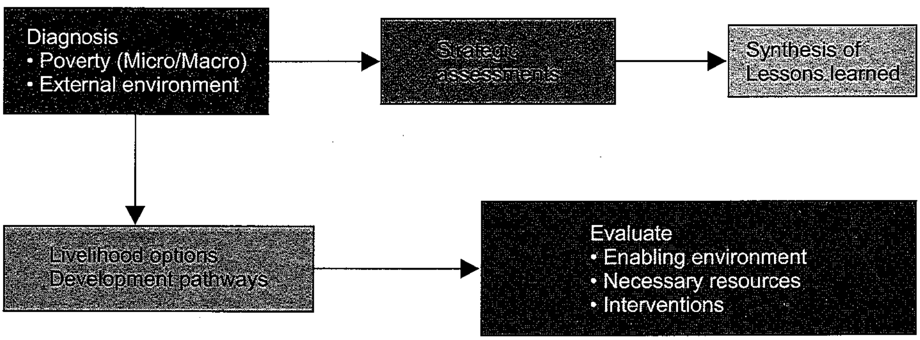

Figure 7. Framework guiding ICRISAT's global theme on SAT Futures and Development Pathways

uptake, adoption and utilization of technologies. Furthermore, poor farmers need access to diverse options and alternative approaches to choose suitable ones. An important question that challenges this global research theme is how agricultural research can improve the payoffs to an array of changing investment opportunities. The ultimate objective is to steer development towards a more sustainable pathway, which addresses the twin problems of poverty and environmental degradation.

The theme aims to deliver vital information and analytical tools that provide a rational foundation for decisions that affect the welfare of farmers and consumers in the SAT. With ICRISAT socio-economics and policy research rooted in a long tradition of working at the farm level, the participatory and multi-disciplinary approach ensures that ICRISAT addresses the pressing concerns in SAT agriculture and the changing external environment at both the micro- and macro-levels (Global theme on SAT Futures and Development Pathways 2002b). With strengthened partnerships with the NARS, the theme effectively contributes to the global research agenda by complementing the efforts of national programs to improve the wellbeing of SAT populations in Asia and Africa. Projects under this theme include:

1. Strategic assessments for agriculture and economic growth in the Asian SAT and implications for agricultural research priorities
2. Strategic assessments for agriculture and economic growth in the African SAT and implications for agricultural research priorities
3. Decision-support system for strategic assessments: Strengthening the predictive capacity for SAT Futures and research priority setting
4. Development pathways and policies for rural livelihoods
5. Situation and outlook reports, global trends on trade and marketing prospects and synthesis of lessons learned
6. Synthesis studies: lessons from success and failures and implications on research direction

Current emphasis – understanding change

Since ICRISAT began its work in 1972, there have been major shifts in cropping patterns, agricultural and trade policy, livelihood opportunities, and other factors. ICRISAT periodically reviews these changes, adjusting research priorities as needed to better focus on its main goal of poverty alleviation.

This was done in three stages, with help from partners all over the world. First, informal discussions with key development investors and sister centers within the Consultative Group on International Agricultural Research (CGIAR) built a framework for the review process. Next, a series of brainstorming meetings were conducted at six ICRISAT locations: Patancheru (India), Nairobi (Kenya), Lilongwe (Malawi), Bulawayo (Zimbabwe), Bamako (Mali), and Niamey (Niger). Finally, the outputs from these meetings were discussed at major stakeholder workshops in Nairobi and Patancheru (Global theme on SAT Futures and Development Pathways 2002c).

These meetings brought together the full range of partners and stakeholders–national research and extension services, CGIAR centers, policy-makers, donor agencies, regional organizations and networks, non-governmental organizations (NGOs), farmer groups, and the private sector (seed companies, input suppliers, and food processors).

The discussions covered rural development in the broad sense; not simply crop improvement (new high-yielding varieties) and crop management (e.g., environment-friendly pest control), but also management of water, soil, and other natural resources; livestock production and its synergies with crop farming; environmental degradation; poverty and its determinants; livelihood strategies employed by the poor; gender issues; health (primarily HIV/AIDS and its impact on agriculture); and policy and institutions that influence agricultural development. Recent results are:

- A clearer understanding of the major changes and their implications for poverty, agricultural development, and sustainability
- Identification of the key issues confronting researchers and development specialists
- Implications for the research community
- Specific recommendations for ICRISAT, to be factored into the research agenda.

Building tomorrow together

ICRISAT and its partners have established an unmatched record of scientific excellence. They have developed technologies that have changed the lives of millions of poor farmers in Asia and Africa and Latin America. But much more remains to be done – and this review process has helped develop a road map for the future.

There is a clear understanding of the problems that lie ahead, and of the possible solutions. The Institute also has a feel for what must be done differently, and precisely which research areas need greater emphasis if it is to alleviate poverty among the poorest of the poor. Most important, partnerships have been strengthened. This road map was developed jointly by ICRISAT and its partners – over 300 institutions were involved in the discussions, directly or indirectly. In essence, partners have helped refine and re-prioritize the research agenda, and reiterated their support for working together.

Key issues and implications for the research agenda

Poverty and food supply. In many parts of Africa, farmers are net **buyers** of food, not sellers. This is due to several factors, including frequent drought, poor soil fertility, lack of technology delivery and adoption, and poorly developed markets. To fight poverty effectively, ICRISAT must focus on research for development, i.e., science that not only expands the knowledge base but delivers direct, tangible benefits to poor farmers.

Diversification of income sources. Farmers throughout Africa and Asia are diversifying their sources of income. Agriculture is one of many livelihood strategies, e.g., off-farm employment, collection and sale of natural resources, remittances, etc. ICRISAT must study this diversification more carefully (e.g., diversification in southern and West Africa is driven by different factors from those in SA) and understand the implications for future research.

Livestock. A major component of the farming system and a major source of cash income for smallholder farmers, the importance of livestock is increasing; by implication ICRISAT plant breeders should increase their emphasis on fodder yield and quality.

HIV/AIDS. This disease is devastating entire communities: reducing life expectancy, creating orphans, wiping out savings, and driving large numbers of people into poverty. Critically, it is causing severe labor shortages in agriculture, affecting sown area and timeliness of farm operations.

Market opportunities. Particularly in risky SAT environments, farmers will not invest in new agricultural technology without good returns. Transformation from subsistence to more commercialized agriculture requires appropriate policy changes and the identification of market opportunities.

Technology research programs need to move toward greater concern for what SAT farmers can sell in the market. Marketing/commercialization issues are often the weak link limiting the sustained adoption of new technology leading to increased production/productivity. There is need to explore post-harvest technologies for SAT crops, so as to add value and develop new markets.

Gender. Genuine agricultural development and equity are not possible unless gender issues are addressed. Men and women have different constraints and different reasons for adoption or non-adoption of new technology. Adoption can be increased by incorporating these differences into research, extension, and impact assessment.

New paradigm for breeding. The traditional breeding paradigm considered variety and environment (G × E). A new paradigm has been suggested: G × E × policy × people × institutions. The new breeding paradigm will integrate resource management, economic realities and socio-cultural factors into breeding research, and ensure that research is conducted not for its own sake but for the direct benefit of the poor.

NARS capacity building. Partners were unanimous in expressing a strong need to strengthen training programs and capacity building, partly because of a continuous loss of NARS staff (AIDS deaths or movement out of the public sector).

New institutional arrangements. Institutions play a critical role in encouraging and sustaining technological innovation. A new paradigm was suggested for institutional arrangements, i.e., move from an 'optimal' blueprint to a more adaptive framework. The new structure should be dynamic, flexible, with structures/channels to:

- Clearly define problems
- Build and manage partnerships
- Draw lessons
- Introduce a market perspective into agriculture.

This system would move away from the traditional NARS-led arrangements to include a much broader and dynamic range of partners who would be held accountable for specific goals, or outputs.

Policy and institutions. These are a key determinant of technology adoption and welfare improvement. A better understanding of how the policy and regulatory environment affects the provision of services (extension, credit, research, infrastructure, etc.) is needed.

The ICRISAT socio-economics research program needs to be expanded, with greater emphasis on markets, policies, and institutional issues (in order to identify effective interventions that will stimulate agricultural development) and on poverty and livelihood strategies. ICRISAT must take a broader perspective, and extend its work to consider non-farm issues that impact on agriculture and market opportunities. For example, research must consider the complete chain from production to consumption – including agro-processing, markets, policy, uptake pathways, etc. A major expansion of the research agenda is not practical, given the resource constraints. However, much of the additional work can be implemented through partnerships with other stakeholders who have expertise in the required areas.

Conclusion

With the dynamics of the external environment surrounding the SAT, as described in this paper, ICRISAT will need to have a continuing brief to monitor this and to use the accumulated information, knowledge and understanding to refine R&D strategies, and to assess priorities and impacts. It will be especially important to build up a better understanding of the dynamics and determinants of poverty in the SAT and how ICRISAT can intervene to help alleviate it. As the World

Bank puts it, ICRISAT should move from counting the poor to making the poor count! Greater and continuing attention to problem diagnosis against this background would seem appropriate.

As discussed earlier, the SAT is continually changing. Trends and major changes must be constantly monitored, and the research agenda accordingly reviewed and modified as needed. Some of the factors yet to be explained are:

- The dynamics and determinants of poverty
- Causal relationships underlying the development of SAT agriculture
- Continuing lags in technology adoption.

Changes in the SAT environment will impact on the research agenda. Coupled with increasing market access, the liberalization of macro-economic and trade policies has increased the relative importance of tradables in the commodity mix. Expansion of markets (inputs and products) has broadened the range of livelihood strategies. New opportunities are arising from broadening institutional partnerships. The direction for future work is to look at agricultural and economic growth including trends and opportunities in the SAT with a vision to stimulate/enhance:

- Breadth and evolution of investment patterns in SAT farming systems
- Diverse rural investment options/or livelihood strategies in farm and off farm enterprises
- Implication of changing investment patterns for policy and agricultural research priorities.

The key issues that need thorough understanding include:

- Coping mechanisms and risk-management strategies of farmers in a risky environment with changing employment and market opportunities
- Farmer investment strategies and priorities
- Impacts of new agricultural technologies.

The ultimate question is 'How can agricultural research improve the payoffs to the diverse and changing investment opportunities in the SAT?'

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Soil and water: the flesh and blood of semi-arid agriculture in Africa

S Twomlow[1]

The Challenge

> *'For the first time, we may have the technical capacity to free mankind from the scourge of hunger... within a decade no man, no woman, or child will go to bed hungry'* (Henry Kissenger, United Nations World Food Conference 1974).

When Henry Kissenger made this statement the first Green Revolution was at its peak, and there was a great deal of optimism over technical capabilities to eradicate hunger. Over the last three decades world food production has grown faster than population. Per capita food production today is about 18% more that it was 30 years ago. Despite this considerable progress in production, there are world-wide inequalities in the availability of food in both developed and deve-

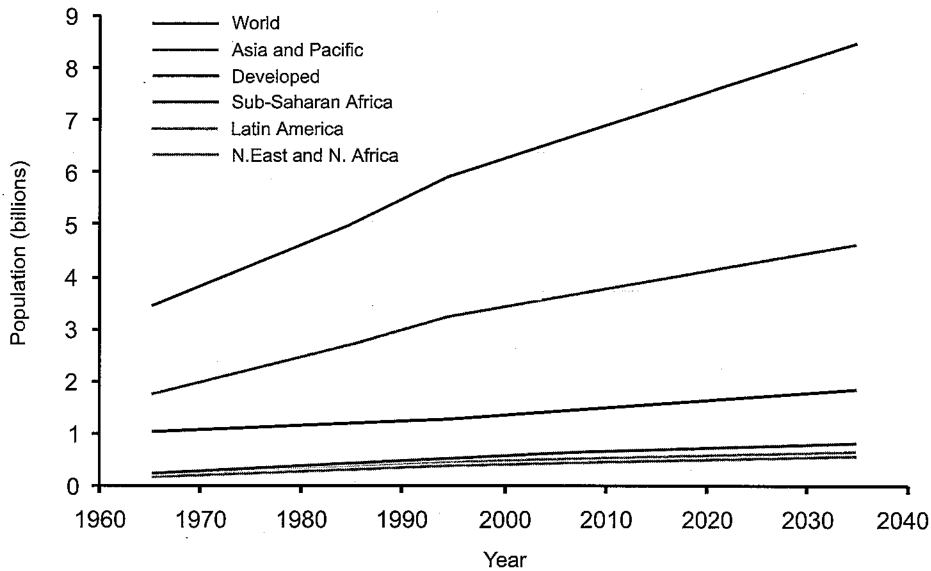


Figure 1. World population trends extrapolated to 2035

Source: FAO 1999

1. Water, Soil and Agro-biodiversity Management for Ecosystem Health, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Matopos Research Station, PO Box 776, Bulawayo, Zimbabwe

loping nations, and concerns are rising over degradation of the natural resource base. It is currently estimated that 1.3 billion people go to bed hungry every night, of whom more than 800 million people (11 million in the USA alone) are under-nourished and susceptible to debilitating diseases caused by micro-nutrient deficiencies and contaminated food and water (FAO 1996; 1999; USDA 2000; Ryan and Spencer 2001; De Vries 2002).

Conservative estimates of world population for 2020 suggest a figure of around 8 billion people, peaking at 8.5 billion by about 2035 (Figure 1). These figures are based on the assumption that access to improved food supplies, health and water facilities, when combined with increased affluence will help stabilize populations, by giving parents confidence that their first two or three children will live to adulthood. The long-term equilibrium for affluent, urban societies seems to be 1.7 births per woman (Seckler and Cox 1994). Unfortunately, the countries, with the highest population growth rates are the poorest, with the greatest levels of under-nutrition (Figure 2). The largest numbers, although declining, are found in Asia where the first Green Revolution has been partially successful. But, it is Africans, not Asians, who bear the brunt of the world food problem, and will continue to do so for the foreseeable future (Fischer and Heilig 1998; Ryan and Spencer 2001).

Both the International Monetary Fund (IMF) and the Food and Agricultural Organization of the United Nations (FAO) regard increases in wealth as the best means of fighting poverty and undernutrition. Regrettably, with increasing afflu-

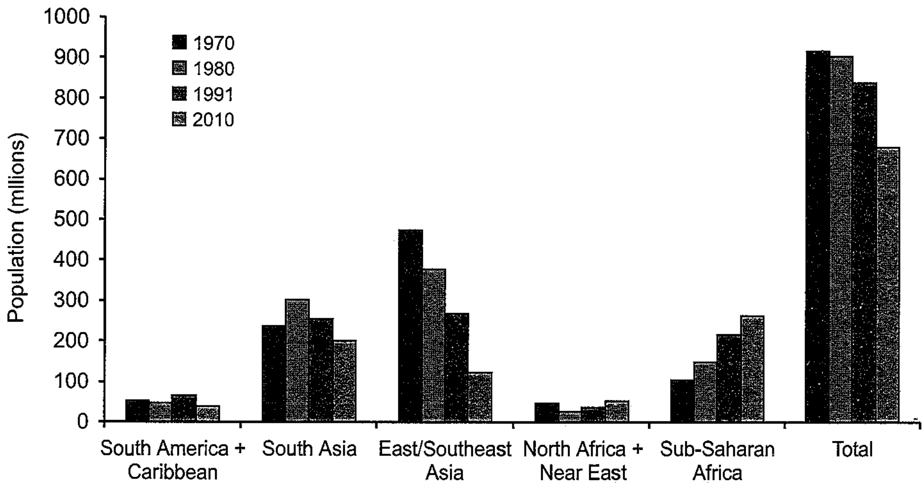


Figure 2. Trends in under-nutrition for emerging areas of the world

Source: FAO 1999

ence, urban populations grow at the expense of rural populations (Figure 3) and inequalities in the demand for food and water will develop and will continue to increase well into the next millennium (Table 1). By 2020 over 4 billion people will be living in towns and cities.

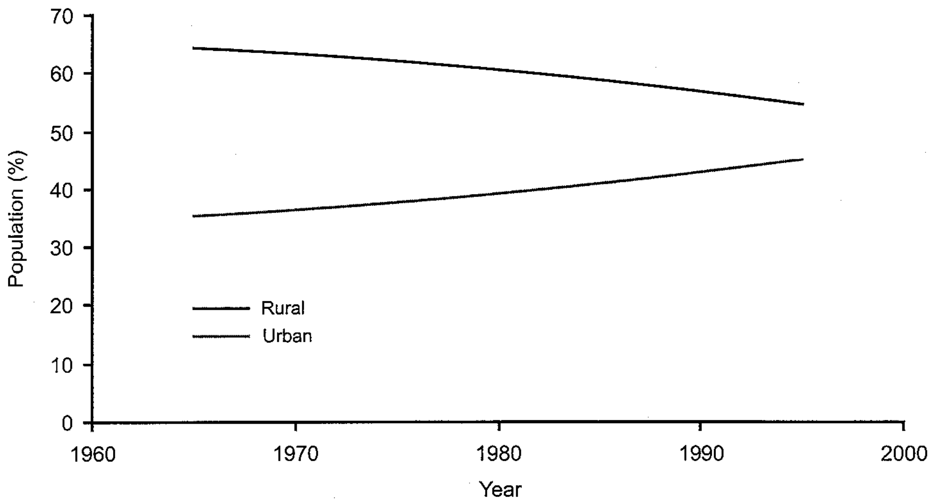


Figure 3. Proportion (%) of world population living in rural and urban environments

Source: FAO 1999

Table 1. Domestic water use and earning capacity (GDP) in various countries compared with 1 ha of irrigated land in a semi-arid country (based on 1991 estimates)

	Developing countries	Egypt	UK	USA	1 ha irrigated land
Domestic water use $year^{-1}$ (m^3)	<100	100	500	2000	15000
Gross domestic product (GDP) (US$)	1500	700	16000	23000	1500–5000

Source: Twomlow and van der Meer (1998)

In fact, as a nation's wealth increases the proportion of animal protein in the diet increases (Figure 4).

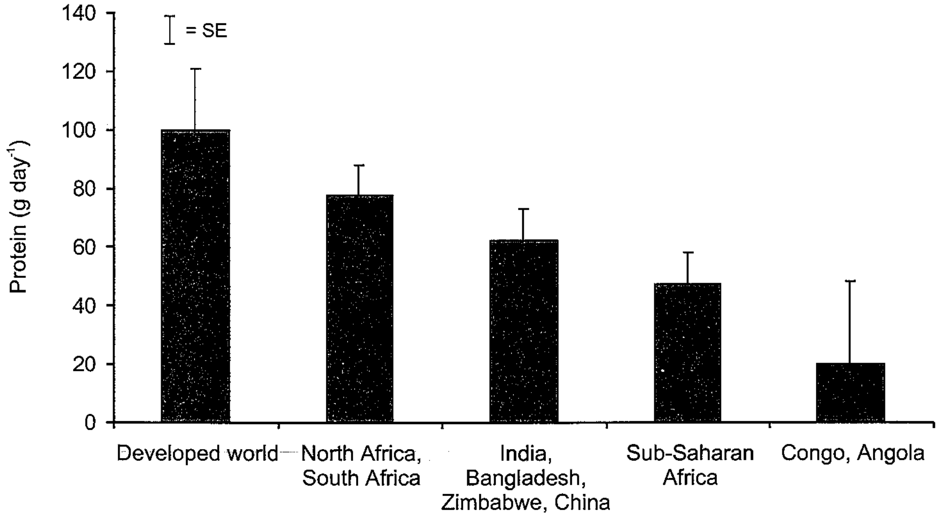


Figure 4. Trends in daily protein consumption (g day^{-1})

Source: FAO 1999

For example:

- China's meat consumption has risen by 10% annually over the past 10 years. This is equivalent to an additional 5 million t of meat each year, which requires an additional 20 million t of feedstuffs [United States Department of Agriculture/Food and Agriculture Situation Reports (USDA/FAS) 1990–97].
- India has doubled milk consumption to 65 million t since 1980, with two-thirds of Hindus indicating that they will eat meat (though not beef) when they can afford to
- Indonesia's chicken flocks were expanding at nearly 20% per annum, as its annual poultry meat production approaches 1 million t (USDA/FAS 1990–96).

Such changes in dietary demands increase the pressures on the world's water resources due to the disparities in the amounts of water required to produce the high-yielding Green Revolution crops and meat (Table 2). Over the last two decades world water demand has tripled.

To address the issues of increasing populations and rising affluence the world needs a Second Green Revolution that will improve the efficient use of finite land and water resources and boost food production by at least 70% over the next 30 years in an environmentally sustainable manner (Waterlow et al. 1998; CBD 2001).

Table 2. Water required to produce 1 kg of food

Food	Water (L kg^{-1})
Potatoes	500
Wheat	900
Alfalfa	900
Sorghum	1110
Maize	1400
Rice	1910
Soya beans	2000
Chicken	3500
Beef	100000

Source: Pearce (1997)

Available resources

Resources available for growing sufficient food are finite, and have never been so stretched, as population pressures increasingly force people to use land of a marginal and fragile nature for both intensive and extensive crop production. The risk of environmental degradation and loss of biodiversity is increasing and crop failures caused by unreliable rains and limited water are becoming the norm, leading to worsening food insecurity (Figure 2). Of the 9 billion ha of land in the world that are available for agricultural use, only 16% of agricultural soils are free from any significant constraints, such as poor drainage, low nutrient status, difficult to work, salinity, alkalinity, or shallowness. Of these favored soils, 60% are in temperate areas, and only 15% lie within the tropics (Wood et al. 2000). The current knowledge of soils in the tropics clearly indicates that there is a considerable diversity among them and that immediate need is to manage this diversity in the context of sustainable agriculture (Box 1). The agricultural land base in Africa is especially poor; most soils require careful management to maintain crop production together with land-improving investment to raise productivity sustainably and low-input use efficiency.

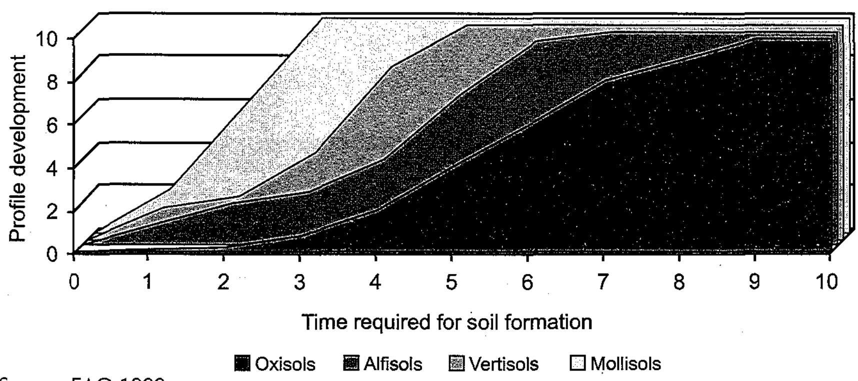
Most of the opportunities for opening new agricultural land to cultivation have already been exploited (Greenland et al. 1998). This is certainly true for the more-densely populated regions of Asia and Europe, where farmers are already using areas to the best of their technical abilities (Fischer and Heilig 1998), without any further genetic improvements on crop yields (Waterlow et al. 1998). However, some large unexploited tracts of land still exist in areas of sub-Saharan Africa (SSA) and South America (Figure 5), but only part of this land could eventually be used for a second agricultural revolution. The largest reserve of potential arable land in the world is the 1700 million ha of acid tropical soils that cover

27% of tropical Africa, 38% of Asia, 51% of tropical America, and 38% of the tropics as a whole. FAO (1996) estimates of land with production potential are strictly technical and do not address or clarify environmental, infrastructural, or institutional limitations. In fact, the use of lands that are marginally suitable for agriculture should, ideally, be removed from production because of their susceptibility to water and wind erosion. The main restriction to the potential production capacity of the remaining land areas is the availability and quality of water (Box 2).

Box 1. Soils and soil formation

Soil covers most of the Earth's surface, in a layer ranging from only a few centimetres to several meters thickness. It is made up of inorganic (rocks and minerals) and organic matter (decaying plants and animals), living plants and animals (including microbial fauna and flora), water and air, that combine to make the edaphic zone of an ecosystem. The soil forms as rocks weather, with air and water collecting between the particles, chemical changes occur enabling plants and animals to colonise the soil. The speed of this process varies with rainfall, temperature and rock types from tens of years in the prairie regions of the world for a few centimeters of soil to develop, to many thousands of years in mountainous regions. Unfortunately, the process of destruction due to misuse or erosion is much quicker, and once destroyed, soil is for all practical purpose lost forever.

Rates of soil formation ('000 years)



Source: FAO 1999

Box 2. Contribution to earth's total (1400 million km^3) water resources (%)

Sea	97.3	Although 70% of the earth is covered by seawater and a further 3% by ice, neither of these is easily transformed into usable water. Less than 1% of the earth's finite water resources is usable for drinking, farming, and industry
Glaciers and polar ice	2.1	
Underground aquifers	0.6	
Lakes and rivers	0.01	
Atmosphere	0.001	
Biosphere	0.0006	

Of all of the earth's water, less than 1% is readily accessible for direct human use and the demands on this resource have grown considerably over the last 50 years (Figure 6). The increase in use of water for irrigation is responsible for a large part of this growth (FAO, 1996), but as incomes rise so does the use per person (Table 1). Although the world's population can count on an annual supply of about 9000 km^3 of fresh water, it is not evenly distributed either spatially or temporally. Hydrologists regard countries where indigenous annual water supplies average less than 1000 m^3 $person^{-1}$ as 'water scarce'. In 1995 an estimated 30% of the world's population lived in countries experiencing moderate to severe water scarcity. This is expected to rise to 65% by 2025 (Table 3). Of the world's available fresh water, agriculture accounts for more than 40% of its total use, and will compete with growing industrial and urban demands over the next century.

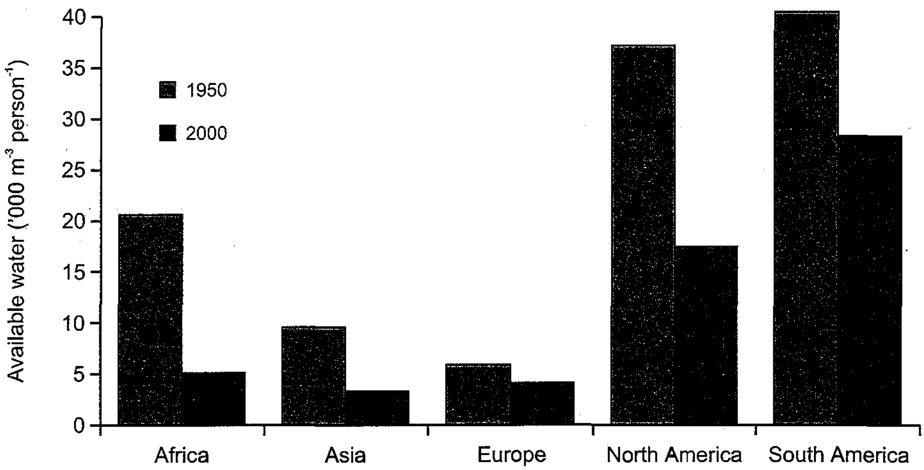


Figure 6. Change in regional water availability per person, 1950–2000

Source: FAO 1999

Table 3. Water-scarce countries between 1955 and 2025 (FAO 1996)

Since 1955	Since 1990	By 2025
Bahrain	Algeria	Comoros
Barbados	Burundi	Egypt
Djibouti	Cape Verde	Ethiopia
Jordan	Israel	Haiti
Kuwait	Kenya	Iran
Malta	Malawi	Libya
Singapore	Qatar	Morocco
	Rwanda	Oman
	Saudi Arabia	South Africa
	Somalia	Syria
	Tunisia	Peru
	United Arab Emirates	Tanzania
	Yemen	Zimbabwe
		Cyprus

The most food-insecure environments in the developing world are in the arid and semi-arid zones (Figure 7), where drought is a major recurring risk, and water scarcity is predicted to increase (Table 3). In the past drought events were considered an unpredictable disruption of normal rainfall patterns. However, recent work in the area of dryland ecology challenges this view and accepts climatic uncertainty as the norm. For example, since Independence in 1980 (excluding the 2001/2 season) Zimbabwean smallholder farmers have suffered at least seven bad drought years that have dramatically reduced livestock numbers in the rural areas (see Figure 8). Such an approach encourages fresh thinking about dryland agroecosystems and the behavior of smallholder farmers. Recent studies conclude that uncertainty is the key constraint to which rural communities must adapt the use of their resources to spread risks. Successful households in these environments are those that are able to diversify economic activities, and exploit different ecological niches and economic opportunities such as new markets and off-farm employment opportunities (Scoones 1994; Mazzucato and Niemeijer 2001).

Other studies have concluded that it is within these same developing regions that 70–75% of the world's agro-biodiversity is to be found (e.g., Templeton and Scherr 1996). Many also argue, some would say justifiably so, that it is in these same regions that much of the crop, plant, and soil diversity is most at risk. However, the question remains, have we been able to evaluate its worth or even sample the existing variability? Or, have we been able to classify and catalog it so that it can be used for commercial product development? From the crop–plant perspective, the Consultative Group on International Agricultural Research

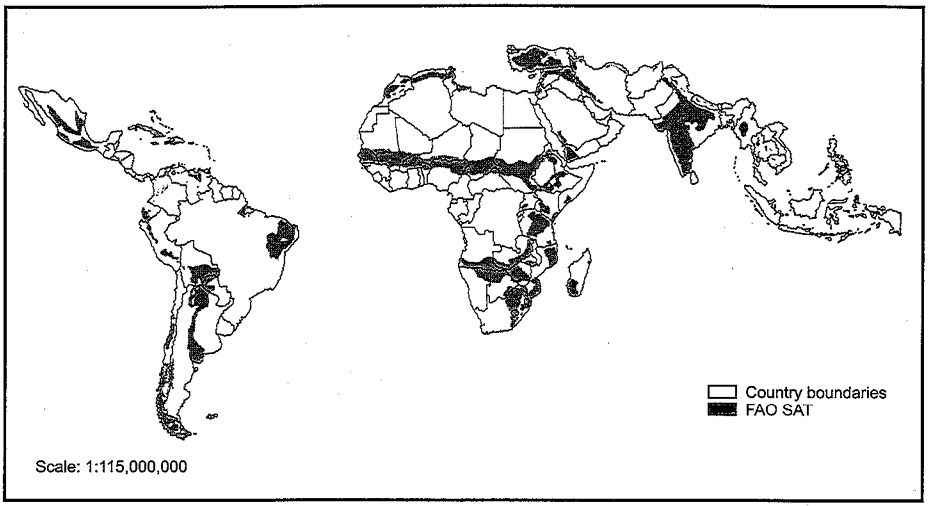


Figure 7. The semi-arid tropics (SAT) of the developing world

Source: FAO 1999, SAT defined as areas with length of growing period (LGP) 75–180 days. All months with monthly mean temperature, corrected to sea level, above 18°C

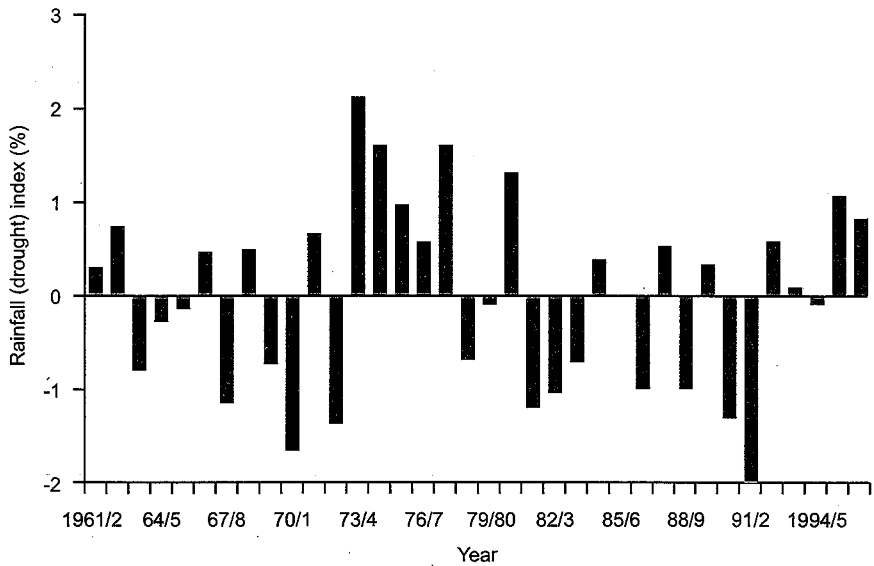


Figure 8. Incidence of drought in southern Zimbabwe over 35 consecutive growing seasons, using the long-term daily rainfall record at Makoholi Experimental Station, Masvingo Province, Zimbabwe (19.5°S;30.5°E, elevation, 1200 m)

(CGIAR) centers have gone some way to conserving a broad spectrum of the world's crop germplasm that falls within their respective crop mandates through germplasm collections, and have, with aid of new biotechnology tools begun to evaluate them (e.g., Monyo et al. 2002). Unfortunately, from a soil biodiversity (Box 3) perspective, there is only a broad understanding of the eco-services provided by soil fauna in terms of nutrient cycling, carbon sequestration and organic matter management (CBD 2001; Ingram and Fernandes 2001; Palm et al. 2001; Swift 2001.), the task of characterization and assessment of the severity of the problem in many regions of the world has only just begun (Swift et al. 2002). Academic debate focusing on a standardization of methods and what is actually meant by soil quality/health, and how this relates to sustainable land use for crop production and ecosystem health is still in progress (Andren et al. 2001; Cannon 2002; Doran 2002; Filip 2002).

Box 3. The soil biodiversity challenge

Soil biodiversity reflects the mix of living organisms in the soil that contribute to a wide range of essential services to the sustainable function of the ecosystem. Soil organisms are the primary driving agents of nutrient cycling, regulating the dynamics of soil organic matter, soil carbon sequestration and greenhouse gas emissions. Modifying soil physical structure and water regimes can have both positive and negative effects on the amount and efficiency of nutrient acquisition by vegetation. For example, overgrazing can compact surface layers, reduce soil water contents and so change the species composition of grassland (Villamil et al. 2001), whilst conservation agriculture can enhance the below-ground diversity of a soil (Saraiva 2002). These services are not only essential for the functioning of the natural ecosystem, but constitute an important resource for management of agricultural ecosystems, yet little is known of the organisms that occur in the soil. The challenges involved in the quantification and manipulation of soil biodiversity are considerable, but characterization and quantification are essential if manipulations are to be managed. The number of species involved, especially of micro-organisms is often very large. The majority of species are poorly defined or not even known, with few if any identification manuals. For example, in 1 m^2 of temperate forest soil more than 1000 species of invertebrates have been identified. The diversity of the microbial component may be even greater. Despite the essential ecosystem services provided by the below-ground biodiversity, it is almost completely ignored in terms of biodiversity conservation and management, even at the inventory level. This is partly due to lack of any agreement on standard methods, although some progress is being made at characterizing the DNA profiles of soils using differential gel electrophoresis techniques (McCaig et al. 1999; 2001; Marsh et al. 2000). Only in the last decade have people become aware of the vast diversity of soil micro-organisms and the associations they have with different plants.

Source: Cannon 2002; Swift 2002

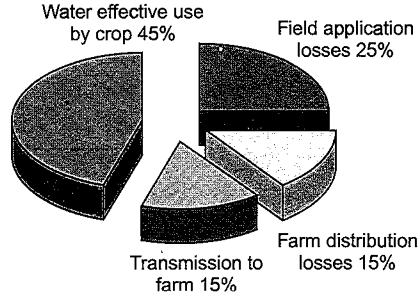
The Green Revolution

Much of the world's increases in food production since the start of the Green Revolution can be attributed to the dramatic yield increases associated with irrigated crops that currently account for more than 30% of the world's total food production from only 16% of the total cropped land area. This phenomenal growth occurred mainly in Asia during the 1960s and 1970s when yields from large formal irrigation schemes increased rice production by more than 250% in Indonesia and tripled rice and quadrupled wheat yields in China. Over the same period, maize yields (mainly of rainfed crops on commercial farms) in Zimbabwe more than doubled, as a result of the best plant breeding program in Africa (Byerlee and Eicher, 1997).

Such intensification in agriculture in both the developed and the developing world, has, however, resulted in a range of environmental issues and concerns. These include poor conservation of irrigation water (Box 4), pollution, damage to wildlife and natural habitats at landscape levels and other issues, both on- and off-farms (De Vries 2002). In the developed world these problems have been largely controlled by scientific investigation and appropriate government legislation. Alas, the same cannot be said for many of the developing nations where water sources have been polluted through the massive use of inorganic fertilizers and pesticides, particularly in many Asian countries that benefited from the technical advances of the Green Revolution. Ecologists argue that the stability of such systems is at risk, as the stability of a productive ecosystem can only be maintained through high biodiversity. However, as outlined by Wood and Lenné (2001), some very productive and naturally occurring ecosystems have a low diversity (e.g., wild rice (*Oryza coarchtata*) in the swamps of Bengal and the grass savannahs of Sudan and Chad where *Sorghum verticilliforum,* the progenitor of cultivated sorghum, is the dominant species. In fact, Wood and Lenné argue that mono-cropping associated with modern intensive agriculture is the net result of humankind's attempt to mimic natural systems. In such systems, crop biodiversity does have a role to play, if scientists ensure that an appropriate range of varieties of a single species are available to farmers so that they can utilize the range of ecological niches within a landscape, and reduce the incidence of pest and disease build up, thus reducing their reliance on pesticides that may harm the natural fauna and flora.

Box 4. The poor performance of irrigation

- Shortage of suitable land for further expansion
- Rising construction costs
- Scarcity of suitable water
- Bureaucratic interference
- Faulty management
- Lack of user participation
- Lack of user training
- Interrupted water supplies
- Poor construction and maintenance
- Up to 60% of water fails to reach crop
- Rising salinity problems



It is questionable, whether the increases attributed to the First Green Revolution observed over the last 30 years or so are sustainable or can be maintained on a world-wide basis (Box 4). The planned levels of production from irrigation schemes have rarely been achieved, and associated environmental (salinization/pollution, silting of reservoirs) and health problems (waterborne diseases) have occurred (Vincent 1996). Yet, many billions of dollars have been invested, under bilateral aid programs, in new projects and or the restoration of old irrigation schemes in countries throughout the developing world. Conservative estimates, based on today's prices suggest an average cost per actual ha irrigated of more than US$ 8000 (Waterlow et al. 1998). In addition to the high transmission losses common to large- and small-scale irrigation schemes, waterlogging and salinization have sapped the productivity of nearly 50% of the world's irrigated land. Unless irrigated fields are properly drained, salts can build up in the soil, making the land infertile. This occurs most frequently when arid or semi-arid areas are irrigated with water of a dubious quality and without appropriate water charges. The most recent estimate of the extent of salinization is between 45 and 80%, of a total of 230 million ha (Ghassemi et al.1995; Oldeman 1994). Effects on crop production vary with the type of crop grown and from year to year. Even when salinity is rated as marginal, its economic effects can be severe, and it is rarely economically viable or technically possible to reverse the situation. Salinity is now estimated to affect 23% of China's irrigated land and 21% of Pakistan's.

If the Second Green Revolution is to address the nutritional requirements of the world's expanding population (Figures 1 and 2), there is need not only to understand the management and technical differences between irrigated and rainfed agriculture, but also the differences between formal and informal irrigation in semi-arid regions (Table 4). With the increasing recognition that many of the formal schemes have frequently failed to meet the needs of the farmer (Box 4), attention as turned to irrigation management and informal small-scale irrigation projects that involve farmers from the scheme's conception and frequently involve the supplemental irrigation of a rainfed crop. In contrast to formal schemes, at the informal level the process of development must be slow and incremental, with low investment sustained over a long period, initiated, organized and controlled by the landholders. This enables the development of suitable infield systems that are within the technical capabilities of smallholder farmers, thus encouraging active farmer participation in the development process, rather than farmers being the object of the development. Such a process allows more sustainable and environmentally friendly technologies to be more readily adopted and adapted (Okali et al. 1994).

Examples of informal irrigation include:

- Community gardens using limited ground and surface water resources in Zimbabwe
- Small basin irrigation in Nigeria
- Water harvesting into tanks for supplemental irrigation of rainfed crops in northern Mexico
- Drip systems for fruit orchards in Yemen.

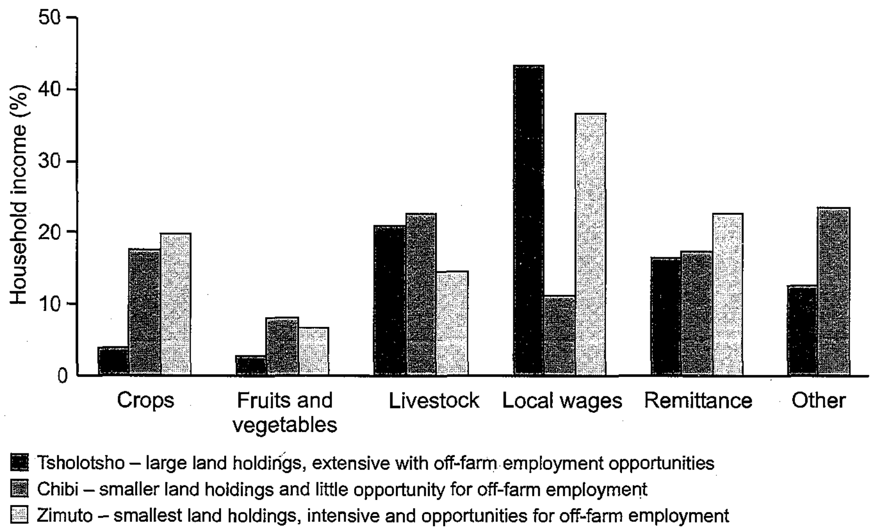
Table 4. Comparison of rainfed and irrigated agriculture in semi-arid regions

	Irrigated		Rainfed	
	Informal	**Formal**	**Traditional**	**Water harvesting**
Cost	Moderate	High	Low	Moderate
Structures	Some	Large	No	Possibly
Management				
Control	Farmer	Scheme	Farmer	Farmer
Technology	Indigenous + New	New	Indigenous	Indigenous + New
Inputs/Outputs	Moderate	Moderate	Moderate	Low
Adoptability	Farmer initiated	Imposed	Accepted	New/accepted
Reliability	Increased	Variable	Poor	Increased
Flexibility	Flexible	Limited	Limited	Good
Crops	Very wide	Wide	Limited	Wide
Crop stress	Some	Absent	Present	Some
Salinity	Some	Present	Absent	Absent
Social				
Land tenure dynamics	Established	Changes	Established	Changes
Market outlets	Yes	Essential	Yes	Yes

Source: Twomlow and van der Meer (1998)

Land use, even intensive, does not necessarily lead to degradation. Proper short-term investments in inputs (water, fertilizer, seeds) and long-term investments in structures and equipment (pumps, tractors, dams, terraces) can conserve soil and water, while allowing productive and sustainable agricultural land use. The same applies to water: its use for growing crops does not have to lead to shortages and pollution. However, if conditions are such that farmers cannot invest in inputs and structures, human activity will continue to degrade natural resources and peoples livelihoods, unless off-farm employment can help provide an income without destroying the natural resource base (see Box 5). Societies and their institutions must continue to invest for the long term in water and land management structures and in education to halt degradation.

Box 5. Income-generating livelihood strategies for three locations in Zimbabwe along the 500–600 mm isohyets



People left behind by the Green Revolution

Unfortunately, over the same time period as the First Green Revolution rainfed production systems, particularly those in semi-arid regions of Africa and South America received little financial investment, even though 84% of the world's arable crop land will still rely on rainfall for the foreseeable future. Consequently, there is an urgent need to focus on the people left behind. These people live in the more marginal areas (low fertility, high risk of crop failure, environmental degradation) and face educational, economic, and consequently technical constraints that need to be overcome to improve their standard of living. The fundamental question that must be asked is, 'How much food can you grow on 1 ha of land in a sustainable manner?' The answer to such a question not only depends upon a range of agro-ecological issues, over which a farmer may have some influence, but also the continuum of prevailing political and economic scenarios that are outside the influence of smallholder farmers (Box 6).

Box 6. How much food can you grow from 1 ha of land?

This depends on:

- Amount of sunshine and the length of the growing season – which may be affected in the longer term by global warming
- Amounts of nutrients available, from the soil and from fertilizers, and the absence of plant poisons like excess salt in the soil
- Amount of water available to the plants, from rain or from irrigation
- Performance characteristics of the crop varieties being grown
- Land tenure situation

These effects on productivity are clearly shown in Figure 9 which compares the three distinct farming systems that were characteristic of Zimbabwe and its successful maize breeding program, across four different agro-ecological (Natural Regions) zones. In Natural Regions IIa and IIb agricultural soils and rainfall are not limiting compared to Regions III and IV where the probability of receiving good rainfall is 50% or less and soils are fragile and often granitic in nature. Large-scale commercial farmers have the economic resources to overcome many of their environmental limitations, are able to purchase agrochemicals, and can afford irrigation, thus ensuring reliable crop yields, often twice those achievable by smallholder farmers with the same natural resource base.

Unhappily, population pressures throughout Africa, and Central and Latin America are forcing people to increasingly crop land of a diverse and fragile nature (Figure 10), where the risk of environmental degradation through the losses of soil and water are high and crop yields are unreliable (Figure 11). The problems that have to be addressed in these regions are largely due to inappropriate production methods and the long neglect of that sector, they include:

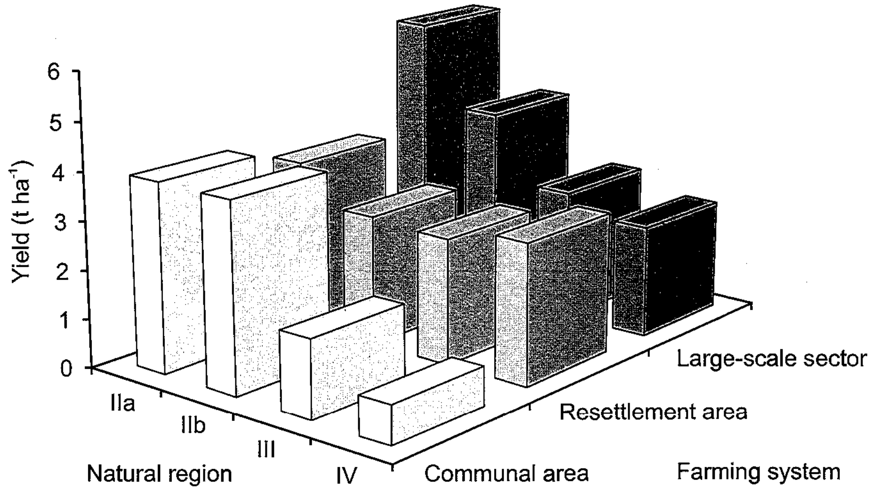


Figure 9. Variations in maize grain yields across natural regions II, III and IV for large-scale commercial, resettlement and communal areas, smallholder farming systems during the 1995/6 growing season in Zimbabwe

Source: Masilela and Mweiner 1997

- Loss of organic matter from the soil
- Inadequate nutrient composition
- Inadequate irrigation (quality and quantity of water)
- Soil erosion

If the effectiveness of crop production in these marginal rainfall regions is to be improved, cultural practices which conserve the fragile soil resource and extend the period of water availability to the crop are essential. Governmental (GOs) and non-governmental organizations (NGOs) have been working towards the development of improved tillage/soil management systems that conserve soil and water resources and improve the productive potential of these areas. Unfortunately, many of these programs concentrated on the development of a technological package through researcher-managed trials, with only limited consideration given to the scant resources and constraints experienced by the smallholder farmers for whom they were intended. To raise living standards any interventions must be coincident with the farmers' aims and objectives.

It is therefore essential that research and development workers understand the resources, constraints and options within which individual farmers operate. This includes identifying who actually grows the crop and who will use the new technological interventions. All too frequently in the past, the research and dissemination process has ignored the role of women, particularly in Africa, where, to be politically correct, they provide up 75% of the person power in agriculture.

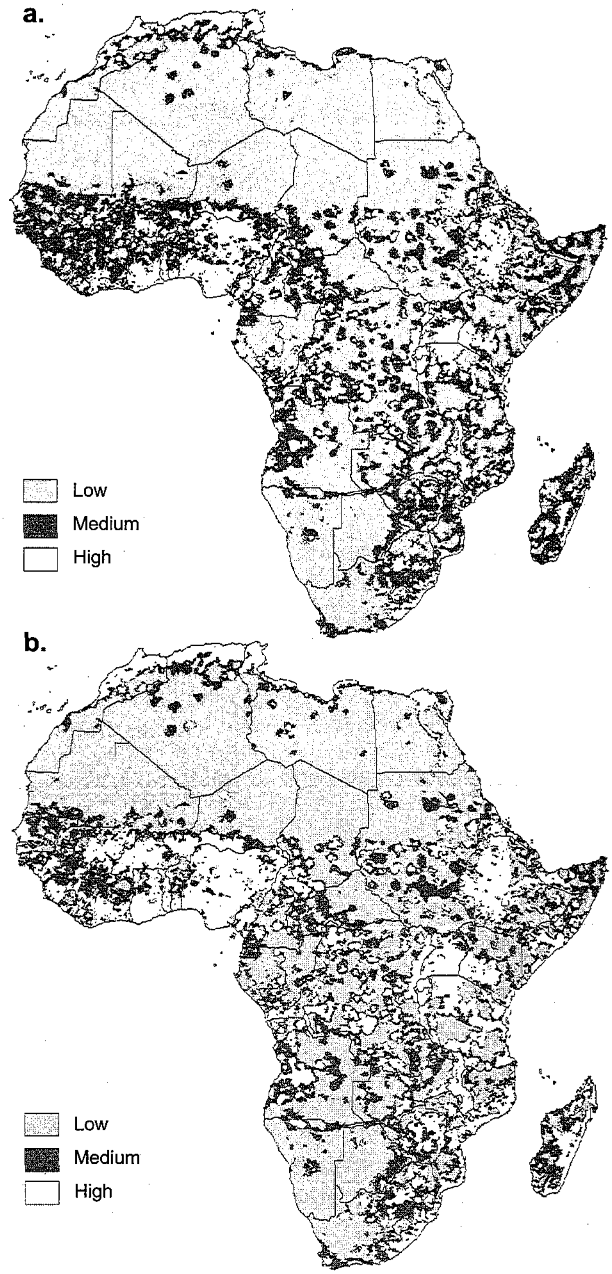


Figure 10. Projected human population changes between a. 2000 (820 million) and b. 2040 (1831 million)

Source: Thornton et al. 2002

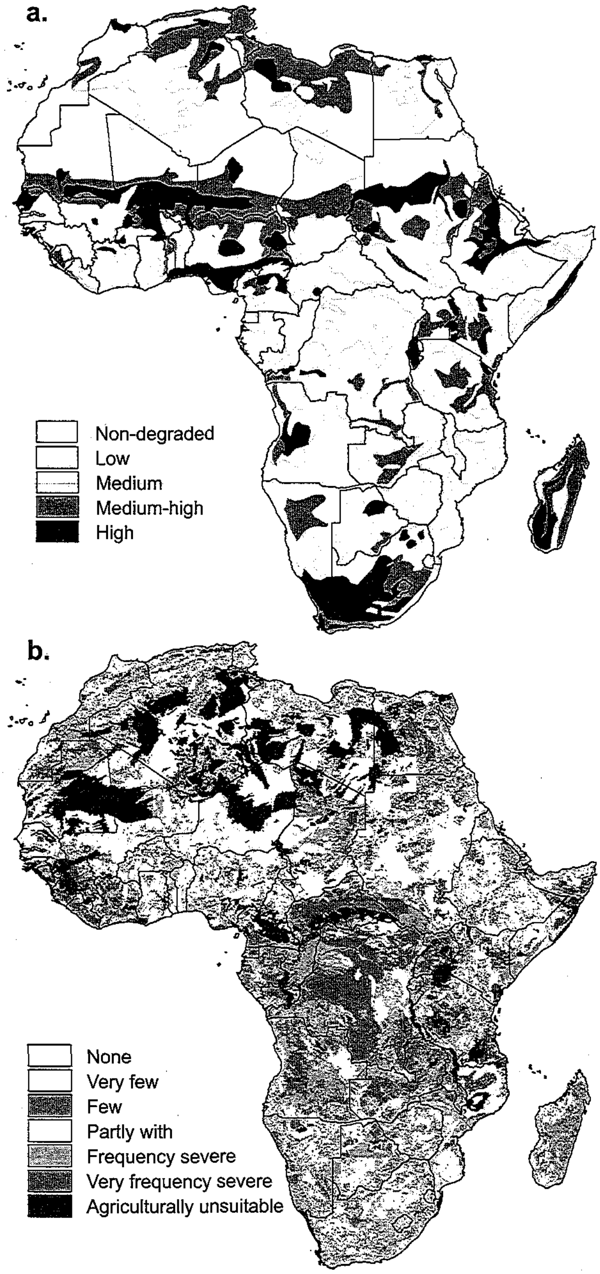
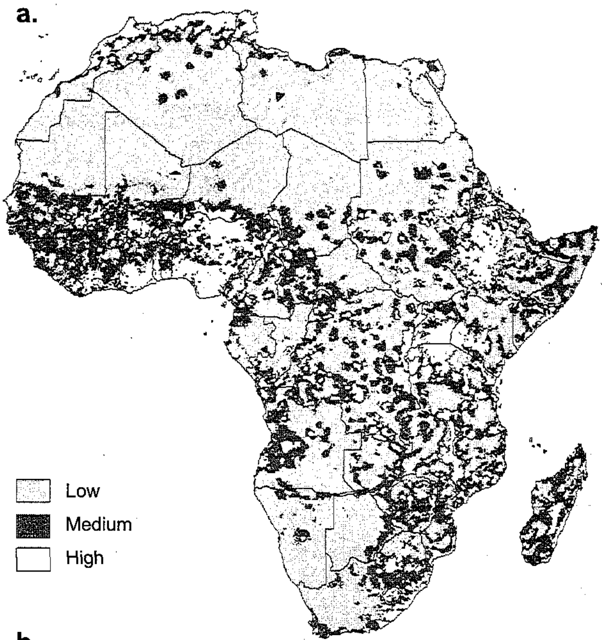
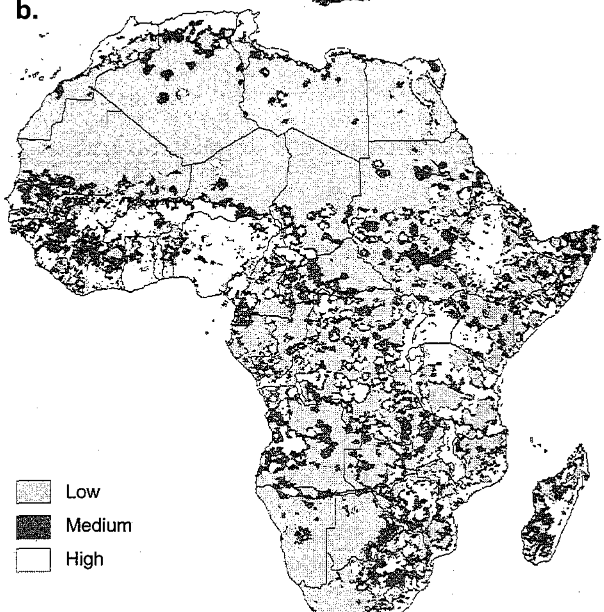


Figure 11. Human-induced a. soil degradation severity, and b. soil fertility constraints

Source: Thornton et al. 2002





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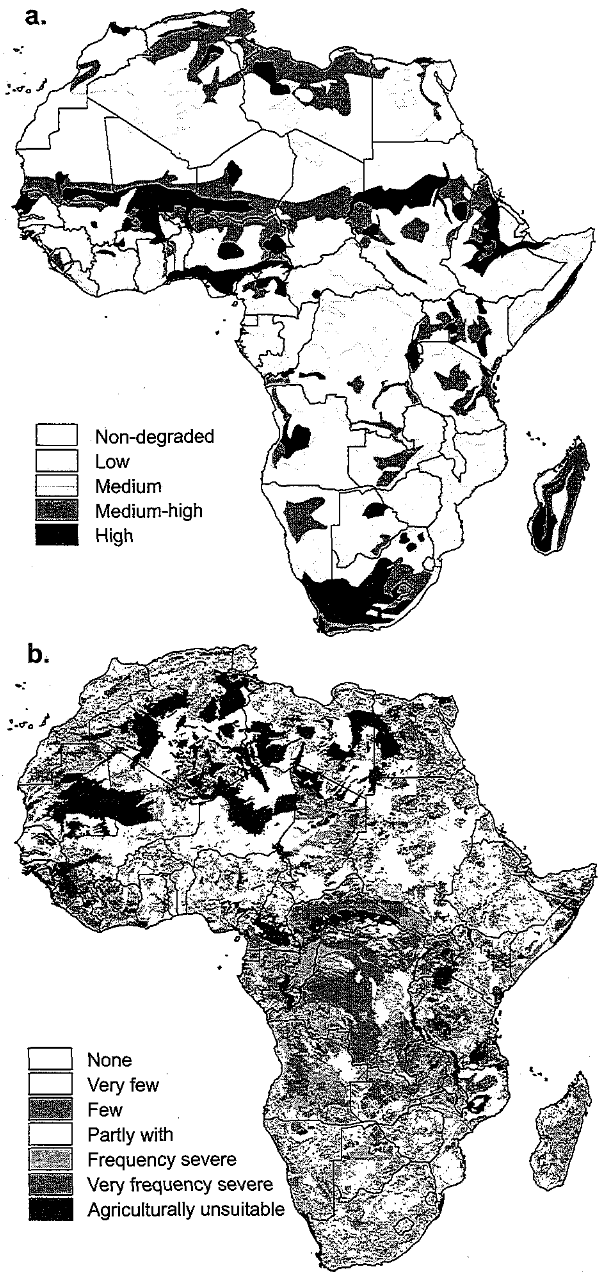

Figure 11. Human-induced a. soil degradation severity, and b. soil fertility constraints

Source: Thornton et al. 2002

The issues facing SSA

The agroecosystems of SSA are diverse and vast with water a transient resource in both space and time that makes drought a recurrent feature of their agricultural landscape (Figure 8). In fact, it is increasingly unusual for drought not to occur somewhere in Africa each year (Sear 1995). Despite this know-ledge, and the dependence of most African economies on rainfed agriculture, the advances in productivity have been patchy and disappointing, given the considerable investment in public sector agricultural research (Anderson 1992; Ryan and Spencer 2001). At the beginning of the independence movement in 1960, Africa was self-sufficient in food and a leading agricultural exporter. In contrast, Asia was the epicenter of the world food crisis. But by the mid-1960s, Asia had launched the Green Revolution, which presently adds 50 million t of grain to the world's food supply each year (Byerlee and Eicher 1997). Over the last 10 years the five African sub-regions have experienced sharply divergent trends in productivity. West and North Africa have seen fairly solid annual growth of about 3–5% within the agricultural sector. Central Africa has seen solid growth in some commodities (cereals 4.0 %, cocoa 2.6%) and a decline or flat output for others (coffee –5.4 %, oil crops 0.8%). This is in sharp contrast to Southern and Eastern Africa where per capita grain yields continue to decline, despite the adoption of new crop varieties (FAO 1999). In the past 20 years Zimbabwe, Kenya, Tanzania, and Malawi have changed from net cereal grain exporters to grain importers. Poverty is worsening in each of these nations' rural areas, compounded by the HIV/AIDS pandemic and economic structural readjustment programs (Devereux and Maxwell 2001).

Many of the agricultural landscape changes taking place in Africa as a whole reflect higher community expectations and opportunity, developed in response to an integration of urban and rural livelihoods, physical (roads) and social (schools) infrastructure development, and general economic growth (Carney and Farrington 1998). These new expectations and opportunities compete for resources available for investment choices at the rural household level (often at the expense of re-investment in the agroecosystems), or encourage over-exploitation of the natural resource base (Barbier 1998; Waterlow et al. 1998).

As a result the agroecosystems of Africa have developed in response to the needs of both rural and urban populations of the region (Barrow 1988; Reij et al. 1996; Barbier 1998). The traditional production systems of the rural households are thought to be generally sustainable under conditions of low population pressure and lack of market integration, with system productivity geared towards subsistence. These systems remain in a sustainable equilibrium until change, such as population growth or external economic pressures, occurs at too fast a rate (Fischer and Heilig 1998). Such increases in internal and external forces can bring about an intensification of agriculture, or an extensification into marginal lands, as is the case in much of SSA. For the latter, the risk of crop failure, environmental degradation and loss of biodiversity increases (Gregory and Ingram 2000) due to inappropriate management practices that mine the soils of nutrients and organic matter. A decrease in land degradation as a result of agricultural intensification has been reported in some instances, such as Machakos in Kenya (Tiffen et al. 1994). However, intensification without additional external inputs generally leads to lower productivity and land degradation, through the combination of nutrient mining and poor soil protection. For example, soil fertility management at the smallholder level in Zimbabwe (Mapfumo and Giller 2001), and much of semi-arid Africa (Reij et al. 1996; Buresh et al. 1997; Bationo et al. 1998; Hillhorst and Muchena 2000), is at a crisis point, as extensification and low-input intensification of agroecosystem productivity takes place at the expense of the common property resource base, which is the source of many of the traditional soil fertility amendments (e.g., leaf litter, or termitaria). On-going ICRISAT survey work is helping understanding of how communities manage soil fertility inputs in relation to the non-contiguous nature of field ownership, particularly as some plots are large distances from the homestead, making their cultivation difficult (see Figure 12). Consequently, as the distance from the homestead increases, the levels of management and intensification decrease accordingly. Gradients in soil fertility being the norm rather than the exception as the distance from the homestead increases in the majority of smallholder farming systems in SSA (Tilahun Amede, personal communication; Ndjenga and Sibiry, personal communication; Twomlow and Ncube 2001).

Marginal lands once used for grazing are being cultivated, remaining grazing areas and woodlands are over-exploited, and this results in the degradation of the natural resource base (Lal 1998). At the plot/field level this degradation results in overall reduction of system productivity, due to three principal soil degradation processes, physical, chemical, and biological, that can lead to desertification (Box 7). Although most rural households are conscious of the quality and limitations of their natural resource base, household subsistence needs and the lack of rural markets are the major obstacles to the uptake of technological interventions (Dixon et al. 1989; Sanders et al. 1996; Barbier 1998; Scoones and Toulmin 1999; Ryan and Spencer 2001). As Lal (1987) points out, 'Subsistence farmers, who face famine, would consider a successful technology to be one that produces some yield in the worst year rather than one that produces high yields in the best.'

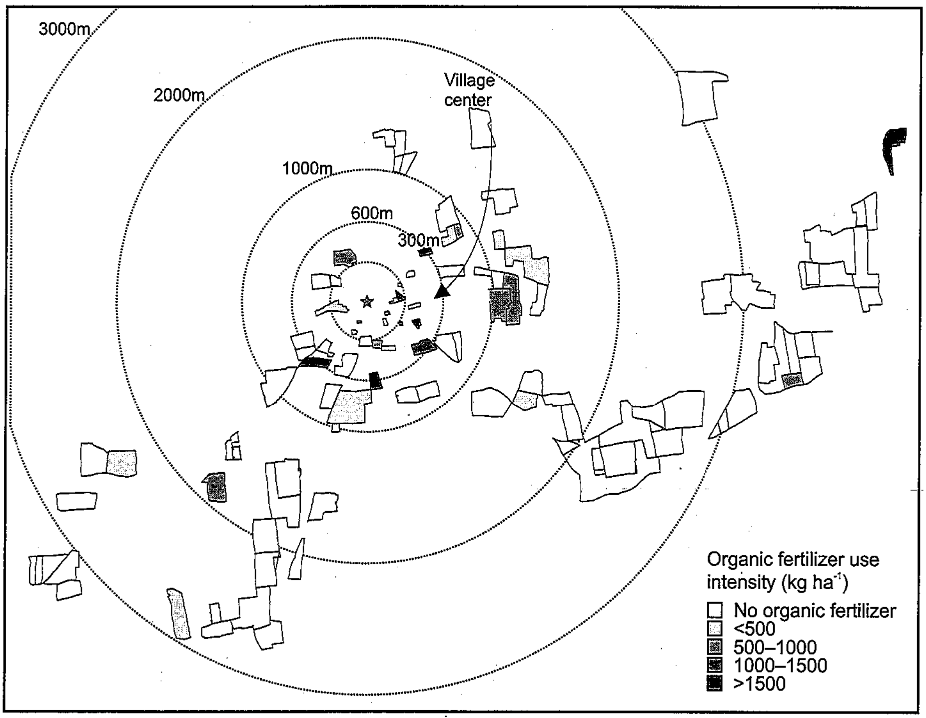

Figure 12. Soil fertility management practices Tafalan Were, Mali

Source: Sibiry and Ndjenga, personal communication

Box 7. Desertification

The United Nations Convention to Combat Desertification (UNCCD) recognizes desertification as land degradation occurring in the arid, semi-arid and dry sub-humid areas of the globe, and land degradation as a loss of both economic and environmental potential. In addition to food productivity losses and increasing poverty, dryland degradation results in significant reductions in carbon storage in soils, contributing to global warming. It also causes losses of biodiversity, including both flora and fauna, affecting the potential for full utilization of crop, livestock, and tree genetic resources in agriculture. Desertification also triggers soil erosion because of the loss of vegetative groundcover exacerbating water erosion and flash floods. These accelerate siltation of rivers and lakes and pollute water reserves.

To date, agricultural research has been successful in boosting productivity and has gone some way to alleviating poverty. However, it is now recognized, on the broader agroecosystems scale that many development projects have failed because they focused on a particular natural resource sector (crops, forestry, livestock, water etc.), while neglecting other users that also compete for the natural resources to achieve their livelihood strategies (Blench 1998; Critchley and Reij 1996). Ian Johnson, Chairman, CGIAR, has observed that such mismanagement has been termed the 'Achilles heel' of long-term sustainable development (CGIAR 2000). The major lesson learned is that the lack of participation by the direct and indirect beneficiaries at the project design stage contributes to project failure. Suggesting that the researcher, and the extension and development communities be aware of inter-sectoral linkages is nothing new. What has been missing is an effective framework that allows research to better accommodate this broader range of factors and players and to be aware of the nature, causes, and potential results of conflicts and constraints within agroecosystems.

The framework currently being discussed by the CGIAR is integrated natural resource management (INRM), a conscious process of incorporating multiple aspects of natural resource use into a system of sustainable management to meet explicit production goals of farmers and other uses (e.g., profitability, risk reduction) as well as the goals of the wider community (sustainability) (CGIAR 2000). Given this definition, and considering elements of the sustainable livelihoods approach, the issue of 'scale' becomes a critical element in the success of development projects.

Issues of scale

As the scale of interest changes, the nature of biophysical and socioeconomic determinants of a system's productivity also change; since a phenomenon at a plot scale may be less important at the farm, community, or regional scale and vice versa. Consequently, spatially robust INRM approaches and methods need to be developed and applied at varying levels of scale that will contribute to the globally significant issues of poverty alleviation, environmental degradation (biodiversity, desertification, etc.), and climate change (Bennet 2000; Gregory and Ingram 2000; Scoones and Toulmin 1999; Lovell et al. 2002). Table 5 summarizes the biophysical and institutional boundaries that might be considered when addressing issues of scale. Boundaries are central to INRM because they specify the area over which jurisdictions apply, as well as the roles to which particular actors are assigned (Murphree 2000). Specifying jurisdictional zones is, nevertheless, easier said than done, not least because administrative bound-

Table 5. **Hierarchical levels of observation to address issues of scale from ecological and social perspectives**

Ecological boundaries	Social boundaries
Ecozone: Based on broad-scale physiography and vegetation, controlled by climate, e.g., dry savannah **Ecoregion:** Subdivision of ecozone regional climate, surface topography, vegetation, e.g., commercial versus subsistence farming **Ecodistrict:** Land resource area parent material, surface topography, e.g., major drainage basin	**Regional and national** Community and ethnic grouping
Soil landscapes: Dominant landscape component, e.g., major soil unit that influences land use – catenas	**Communities** Villages and chieftainships
Farm unit (ecosite): e.g., cropping system or grazing, gradients in soil fertility **Plot/Quadrat (ecoelement):** e.g., comparisons of change within and between farms **Microsite:** Characterization of soil biophysical attributes	**Private and communally held property**

aries, infrastructural links, ethnic groups, community limits, and informal networks seldom correspond with physical resource boundaries, to the extent that these can be agreed upon. To complicate matters further, INRM involves the integrated management of a multitude of such common-property, open-access, and privately owned resources as cropland, pastures, forests, and water. Each has an associated complex of often-conflicting interests held by stakeholders both inside and outside the particular resource boundary (Nemarundwe 2001).

If the CGIAR system-wide aim of improving INRM is to contribute more broadly to sustainable rural livelihoods, there are various pathways that can be followed.

The sustainable rural livelihoods framework (Carney and Farrington 1998) seeks to improve the lives of poor people and to strengthen the sustainability of their livelihoods. It aims to help people understand and manage the complexity of rural livelihoods through holistic analysis of the five different types of capital asset (natural, manufactured, human, social, and financial), upon which individuals and groups draw to support themselves (Figure 13). INRM is thus being promoted on a very wide range of scales. In all cases, it seeks to address whole agroecosystems, which, by nature, are complex. Thus, many interactions have to be addressed (Sayer and Campbell 2002). These include: direct interventions to improve the status of the natural resource base, strengthening

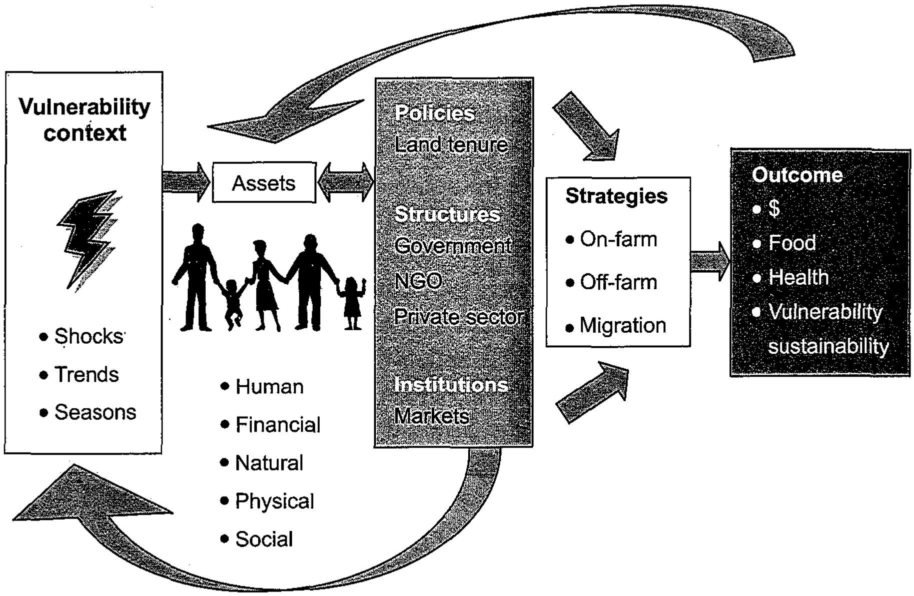

Figure 13. The sustainable livelihoods approach

Source: Tanner, personal communication

farmer knowledge and skills, improving organizational linkages that promote better learning and sharing of ideas between the R&D community and the end-user/beneficiaries, support to micro-finance and formal credit schemes, and improving access to input and output markets. Given the multidisciplinary and complexity of such an initiative, it will be necessary to pursue a strategy at a macro-level aimed at supporting the evolution of policies that bring greater benefits to the rural communities, i.e., the custodians of the natural resource base, while at the same time providing support to networking between various organizations working on INRM issues at a micro-level. For an INRM approach to work it should have an in-built flexibility that gives due cognizance to the needs and aspirations of the rural community. Such an approach means that technologies/interventions should not be imposed on the households, but they should be exposed to a basket of options, and be allowed to develop and modify as they wish.

Despite these issues, increased food production has a vital role to play in enhancing food security, peace, democracy and natural resource management, including biodiversity, in the developing nations of the world in the 21st century (Waterlow et al. 1998). Unfortunately there are five competing schools of thought on agricultural development for food security and ecosystem health (Devereux and Maxwell 2001) that currently influence and confound the development debate:

- **Environmental pessimists:** Follow a neo-Malthusian argument that many agro-ecological systems have been too thoroughly degraded to recover and population growth is exceeding the rate of technology development
- **Business as usual optimists:** Hold a belief in the markets and that supply will always meet increasing demand, i.e., biotechnology and expansion of cultivated area will be able to meet the demand
- **Industrialized world to the rescue:** The looming food gap will be met by modernized agriculture based in the North at the expense of smaller-scale and more marginal farmers in the South who will be forced out of business
- **New modernists:** Believe in growth through high external-input farming, either on existing Green Revolution lands or 'high potential' areas missed by the past 30 years of agricultural development. Increase the use of agro-chemicals and high-yielding hybrids and reduce reliance on local resources whose exploitation contributes to the degradation of the ecosystem
- **Sustainable intensification:** Low-input farming can be highly productive provided the farmers participate fully at all stages of the technology development and extension process.

Which school of thought fits with your assessment of the situation?

Conclusions

Sustainable management of agroecosystems is as much a function of human capacity and ingenuity as it is of biological and physical processes. Yet, many of the recommendations and conventions currently being debated, with a view to their implementation in the developing world, assume infrastructures and critical mass of skilled technocrats that will be able to monitor and address many of the emerging environmental concerns. Unfortunately, this is not the case in many countries. In a recent study of soil research capabilities in SSA Vlek (1995) concluded by saying: 'Claiming that a rich research database on soils does exist in Africa borders on recklessness, as it accepts a situation that would be considered utterly unacceptable in the scientific community in the West, if it were asked to deal with the array of problems such as those prevailing in SSA.'

To date a great deal of the work in agricultural development in Africa and much of Asia as focused at the plot and farm level, and it now needs to be extrapolated to broader regions and more sites in an attempt to answer one key research question: **'Under what conditions will rural households be encouraged to reinvest in their agroecosystems?'** However, to answer this key question the following issues may have to be addressed in part or as a whole:

- **Why is change not occurring?**
- **Why are yields declining?**
- **Where is growth going to occur over next 10–20 years?**
- **Does INRM have a role to play?**
- **Can Africa afford the luxury of sustainability and biodiversity in the short term?**
- **What is the short term?**

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Genetic diversity, arthropod response, and pest management

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Introduction

The ultimate goal of pest management is to increase productivity, maintain ecological integrity, and conserve the environment. Sustainable yield in agroecosystems in the semi-arid tropics (SAT) is derived from proper nutrient management, efficient use of soil moisture, and ecological balance of the fauna and flora. The loss of yield due to insect pests, despite heavy pesticide use, is because of the cultivation of homogeneous monocultures, which do not possess the necessary ecological defense mechanisms to tolerate or contain pest populations. Many of the agronomic practices followed for raising crops also have an adverse effect on the activity and/abundance of natural enemies of pests. Mono-cultures do not have the necessary environmental resources and opportunities to be able to suppress pest damage effectively (Altieri 1994). Modern agriculture has led to the development of crop cultivars that produce high yields, but lack the ability to resist pest attack, and the integrated pest management (IPM) approaches have not addressed the environmental problems of modern agriculture. Much emphasis has been placed on identifying alternatives to the synthetic chemicals, which are blamed for most of the problems associated with conventional agriculture. There is a growing tendency to use microbial pesticides, natural plant products, or natural enemies as substitutes for agrochemicals. The instability of the agroecosystems that can be linked to the expansion of monocultures needs to be repaired by restoring the elements of ecological homeostasis through the augmentation or enhancement of biodiversity.

Genetic diversity and crop production

Traditional cropping systems (mixed or intercrops) have given way to monocultures in many parts of the world, resulting in frequent outbreaks of insect pests and diseases. To illustrate this scenario, the example of the cotton (*Gossypium hirsutum*) crop, which is a major crop in many parts of the world can be used. Cotton is subject to the depredations of a large number of insects and diseases. The need to realize the highest crop productivity per unit of time, and farm

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mechanization have led to the adoption of modern farming technologies that rely heavily on irrigation, high-yielding (but insect-susceptible) varieties fertilizers, and pesticides. As a result, the diverse and sustainable production systems of the past have given way to the highly productive monoculture systems of today. Elimination of alternate hosts has led to decreased predator and parasite populations and an increase in insect abundance (Southwood 1975). Large-scale monoculture of cotton has resulted in heavy outbreaks of pests and diseases, particularly the bollworm (*Helicoverpa* spp.) complex and the whitefly (*Bensia tabaci*). As a result, farmers resort to indiscriminate application of pesticides. Apart from causing a temporary reduction in yield losses, pesticide application has adverse effects on the environment, and finally the farmers find it difficult to grow the crop, from which they intended to make a fortune. As a result of failure to minimize insect pest losses cultivation of cotton had to be abandoned in Peru (Doutt and Smith 1971), and in some parts of India and Australia. As a consequence of the failure of control operations and increasing pesticide application costs, there is a renewed interest in traditional mixed and intercropping systems to minimize pest-associated losses, and reduce over-dependence on pesticides for sustainable crop production. Some of these agricultural practices have been developed over centuries of experience and have stood the test of time (Zadoks 1993). However, in most cases economic returns take precedence over ecological sustainability in keeping pace with rising populations and meeting the ever-increasing demands for food, fiber, and shelter.

Inter- and mixed-cropping systems are prevalent in many parts of the world, and therefore, it is important to understand arthropod responses to improve pest management in these systems. Arthropod responses to crop hosts are quite complex. A two-crop mixture with 6 herbivores and 6 natural enemies can lead to 364 ecological interactions, and possibly an equal number of evolutionary responses (Andow 1991). Therefore, taxonomically diverse plant communities would suffer less herbivore attack than single-species plant stands (Tahvanainen and Root 1972). Arthropod responses to plant diversity have provided the most supporting evidence for this hypothesis (Goodman 1975). It is believed that monocultures are most likely to lead to pest outbreaks. However, if this were true, then time-averaged density of arthropod herbivores would be much greater in monocultures than in polycultures (Pimental 1961). Also, if the magnitude of population fluctuations is similar in monocultures and ploycultures, then the chances of outbreaks would be greater in monocultures than in polycultures. However, the interactions between herbivore arthropods and their crops hosts are quite complex and the outcome depends on a number of biotic and abiotic factors (Altieri et al. 1978; Lenné and Wood 1999).

Genetic diversity and pest management

Diversified cropping systems such as those based on inter-, mixed cropping or agroforestry are stable and conserve natural resources. Crop diversity not only helps in regulating the abundance of anthropod herbivores, but also increases the efficacy of natural enemies. It is presumed that greater biological diversity of a community leads to greater stability of the community (Pimental 1961). However, such a contention has not been supported by empirical data (van Emden and Williams 1974). The goal of pest control is not based on stabilizing the pest populations, but on limiting them. Therefore, if large population densities of a pest could be tolerated, then our aim should be to reduce the magnitude of fluctuations in such populations. However, large pest populations are not often tolerated, and the goal of pest control is always to reduce the pest population to below economic injury levels (Stern et al. 1959; van Emden and Williams 1974; Sharma and Ortiz 2002). Insect population dynamics is greatly influenced by the vegetational diversity in an ecosystem. Generally, insect pest density is not reduced to the same degree in all polyculture systems (Risch et al. 1983). Polyphagous pests exhibit varying levels of activity on different plants in an assemblage. The type of vegetation in a field also affects the activities of the natural enemies of insect pests. Genetic diversity in agroecosystems can be used to minimize pest-associated losses manipulated by increasing species diversity through i) growing polycultures (mixed or intercropping), ii) using trap crops, iii) adopting a push–pull strategy, iv) eliminating non-crop weed hosts, and v) using multi-lines and synthetics.

Polycultures

Polyculture is one way of increasing genetic diversity. Plant diversity influences the relative abundance of herbivore arthropods and their natural enemies. The long-term association between plants, arthropods, and the natural enemies has led to complex interactions amongst them. Plant diversity may involve two or more crops called mixed or intercrops, or a crop and weeds. In some cases, different varieties of the same crop flowering at different times can also be planted as mixed crops (e.g., mixed planting of early- and late-flowering pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) in West Africa). Agronomically similar genotypes, but with different genes for insect or disease resistance, can also be planted as multi-lines or synthetics. The spatial arrangement of plants can vary widely from intimate mixtures to varying proportions of different crops, depending on crop maturity and height. Such cropping systems are widely practiced in Asia. It can also involve temporal overlap that varies in extent from none (as in case of crop rotations), to relay cropping (some overlap), or intercropping (complete overlap). The variation in species diversity over space and time can be exploited to minimize losses due to insect pests, to encourage the activity of natural enemies, and to increase the productivity potential of land per unit of time. Polycultures are ecologically complex because of their influence on insect pests and their natural enemies (van Emden 1965). The total crop yield in polycultures is greater when estimated as a land equivalent ratio (LER). However, the role of polycultures or plant diversity should be carefully assessed for its effects on insect damage, and the activity and abundance of natural enemies. Also, the effects of plant diversity on pest damage can change over time and locations, depending on the herbivore diversity, and interactions among the harmful and beneficial insects. Population densities of insect pests are frequently lower in polycultures (Risch et al. 1983) because of associated resistance or resource concentration (Root 1973), and the action of natural enemies (Russell 1989). Specialist insects are generally less abundant in diverse habitats because of the low concentrations of their food in the habitat and the increased activity of natural enemies. Diverse plant communities also act as a source of alternative prey, nectar, pollen, and breeding sites for natural enemies.

Genetic diversity and reduction of pest damage

Plants in polycultures are likely to have fewer individuals of a species, i.e., a lower herbivore load feeding on them than in monocultures (Andow 1991). Based on published information, yield loss was lower in polycultures than in monocultures in 14 cases out of 20 (the herbivore density being lower in polycultures than in monocultures) (Andow 1991). However in some cases, the yield loss was greater in polycultures than in monocultures. Reduction in insect damage in intercrops is one of the factors contributing to increased productivity in intercropping systems (Amoako-Atta et al. 1983).

A carefully selected cropping system (intercropping or mixed cropping) can help reduce pest incidence, and/or, minimize the risks involved in monocultures. Different degrees of insect injury occur when a host plant is raised with different companion plants. A reduction in pest numbers and increase in predators has been observed when black gram (*Vigna mungo*) is intercropped with sorghum or pigeonpea (*Cajanus cajan*) (Sharma et al. 2000). Relay intercrops of rape (*Brassica juncea*), wheat (*Triticum aestivim*), and sorghum in cotton resulted in lower aphid abundance, and greater activity of the aphid predators than in monocultured cotton (Parajulee et al. 1997). Sorghum shoot fly *(Atherigona soccata)* and sorghum midge (*Stenodiplosis sorghicola)* damage is reduced when sorghum is intercropped with leguminous crops (Hardas et al. 1980). Intercropping sorghum with cowpea (*Vigna unguiculata*) or lablab beans (*Lablab purpureus*) reduced the stem borer, *Chilo* *partellus* incidence by 50%, and increased the grain yield by 10–12% over that of sole-cropped sorghum (Mahadevan and Chelliah 1986). Intercropping chickpea (*Cicer arietinum*) with mustard (*Brassica compestris*) or safflower (*Carthamus tinctorius*) (Das 1998), pigeonpea with cowpea (Hegde and Lingappa 1996) and sorghum (Mohammad and Rao 1998), and tomato (*Lycopersicon esculentum*) with radish (*Raphanus sativus*) (Patil et al. 1997) results in reduced damage by cotton bollworm/legume pod borer, *Helicoverpa armigera*. Intercropping clover (*Trifolium alexandricum*) deters the cabbage (*Brassica olearacea* var. *capitata*) root fly (Finch and Edmonds 1994). Carrot (*Dacus carota*) intercropped with lucerne (*Medicago sativa*) has also been shown to suffer less damage by carrot rust fly, *Psila rosae* (Ramert 1993). The rust fly populations were greater in monocultures when the plots were placed next to each other or surrounded with a non-host, but there were no differences when the plots were surrounded by bare soil (Ramert and Ekbom 1996). *Diaphania hyalinata* population density is lower in polyculture (maize–cowpea–squash) than in monoculture (squash, *Cucurbita maxima* alone) (Letourneau 1986). Intercropping beans (*Vigna aconitifolia*) in collards (*Brassica oleracea* var. *sabellica*) decreased flea beetle densities on the collards and minimized leaf damage (Altieri et al. 1977).

Genetic diversity and increase in pest damage

Genetic diversity does not always result in reduced pest populations. It appears to be insect-pest and site-specific, as well as being affected by other biotic and abiotic factors. Even though individual species are likely to be less abundant in polycultures, it is likely that more herbivore species may feed on a crop in polycultures than in monocultures. The effect of entire herbivore fauna on crop plants in polycultures and monocultures can be measured by removing the herbivores from both the systems by using insecticides. Comparing plant damage and yield loss in both the systems can determine the effect of genetic diversity on insect abundance, yield loss, and sustainability of crop production. Oligophagous insects that are closely associated with their host plants, may not be affected by the presence of non-host plants during the process of host finding (Lambert et al. 1987), while intercropping may provide alternative food sources and shelter for polyphagous insects. Thus, generalizations about the reduction of herbivore densities in diversified crops are not warranted (Kareiva 1987). There are several examples indicating that crop diversification has no effect on insect damage, and that it at times results in increased pest densities. Thonhasca and Byrne (1994) suggested a meta-analysis approach to analyzing crop diversification experiments. In this approach, similar studies could be combined through an index that would measure the degree of effect of interest (Glass 1976). One of these indices, 'the effect size' (Cohen 1977) has been used widely in meta-analysis (Gurevitch et al. 1992). Meta-analysis has shown that crop diversification has a moderate effect on herbivore abundance. However, despite their statistical significance, such effects are not impressive, particularly when the annual replications are removed.

Sigsgaard and Ersboll (1999) observed that intercropping pigeonpea with cowpea results in greater *H. armigera* infestation in pigeonpea. Maize–cowpea intercrops do not affect the oviposition behavior of the spotted stem borer, *Chilo partellus* infesting maize (*Zea mays*). However, increased levels of parasitism have been observed in the intercrop (Pats et al. 1987). The intensity of *Trachylepida* sp. attack on *Cassia fistula* seeds was lower in isolated plants than on those in mixed stands, indicating that diversity does not always result in a reduction in pest attack. Intercropping cotton with green gram provided favorable conditions for increase in pest numbers (Sharma et al. 2000). The leek moth (*Acrolepiosis assectella*) – a monophagous pest, laid the same number of eggs on monocultured leeks (*Allium porri*) as on those intercropped with high and low densities of clover (Asman et al. 2001). The leek retains its attractive power in association with small quantities of cabbage or tomato, but loses its attractiveness in the presence of larger quantities of tomato and cabbage (Lecomte et al. 1987). Alfalfa (*Medicago sativa*) forage grass mixtures may reduce potato (*Solanum tuberosum*) leafhopper damage to alfalfa by emigration, and reduce subsequent hopper burn. However, increased activity of *Empoasca* sp. had been observed in the presence of preferred hosts as the densities of non-preferred hosts increased (Smith et al. 1992).

Trap crops

Trap crops attract insect pests and other organisms so that pest incidence on the target crop is minimized. Reduction in pest damage is achieved either by preventing the pests from infesting the target crop or by concentrating them in a certain part of the field where they can be easily destroyed (Hokkanen 1991). Success in developing effective protocols for trap crops depends on the differences in relative preference for the trap crop by the target pest, as well as the proportion of the area sown to the trap crop. However, the choice of the trap crop will depend on the region, the crop to be protected, and the effectiveness of the system. The principle is similar to associated resistance, in which the insect pests show a distinct preference for certain plant species, cultivars, or a crop stage. Crop stands can be manipulated in time and space so that attractive host plants are offered to the insect pests at a critical stage of insect development. The insects concentrate at the desired site on the trap crop, and as a result, the main crop need no be treated with insecticides and thus, natural control of insect pests remains operational in most of the field.

Trap cropping is particularly important in subsistence farming in the developing countries, and its application in cotton and soybean (*Glycine max*) has been very successful (Newsom et al. 1980). In cotton/sesame intercrops, row strips of sesame (*Sesamum indicum*) (constituting 5% of the total area) can be used as a trap crop to attract *Heliothis* spp. away from the main crop of cotton. Sesame, which is highly attractive to *Heliothis* species (from the seedling stage to senescence), attracts large numbers of insects away from the cotton. It also attracts the parasitoid *Cardiochiles sonorensis*, which parasitizes large numbers of *Heliothis* larvae (Pair et al. 1982). Sunflower (*Helianthus annus*), marigold (*Tagetes* spp.), sesame, and carrot have all been used as trap crops for *H. armigera* control (Sharma 2001). A wild relative of potato, *Solanum viarum* has also been suggested as a trap crop for *H. armigera in tomato* (Talekar et al. 1999). Trap crops such as yellow flower sweet clover (*Melilotus officinalis)*, common vetch (*Vicia sativa*), red clover (*Trifolium pratense*), lucerne (*Medicago sativa*), and mugwort (*Artemisia vulgaris*) have been found to be more attractive to *Lygus* spp. than lettuce (*Lactua sativa* var. *capitata*) (Ramert et al. 2001). Interplanting cotton with alfalfa as a trap crop has been found to be effective against *Lygus hespersus* (Godfrey and Leigh 1994). However, the effectiveness of the trap crop depends on the degree to which *L. hespersus* is attracted to alfalfa relative to cotton (Sevacherian and Stern 1975). Mowing could also enhance the effectiveness of the trap crop by stimulating its re-growth (Godfrey and Leigh 1994, Mensah and Khan 1997).

The use of trap crops, especially in strip-cropping systems varies effectiveness across crops and cropping systems (Hokkanen (1991). Trap crops and diversionary hosts have been widely used in the past to reduce damage caused by *H. armigera*, but have seldom been successful (Fitt 1989). Although infestation of cotton by *H. armigera* has been reduced by late-sown maize and sorghum (Nyambo 1988), their comparatively short attractive periods, and the potential of earlier-sown crops to increase pest populations are the major disadvantages. In strawberries (*Fragaria* spp.), the use of German chamemile, *Matricaria reculita* as a trap crop did not reduce pest populations of *L. rugulipennis* (Easterbrook and Tooley 1999). At times, the high reproductive rate of the insect on the trap crop might mitigate the effectiveness of this technique. Therefore, it may be necessary to control the target pest on the trap crop through chemical pesticides or other means.

Push–pull strategy

A push–pull strategy was developed to control *Heliothis* spp. on cotton by the combined effect of an attractant crop and a feeding deterrent (Pyke et al. 1987). Later, the system was used to protect onions (*Allium cepa*) from onion fly, and described as stimulo-deterrent diversion (Miller and Cowles 1990). A push–pull strategy to manage cereal stem borers in maize-based farming systems has been developed in Africa (Khan et al. 2000; 2001; van den Berg et al. 2001). It involves both a trap crop and a repellent crop, enabling stem borers to be simultaneously repelled from maize plants, and attracted to the trap crop. Napier grass (*Pennisetum purpureaum*) and Sudan grass (*Sorghum sudanense*) can be used as trap crops, while molasses grass (*Melinus minutiflora*), together with silver leaf desmodium (*Desmodium uncinatum*) and green leaf desmodium (*D. intortum*) as repellent crops for the ovipositing females of the stem borers (*C. partellus* and *Busseola fusca*). When intercropped with maize molasses grass not only reduces stem borer infestation, but also increases stem borer parasitism by *Cotesia flavipes* (Khan et al. 1997). Napier grass, which attracts the ovipositing females, is unsuitable for the growth and development of *C. partellus* larvae (van den Berg et al. 2001).

Non-crop weed hosts

Maintaining non-crop weed hosts that serve as a source of alternate prey, nectar, and pollen for pest natural enemies is another way of increasing diversity to reduce crop damage. A threshold level of weed hosts can be maintained either along the field borders or within the crop such that the presence of weeds does not affect the crop yields adversely. Allowing weeds to grow with collards considerably decreased flea beetle densities on the collards and minimized the leaf damage (Altieri et al. 1977). Weed diversity had also been found to reduce the incidence of fall armyworm, *Spodoptera frugiperda* in maize (Altieri and Whitcomb 1980).

However, maintaining weeds in and around the crop does not always lead to reduced pest damage. Weed diversity does not reduce the density of earworm, *Helicoverpa zea* in maize (Altieri and Whitcomb 1980). Smith et al. (1994) observed that the activity of potato leafhopper in the presence of crabgrass (*Digitaria sanguinalis*) was 2–4-fold higher than in the presence of alfalfa alone under equivalent vegetation density. The leafhoppers preferred to oviposit and reside on pure alfalfa rather than in alfalfa mixed with crabgrass. Leafhopper activity also increased as the concentration of crabgrass increased compared with equivalent alfalfa densities. Weed cover also increases the damage by Oriental armyworm, *Mythimna separata* in pearl millet.

Multilines/synthetics

The feeding preference of herbivores can be altered by including genetically diverse crops with similar maturity and height. Higher biological control of the cereal leaf beetle, *Oulema melanopus* has been achieved with mixed cropping of beetle-resistant and beetle-susceptible wheat varieties than with pure stands of either one of the varieties (Casagrande and Haynes 1976). Simulated growth of aphid predators on the susceptible plants in variety mixtures also slows down the rate of development of virulent aphid biotypes (Wilhoit 1991). The combined effect of varietal mixtures and natural enemies are very effective in suppressing pest populations.

Genetic diversity and arthropod response: nature of interactions

Several studies have attempted to explain the ecological mechanisms underlying differences in the dynamics of insect herbivores and their natural enemies in simple and diverse crop habitats (Tahvanainen and Root 1972; Root 1973; Bach 1980a and b; Risch 1981; Altieri and Letourneau 1982; Altieri and Gliessman 1983; Kareiva 1982; Ramert and Ekbom 1996; Roda et al. 1997a and b). Arthropod response to genetic diversity is influenced by: associated resistance, resource concentration, and the influence on activity and abundance of natural enemies. The effects of resource concentration and natural enemies on herbivore arthropods are complementary, but, in some crop combinations, these responses may be antagonistic.

Associated resistance

Associated resistance leads to reduced herbivore attack because of a plants' association with genetically or taxonomically diverse plants, because of the influence of genetic diversity on the activity of natural enemies, reduced concentration of the host plant, or as a result of interaction of both. Associated resistance can be measured by comparing the herbivore populations in taxonomically or genetically diverse plants with pure stands of the same species or a genotype.

Resource concentration

To explain the general reduction of pest densities in diverse plant communities, Root (1973) proposed the resource concentration hypothesis and the natural enemy hypothesis. The resource concentration hypothesis suggests that under monoculture, where the same plant species is cultivated over large areas, the herbivores find a concentrated source of food in one place, which supports uninterrupted population build up. The food plants in pure stands are also detected and colonized easily. Insect pests, particularly the specialists, exhibit longer tenure on the crop host, and higher feeding and reproductive success in monocultures. The relative concentrations of the crop hosts in monocultures and polycultures affects incidence and damage by herbivore arthropods. As a result of resource concentration, herbivore arthropods with a narrow host range are more likely to remain where the host plants are abundant.

In a maize–bean polyculture, and a low-density and high-density maize monoculture (low-density monoculture – polyculture – additive comparison; high-density monoculture – polyculture – substitutive comparison); *Dalbulus miadis* left additive and substitutive monocultures slower than the polyculture. But the remaining population was diluted to a lower insect density per plant in high-density monoculture (substitutive) than in the low-density (additive) monoculture. *Aphis craccivora* is more abundant in groundnuts (*Arachis hypogea*) in substitutive polycultures, but less abundant in additive polycultures (Farrell 1976), while the cabbage aphid, *Brevicoryne brassicae* is less abundant on Brussels sprouts (*Brassica oleracea* var. *gemmifera*) in additive polycultures, but showed similar abundance in substitutive polycultures (Altieri 1984). Thus, the effects of host density and vegetational diversity can be confounded in substitutive designs (Andow 1991).

Natural enemy hypotheses

Development of strategies that help conserve natural enemies thus minimizing the risk of insect pest outbreaks will be crucial for sustainable crop production in the future. The search for the right habitat is imperative if the effectiveness of biological control processes are to be increased, since natural enemies of the crop pests also require such other resources as nectar for feeding by adults, and alternate insect hosts to sustain their populations during periods of low abundance of the principal host. However, such resources may or may not be found in the insect host habitat. Therefore, it is important to increase the habitat diversity to increase the effectiveness of natural enemies. Chemical cues from the associated crops will also confuse the insect pests, and will increase the population densities of locally available parasitoids and predators to enhance the biological control of insect pests.

It has been presumed that lower levels of herbivores in diverse agro-ecosystems were a result of the higher activity of natural enemies (Root 1973). Conservation of natural enemies, which involves protection and maintenance of the natural enemy population in a habitat, can also play a crucial role in increasing the efficacy of biological control in an ecosystem. Movement of the natural enemies also plays an important role in diversified ecosystems (Corbett and Plant 1993). A simple model to measure the response of natural enemies to diversified cropping systems is based on the assumption that movement of the natural enemies can be represented as a diffusion process. Inter-planted vegetation acts as source of natural enemies when natural enemies colonize strip vegetation before crop germination, but acts as a sink when the crop and inter-planted vegetation germinate simultaneously. The magnitude of this effect varies with the natural enemy mobility. There is a strong interaction between natural enemy mobility and experimental design, and results of small-scale experiments with crop diversification must be interpreted with certain amount of caution (Corbett and Plant 1993).

Increase in activity of natural enemies in polycultures

Increasing genetic diversity has been proposed as a means of augmenting natural enemy populations. However, the response of natural enemies to genetic diversity is varied, with some species exhibiting negative responses (Andow 1991). Augmentation of natural enemies through genetic diversity is through such supplemental resources as pollen and nectar, alternate prey, or increased fecundity and movement (Andow and Risch 1985; Sheehan 1986). Cropping systems have been altered successfully to augment and enhance the effectiveness of natural enemies. Hedgerows, cover crops, and weedy borders provide nectar, pollen, and refuge for natural enemies. Mixed planting and provision of flowering plants on the field borders can increase the diversity of habitat, and provide more effective shelter and alternative food sources to predators and parasites. Inter- or mixed-cropping, which involve simultaneously growing two or more crops on the same piece of land is one of the oldest and most common cultural practices in tropical countries (Karel and Ndunguru 1980). Densities of natural enemies have found to be higher in 52.7% of the species in polycultures, while 9.3% species had lower densities (Andow 1991). Predators and parasites have been found to result in higher mortalities of herbivore arthropods in polycultures in 9 studies, lower rates of mortality in 2 studies, and to have no effect in 4 studies (Russell 1989).

Parasitism of the Oriental armyworm larvae, *Mythimna separata,* has been found to be greater in plots with weed cover than in weed-free plots. Populations of coccinellid beetles (*Coccinella transversalis* and *Adalia bipunctata),* lace wings (*Chrysopa* spp.), reduviid and pirate bugs (*Coranus triabeatus)* and spiders (*Lycosa* spp. and *Araneus* spp.) have been found to be significantly higher in a maize–cowpea intercrop than on cotton in adjacent fields. Populations of predators and parasitoids tended to decline with an increase in distance from the border row of the intercrop (Sharma et al. 2000). Greater abundance of the natural enemies in maize–cowpea intercrops has been attributed to the availability of floral nectar, alternate prey (aphids), shelter, and mating and oviposition sites associated with crop biodiversity.

Optimal microclimatic conditions, nectar sources, and alternate hosts may exist in some cropping systems, but not others. For biological control to be successful, it is important to ensure that essential parasitoid resources and hosts coincide in time and space. Some natural enemies may be more abundant in polycultures because of the greater availability of nectar and pollen, and diversity of prey (Bugg et al. 1987) for a longer period of time (Topham and Beardsley 1975).

Bugg et al. (1987) observed greater numbers of *Geocoris* spp. and other predators on knotweed (*Polygonum aviculare*) than on other weed species, which was attributed to the availability of floral nectar and of alternate prey. Green bug, *Schizaphis graminum* on strips of sorghum inter-planted in cotton supported large populations of the coccinellid predator, *Hippodammia convergence* and other predators (Fye 1972). The movement of natural enemies will influence the degree of enhancement of biological control on the adjacent crop (Russell 1989). The abundance of the predatory mite, *Metaseiulus occidentalis* was enhanced when planted adjacent to alfalfa interplants in cotton (Corbett and Plant 1993).

Antagonistic affects of genetic diversity on natural enemies

Specialist parasitoides might be less abundant in polycultures than in monocultures because the chemical cues used for host finding may be disrupted. The boundaries of the host crop in polycultures will be more indistinct, and the parasites are more likely to leave polycultural habitats than monocultural habitats. Colonization by *Pediobius foveololus,* which parasitizes *Epilalina varivestis,* is greater in monocultures than in polycultures (Call and Bottrell 1996). However, the parasitoid stayed longer in the polycultures than in monocultures. The densities of *Coleomegilla maculata* have been found to be greater in monocultures where pollen abundance was greater than in polycultures (Andow and Risch 1985). Also, the foraging success *of C. maculata* was greater in monocultures where the prey density was high, than in polycultures, and the predator tended to stay longer in monocultures. Abundant resources could increase the residence time of natural enemies. *Coleomegilla maculata* dispersed more rapidly in maize–bean–squash polyculture than in maize monoculture, because maize provided a greater abundance of aphids and pollen.

In some crops, there is no increase in predation when they are interplanted with common knotweed, despite greater abundance of natural enemies of the later (Bugg et al. 1987) because there are more resources on the knotweed, natural enemies are less likely to move away from it. Highly mobile predatory insects disperse readily throughout experimental plots, and aggregate in areas with high prey abundance (Doutt and Nakata 1973). However, in certain cases, highly mobile predators are not likely to be enhanced by the presence of alternate vegetation adjacent to crops (Perrin 1975).

Mechanisms of interactions between arthropods and their host plants

In diverse plant communities, a specialist insect is less likely to find its host because of the presence of confusing or masking effects of chemical stimuli from the non-host plants, physical barriers to movement, and changes in the micro-environment of the target insect. Consequently, insect survival may be lower in polycultures than in the monocultures (Baliddawa 1985). Species of insects belonging to different orders are differently affected by genetic diversity (Finch and Kienegger 1997). The efficacy of mixed cropping systems will differ for passive airborne insects such as aphids to active fliers such as butterflies and moths (Banks and Ekbom 1999). Comparisons of insects with similar life histories may provide information about the nature and possible success of intercropping for pest management. Various types of interactions between arthropods and their host plants are discussed below.

Physico-chemical stimuli

Insect pests settle on crop plants only when various physical and chemical stimuli emanating for the host plant are satisfactory. This is more likely in monocultures than in polycultures. The complexity of stimuli involved in host recognition and acceptance makes it difficult to design appropriate cropping systems without adequate knowledge of insect biology, or and insect host plant interactions. Some non-host odors may be repellent to herbivores. For a non-host odor to mask chemical stimuli from the host plant, the non-host odor either interferes with the neutral output from the host odor receptor or affects the insect's central nervous system that is processing of the host-odor stimulus. The insects may also leave the plants in polycultures because of poor and variable quality of the chemical stimuli (Kareiva 1982). The diversity of olfactory stimuli in polycultures might confuse the monophagous insects that are trying to find their host plants. *Phyllotreta cruciferae* is more likely to move to host plants in monocultures than in polycultures (Tahvanainen and Root 1972). The anthomyiid fly, *Delia brassicae* lays fewer eggs on plants in polycultures than in monocultures (Ryan et al. 1980). Laboratory studies have shown that the flies landed on plants in polycultures at the same rate as on the plants in monocultures, but, the non-hosts caused the flies to move more often, spend less time in egg-laying and leave the hosts faster. Polycultures also reduced host finding and increased the host-leaving rates compared to the monocultures (Elmstrom et al. 1988).

Empoasca fabae and *Epilachna varivestis* population densities are negatively correlated with the biomass of the non-hosts in polycultures (Kingsley et al. 1986). In groundnut–bean mixtures, the aphid densities are lower, because the aphids are caught in the hooked trichomes on the bean leaves (Farrell 1976). A chemical stimulus is not necessary to induce a probe in the case of *E. devastans* and *E. kerri motti* (Saxena and Saxena 1974). However, the insects ingested different quantities of food from different species. If the herbivore arthropods do not discriminate between the host and the non-host tissue, then the insects landing on the non-host surface would dilute their numbers, and fewer would land on the surface of host plants, resulting in reduced plant damage and loss in crop yield.

Visual stimuli

Polycultures also influence visual stimuli from the host. Colonization of Brussels sprouts by aphids is lower in polycultures than in monocultures. The non-host plant and the green polythene cover render the host plants less attractive to the aphids because they reduce the contrast between green plants and the brown soil. Visual and chemical stimuli from barley–pea intercrops result in greater abundance of the predator, *Pterostichus melanarices* in the intercrop than in monocrops of barley (*Hordeum vulgare*) or pea (*Pisum sativum*) (Caracamo and Spence 1994). The Papilionid, *Battus philenor* recogni-zes its host plants by their leaf shape, and lays less eggs on host plants surroun-ded by non-host vegetation than on plants around which all non-host plants have been removed (Rauscher 1981). Plant appearance also influences host finding by herbivores in relation to the stage of plant development. Structural complexity or connectedness of the surface where the parasites search for prey may also influence the host-finding ability of the parasites, and as a result, structurally complex habitats may have less parasitism than monocultures (Andow and Prokrym 1990). *Phyllotreta cruciferae* leaves the smaller host plants in polycultures more rapidly (Kareiva 1982). Its ability to respond to variation in host size, however, is influenced by the proximity of nearby hosts. If larger host were nearby, the beetle discriminated between hosts, and settled on the larger hosts. If the host plants were farther away, the beetle could nor locate the larger hosts, and appeared to discriminate poorly.

Emigration

In general, insects are able to distinguish between host and non-host plants. Insects landing on non-host plants tend to leave them more rapidly than those landing on host plants (Bach 1980a; Risch 1981). In this process, the herbivores waste more time in searching on non-host plants, and as a result, leave polycultures more rapidly than monocultures. Emigration is greater from intercropping in several systems (Elmstrom et al. 1988, Garcia and Altieri 1992; Kostal and Finch 1994). This may be due to landing on a non-host by mistake, frequent movement away from the non-host, and or leaving the crop area during movement. Insects usually abandon the non-host plants after a short time (Stadler and Roessingh 1990).

White cabbage intercropped with tall clover had lower oviposition by diamond back moth (*Plutella xylostella*) (a polyphagous pest of most Brassicaceae) than monocultured cabbage (Asman et al. 2001). Some herbivores move more frequently in polycultures that contain more nonpreferred hosts than in monocultures (Risch 1981). Roda et al. (1997a) observed that emigration of leaf-hopper, *Empoasca fabae* was 9-fold higher from pure bromegrass (*Bromus inermis*) and orchard grass (*Dactylis glomerata*) than from alfalfa alone, and 5-fold higher than from mixtures of alfalfa and the grass species. Frequency and mean residency was greater on alfalfa, followed by bromegrass and orchard grass. Although leafhoppers probed for longer periods on grasses, they left the grasses earlier than did the individuals on alfalfa. Repeated encounters with a grass not only diverts the insects from feeding on alfalfa, but also leads to increased movement within the stand, and some proportions of the insects emigrate from the field, thus leading to lower injury to alfalfa (Roda et al. 1997b). Intercropping did not appear to affect the emigration of either leek moth or diamond back moth (Asman et al. 2001).

Effect of physico-chemical stimuli on natural enemies

Plant chemicals from associated plants can either provide cues or mask the attractants to natural enemies. Volatiles emanating from plant tissues also influence the activity and abundance of natural enemies (Elzen et al. 1984; Udayagiri and Jones 1992). Crop diversity increases the movement of natural enemies into certain cropping systems due to attractants from the host plants of the target insect or the absence of feeding deterrents. *Campoletis sonorensis* has been reported to respond to volatile chemicals emanating from damaged plant tissue, and some of them are also attracted to volatile chemicals (*Macrocenrus grandii*) from undamaged plants (Elzen et al. 1983; 1984; Whitman and Eller 1990; Udayagiri and Jones 1992).

Biological control of insects can be improved by growing companion crops that produce chemicals, which attract the natural enemies (Sharma et al. 2002). Insects feeding on plants growing in association with other plant species may be parasitized heavily because of the chemical cues provided by the associated plants, e.g., *Myzus persicae* is more heavily attacked by *Diaerectiella rapae* when the aphid is feeding on a crucifer than when it feeds on beet (*Beta vulgaris*) (Reed et al. 1970). The biological control of beet aphids can be improved by growing crucifers as a companion crop.

In some cases, the chemicals may be repellent to the natural enemy or merely mask the attractive odors of the host plant. Plant chemicals are also imbibed by the insect host as kairomones (attractants) for the natural enemies. Maize produces tricosane, and *H. zea* incorporates tricosane unchanged into its eggs, which *Trichogramma evanescens* uses as a kairomone to find the host (Lewis et al. 1972). The cabbage aphid, *B. brassicae* uses sinigrin to find its host plant, but its parasitoid, *Diaerectiella rapae* uses a related mustard oil – allyl isothiocyanate to find the host plant, and then the aphid (Reed et al. 1970). These indirect effects of host plants on natural enemies can have a great bearing on biological control of insects in diverse cropping systems.

Nutritional quality of food. Polycultures may also alter the nutritional quality of the host plants, and influence host-finding by the insects by altering the chemical composition of the cues released by the host plant.

Microclimatic conditions. Microclimate in terms of relative humidity, temperature, shading, and shelter also influence the activity and abundance of herbivore arthropods and their natural enemies.

Influence of genetic diversity on monophagous versus polyphagous species

The resource concentration and activity of natural enemies influence monophagous and polyphagous species differently. A monophagous species is likely to be less abundant in polycultures than in monocultures. For polyphagous species, if the natural enemy hypothesis accounts for its response, then its population density should be lower in polycultures than in monocultures. Most polyphagous species have higher densities in polycultures than in monophagous species (Andow 1991). Arthropods respond to polycultures differently, depending on the number of host plants in the polyculture, and the relative preference of the herbivore for different host plants. In general, resource concentration has a greater effect on herbivore response to polycultures than on natural enemies, but the natural enemies also act concurrently (Risch et al., 1983; Sheehan 1986). The effect of resource concentration on polyphagous pests is more obscure than on monophagous pests. Some polyphagous insect species alternate host plants between generations in a temporal sequence, while some species change their hosts simultaneously within a generation. If immigration into the polycultures is low because of difficulties in host finding or potential immigration is low then sequential polyphagous pests are expected to have higher population densities on the second host in polycultures than in monocultures, as they have already colonized the polycultures during the first generation. Of the 9 populations of sequential polyphagous pests examined, 7 were more abundant, and one was less abundant on the second host in polycultures than in monocultures (Andow 1991). Inter-planted vegetation may also act as a source of natural enemies. When natural enemies colonize the intercrop before the main crop, it may act as a sink when the main crop and intercrop are at susceptible stage for the target pest at the same time (Corbett and Plant 1993). Unless and until natural enemies are present, and are well established in sufficient numbers before the initial pest arrives, they cannot respond fast enough to exercise control on the pest populations. The presence of maize and cowpea crops within a cotton system increases the abundance of beneficial insects in the cotton field prior to the arrival of sucking pests such as aphids and whitefly, and *H. armigera* in time for them to have a positive effect.

Conclusions

Associated resistance plays an important role in many polycultures, although there are distinct exceptions. The resource concentration hypothesis explains many of the observed responses of arthropods to polycultures and monocultures. However, the effects of host concentration in polycultures on polyphagous pests have not been fully understood. The increased activity of natural enemies due to increased availability of nectar, pollen, and alternate preys also plays an important role in decreasing pest damage in diverse ecosystems. The circumstances under which the effect of natural enemies will result in significant mortality of crop pests have not been fully understood. Some of these interactions are related to the evolutionary history of a particular plant and the arthropod, and the ecological interactions involved in the process may unravel the effects of genetic diversity on herbivore arthropods and their natural enemies.

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Effect of organic resources management on soil biodiversity and crop performance under semi-arid conditions in West Africa

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Introduction

Semi-arid areas face reduced soil productivity due to a decrease in optimum functioning of soils in their ecosystems. Soil organic matter depletion due to inappropriate cropping systems and management enhances these soil function losses in the prevalent low external input agricultural systems. The functions that are failing include recycling nutrient and carbon, soil physical conditions, and maintenance of biological qualities. The processes involved make soil a dynamic part of the biosphere in which soil microorganisms and fauna are vital components.

To date, little is known about the mediated processes of soil organisms in semi-arid areas, particularly those in West Africa. The diversity and role of soil organisms in the maintenance and the regulation of soil fertility have been largely ignored by traditional and conventional agriculturists. In high-input agricultural systems, the importance of soil organisms has often been disregarded, as physical manipulation of the soil, disease and pest suppression, and nutrient supply have been increasingly provided by human inputs rather than by natural processes (Brussaard et al. 1997). Recent research, however, demonstrates that practices which eliminate beneficial soil faunal communities are unlikely to be sustainable in the long term, especially in low-input agriculture systems based on organic fertilization (Lavelle et al. 1994; Wardle et al. 1999).

According to their size soil organisms are usually classified into microflora, micro-, meso- and macro-fauna (Swift et al. 1979). Within these major categories soil organisms are grouped according to their functional attributes that often transcend morphological and taxonomic boundaries (Beare et al. 1997).

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Brussaard (1998) distinguished three types of soil organisms:

- **Root biota** – Organisms that live in association with the living plant, either beneficially or detrimentally affecting plant growth, e.g., nitrifying bacteria, mychorizae
- **Decomposers** – Microflora and micro-/meso-fauna acting as regulators of numbers of activities of microorganisms and microbial feeders. This group involves meso- and macro-fauna that additionally comminute litter entering the soil without physically reworking the mineral part of the soil
- **Ecosystem engineers** – Meso- and macro-fauna that create microhabitats for the other soil biota by reworking the soil. Earthworms and termites are considered as the most important ecosystem engineers in soil because by modulating soil physical and chemical properties they have far-reaching and lasting effects on other species.

This paper investigates the impact of different methods of organic resources management on soil biodiversity with special attention to soil fauna their interactions and impact on crop performance. Selected studies are reviewed that underscore the key role of these organisms in controlling soil functions and their importance in ecosystem studies.

The key role of soil fauna in the semi-arid West Africa

Soil fauna and the rehabilitation of crusted soil

In the Sahelian zone of Burkina Faso, the combined effect of organic matter depletion due to overgrazing, continuous cultivation, and climatic conditions has resulted in the increase of bare soil and unproductive land characterized by low infiltration capacity, nutrient imbalance, reduced biodiversity, and low primary production (Mando et al. 1999). Many efforts have been made to fight against land degradation by constructing bunds of stone lines, sowing grass, or planting trees. But all these attempts were hampered by the crusted state of the degraded soil, which limits the infiltration necessary to enable land rehabilitation. Mando and coworkers investigated the role played by soil fauna with special attention to termites in the rehabilitation of these crusted soils. Surface-placed organic material in crusted soil was used to attract termites (*Odontotermes* and *Microtermes* spp.) with the hypothesis that the presence of dry vegetative material on structurally crusted soil would trigger termite activity and thereby improve soil infiltration sufficiently to activate vegetation establishment. Termites activities in mulched plots was excluded by the application of insecticide (Dieldrin® applied @ 500 g a.i. ha^{-1}) and compared to the bare soil plots and those that were mulched but not treated with insecticide.

The study showed that termites perforated the crust, resulting in 84 surface macropores m^{-2} compared to none in the absence of termites (Mando 1998). Soil porosity was increased (Mando et al. 1996) leading to water infiltration and reduced soil resistance to penetration (Mando 1997). Soils with mulch and termites had significantly higher plant cover, biomass, and diversity than to soils with mulch but without termites and those without mulch (Mando and Stroosnijder 1999; Mando et al. 1999) (Table 1). No vegetation developed in the bare soil. The zero production on bare plots and the very low production in the non-termite mulched plots indicated that removing human or animal pressure from already crusted soil, or protecting it against the impact of rain drops cannot rehabilitate the productivity of structurally crusted soil in a short period. Moreover, increasing sediment trapped by the many tiny physical barriers create by the mulch itself was inefficient in restoring soil productivity without termite contribution. It was concluded that termites in the Sahel can be friends and not enemies and that farmers can make 'pests' work for them (Mando and van Rhennen 1998).

Table 1. Termite- and mulch-mediated processes in crusted soils in West Africa

	Soil[1]		
Measured parameter/year	**Bare**	**With fauna**	**Without fauna**
Termite-made voids (number m^{-2})	0 [b]	84 [a]	0 [b]
Runoff (% annual rainfall)			
1993	82 [b]	68 [b]	60 [b]
1994	68 [a]	47 [a]	39 [a]
1995	79 [b]	53 [b]	49 [c]
Vegetation cover (%)			
1993	0 [b]	3.6 [b]	0 [b]
1994	14 [a]	96 [a]	150 [a]
1995	5 [a]	32 [b]	56 [c]
Dry matter yield (t ha^{-1})			
1994	0 [b]	0 [b]	3.2 [a]
1995	3.2 [a]	1.3 [b]	1.3 [b]

1. Treatments followed by the same letter do not differ significantly
Source: Mando and Stroosnijder (1999)

Soil fauna and the decomposition of organic resources

Soil organisms provide a number of services including decomposition of organic matter, nutrient cycling, bioturbation, and suppression of soilborne diseases and pests (Brussaard et al.1997). It is well known that after the development of phylloplane micro-flora in the litter decomposition processes, the litter is colonized by saprophytic microorganisms whose degradation of plant structural polysaccharides is an essential prelude to feeding by soil invertebrates. The litter is comminuted and ingested by soil invertebrates. Invertebrate faeces and litter fragments are incorporated into the soil where further microbial action results in the formation of humus (Collins 1981). However, the ability of such soil fauna as termites to feed on fresh litter without any previous attacks has been shown by Wood (1976) suggesting that ecosystems engineers plays a key role in such decomposition processes in tropical areas.

A field experiment to investigate the interaction impact of soil fauna and organic resource quality on the decomposition of applied organic material was conducted in the central southern part of Burkina Faso during the rainy season, 2000. The experimental design was a split plot with four replications. The main treatment was plots untreated or treated with pesticides [Dursban® (chloropyrifos @ 400 g a.i. ha^{-1}) and Endocoton® (endosulfan @ 450 g a.i. ha^{-1})]. The sub-treatments consisted of mulches of maize or *Andropogon* spp. straws, application of cattle dung, compost, sheep dung, and an untreated control. Litterbags of two mesh sizes: a. 1 mm (to exclude most fauna activity); b. 4 mm (to allow soil fauna access to the organic material) were used. In each plot, litterbags a and b each containing 100 g of the same material that as on the plot were placed. Half of the litterbags were buried 30 cm deep and half left on the soil surface. Organic material was applied at the rate of 40 kg N ha^{-1}. The experi-ment was conducted on an Eutric Cambisol with loamy to loamy-clay texture, pH of 6.6–7.2, and a top soil C:N ratio of 17.

The results showed that without soil fauna contribution, up to 96% of *Andropogon* spp. straw, 70% of cattle dung, and 34% of maize straw would not have been decomposed until harvest (Ouédraogo et al. 2003a). Soil fauna contribution to organic material decomposition was higher in low-quality material, and high-quality material was decomposed when that of low quality was not available.

Organic resource management and soil fauna diversity in the semi-arid conditions of West Africa

Numerous studies have shown that agricultural management decreases soil biodiversity and alters the structure of soil biological communities as compared to those of native forest or grassland ecosystems (Lavelle et al. 1994; Beare et al. 1997; Black and Okwakol 1997). These changes can be attributed to at least three factors commonly associated with agricultural intensification:

- An increase in the frequency and magnitude of perturbation that result from land use changes and site preparation
- A reduction in the quantity and quality of organic resources returned to the soil
- The use of such compounds as industrial fertilizers and pesticides that can have drastic effects on soil organisms.

In the semi-arid conditions of West Africa, many studies have shown that judicious management of organic resources can bring about soil rehabilitation, enhanced soil quality, and improved crop production (Bationo and Mukwunye 1991; Mando 1997; Ouédraogo et al. 2001). This would help meet the needs of the growing population farming in low external input agricultural systems. This implies there is potential for agricultural intensification through soil management such as tillage, fertilizer use, and integrated crop and animal production.

Organic inputs into tropical soils of the tropics comprise a wide range of materials including crop residues (above- and below-ground), green manure, animal manure, composted material, weeds, prunings, household wastes (Myers et al.1994; Fernandes et al.1997). The impacts of cropping system and organic resources management on the dynamics of soil faunal community were assessed on the central plateau (12°–25' N, 1°–21' W) of Burkina Faso. The impact of tillage, fertilizer use, and organic resource quality interaction on soil-fauna dynamics were investigated. In the experiment Tropical Soil Biology and Fertility (TSBF) methods were used to estimate soil faunal populations after harvest. A soil core (30 × 30 × 30 cm) was taken from each plot. The core was divided into two layers, 0–10 cm and 10–30 cm deep. All soil fauna were collected and stored in 70% alcohol, counted, and identified. A split-plot design with three replications was used with till and non-till as main treatments. The sub-treatments consisted of single applications of maize straw (S), sheep dung (SD), compost (CO), and urea 1 (U1) @ 40 kg N ha^{-1}, and single applications of urea (U2), or combined organic material [(S+U) and (SD+U)] @ 80 kg N ha^{-1}, and the control. The combined organic material and fertilizer treatments were repeated for half organic material (40 kg N ha^{-1}), and half fertilizer (40 kg N ha^{-1}).

The following classical Hill's (1973) diversity number (H) was calculated for all treatments:

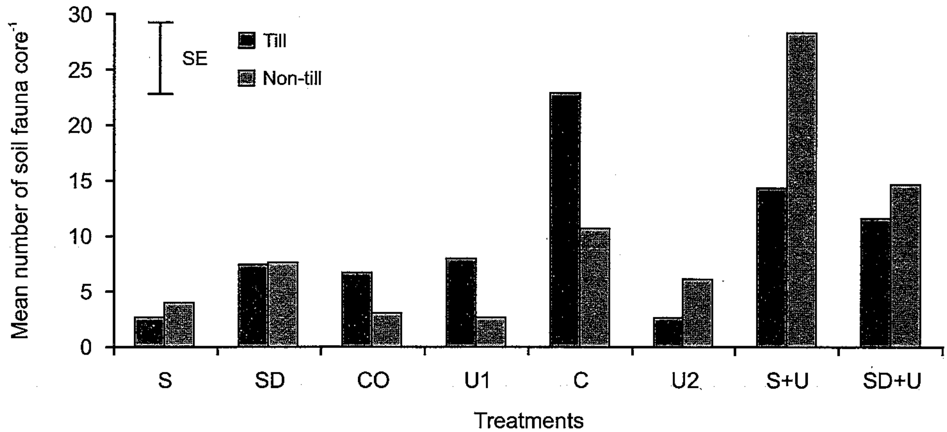
$$H = e^{-\sum_{i=1}^{N} pi \log pi}$$

Where: pi is the probability of occurrence of species i, and N the total number of species.

The hypothesis tested in this experiment is that judicious management of organic resources may improve crop performance and the maintenance of soil biodiversity.

Organic resources management impact on soil faunal population dynamics

Figure 1 shows mean number of soil faunal population per core as affected by organic resources management. Application of single-source organic material such as maize straw or sheep dung in the tilled system reduces the size of soil fauna populations. Combining organic material and fertilizer tended to increase the size of soil fauna populations but this number was still lower than that of the control plot. In the non-tilled system, no significant difference in soil fauna numbers between the control and the treatments when applied @ 40 kg N ha^{-1} was observed. However, when organic material was combined with fertilizer the number of soil fauna increased significantly, and was higher in the maize straw treat-ment than in the sheep dung plot. When urea alone was used, increasing the rate of urea applied decreased the soil fauna population size. The highest reduction in soil fauna population was observed in the high urea rate (80 kg N ha^{-1}) treatment.



S = maize straw, SD = sheep dung, CO = compost, U1 = urea (40 kg N ha^{-1}), C = control, U2 = urea (80 kg N ha^{-1}), S+U = maize straw + urea, SD + U = sheep dung + urea

Figure 1. Mean number of soil fauna with single and combined organic resources/urea application

Reduction of soil fauna population at harvest by the application of organic material indicates that the application of organic material induces processes which lead to a decrease in soil faunal populations. The significant raise in soil fauna numbers after the addition of urea to organic material indicates that these processes have a link to N deficiency. Indeed, Ouédraogo et al. (2003b) showed that N was a limiting factor to organic matter build up in this soil. Therefore, the single application of organic material stimulated the microbial population that mineralized soil organic matter to meet the N needs of the increased population. Soil organic matter created conditions favorable to soil fauna activities and the use of the soil environment as a habitat. This indicates that management practices which decrease soil organic matter have a drastic impact on soil fauna population size under semi-arid conditions of West Africa and make soil fauna populations directly dependent to soil organic matter status (Figure 2a and b).

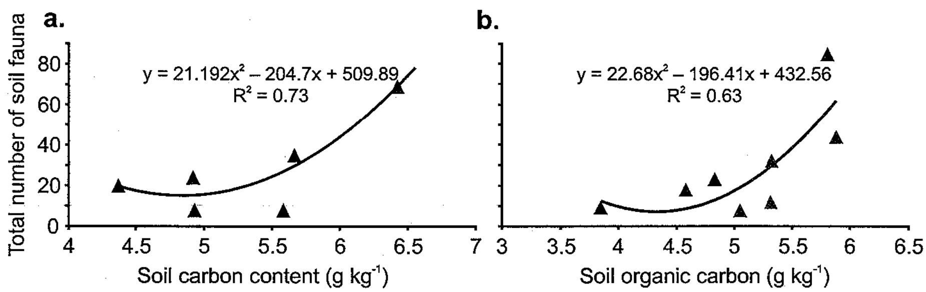


Figure 2. Correlation between populations of soil fauna and soil organic matter content in a. tilled plots and b. non-tilled plots as affected by the treatments

Organic resources management impact on soil faunal diversity

From Figure 3a and b, it may be noted that a single application of organic resources into the tilled system resulted in higher soil fauna diversity than the application of sheep dung, but this diversity was reduced significantly when the treatment was combined with urea (Figure 4). This may be explained by the easy availability of nutrient with the use of high quality organic material as food by many decomposer communities, ecosystem engineers, detritivores (*Coleoptera*, myriapods) that attracted many predators of soil fauna (ants and arachnids) (Figures 5a and b). In contrast, diversity was lower in maize straw plots than in sheep dung plots suggesting that only specific groups of soil fauna were acting there. Termite populations are known to be able to feed on low-quality material. Diversity in this situation seems to rely on food quality. Combining organic material and urea reduces soil fauna diversity in sheep dung plots suggesting that accelerated organic material decomposition and reduced food availability to soil fauna communities may have occurred. The addition of urea to organic material in the tilled system increased fauna diversity and this indicates that low-quality organic material combined with fertilizer made many soil fauna communities' food sources more available.

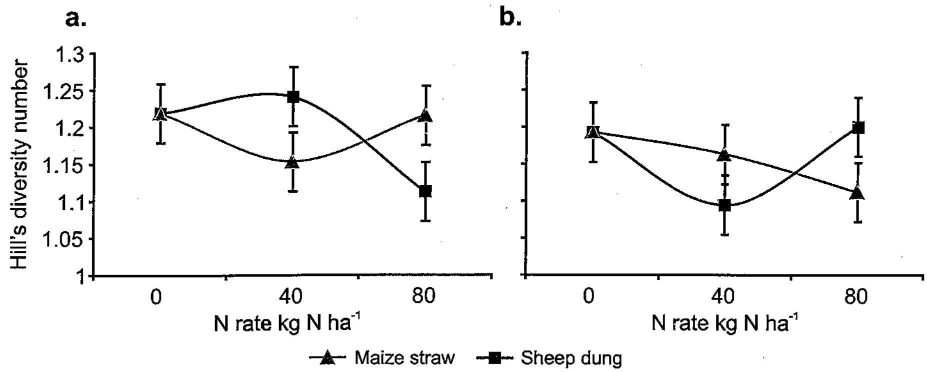


Figure 3. Single or combined organic resources/urea and Hill's diversity number in a. tilled plots and b. non-tilled plots

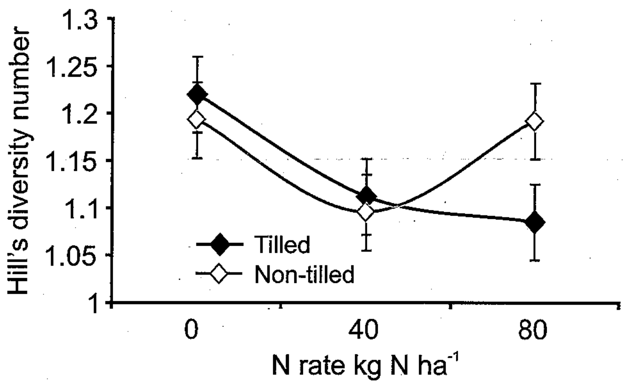
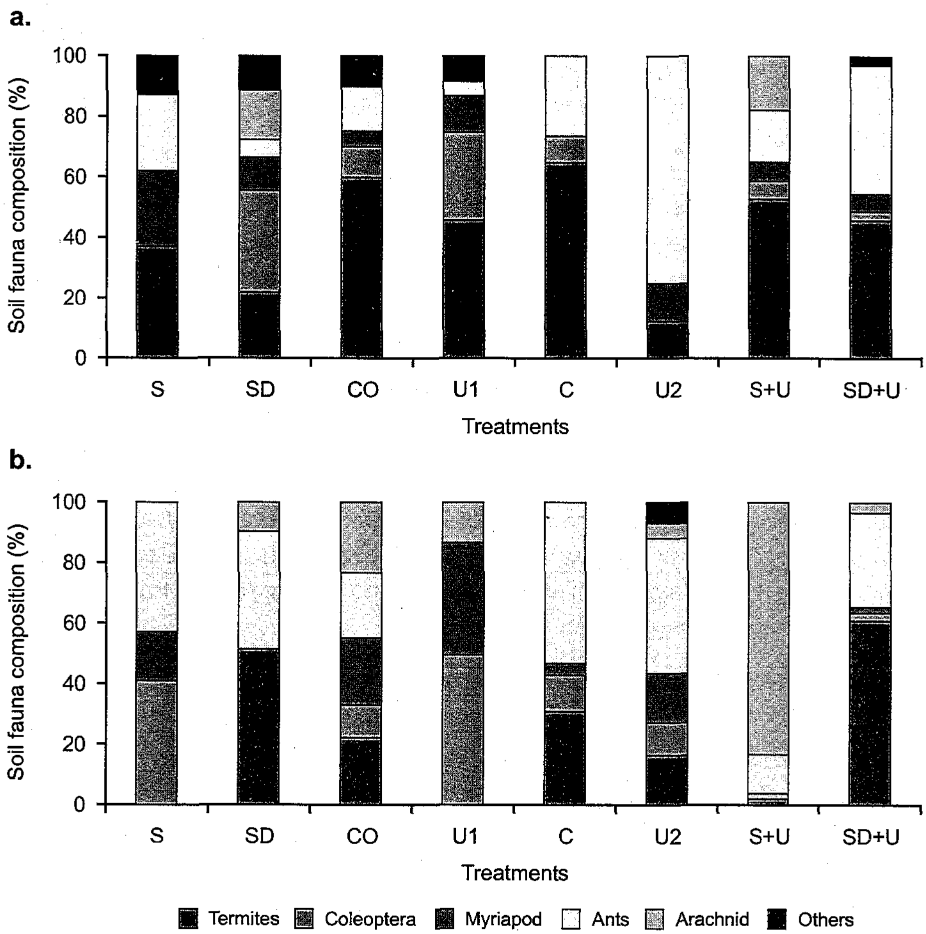


Figure 4. Single urea application and Hill's diversity number



S = maize straw, SD = sheep dung, CO = compost, U1 = urea (40 kg N ha^{-1}), C = control, U2 = urea (80 kg N ha^{-1}), S+U = maize straw + urea, SD + U = sheep dung + urea

Figure 5. Diversity of soil fauna in a. tilled and b. non-tilled plots

When surface-placed, there was higher diversity in single-applied straw than in sheep dung, indicating that maize straw attracted many soil fauna communities. Maize straw may be used as a habitat or refuge by such organisms as myriapoda and coleoptera. Low diversity at high numbers in surface-placed maize straw when combined to urea indicates that a dominant fauna was acting in this treatment. This was related to arachnid numbers, which consisted of about 80% of the soil fauna attracted (Figure 5b).

Ants and arachnids, or coleoptera of the family *Staphynilidae* (carnivorous beetles) were obviously attracted by the increased termite population and were acting as termites enemies contributing to the depression. Whether reduced termite populations had positive or negative impact in soil functioning and crop performance will depend on the roles played by termites as beneficial organisms or pests.

Single applications of fertilizer N reduced soil fauna diversity whatever the technique used for soil management, i.e., tillage or non-tillage (Figure 4). Moreover, increasing fertilizer application rate in the tilled system increased the loss of soil fauna diversity. This may be due to a high decrease in food availability due to fertilizer addition with accelerated mineralization, or increased soil acidification that may occur with the single application of fertilizer N (Ouédraogo et al. 2003b). In non-tilled plots, increased diversity at very low soil fauna population size following the application of urea (80 kg N ha^{-1}) may suggest that no leading process from a specific group of soil fauna was observed.

Soil fauna and crop performance

While it is well known that many groups of soil fauna may act as serious pests, recent studies have shown areas of beneficial contribution of soil fauna to crop performance improvement (Swift et al.1979; Lavelle et al. 1999). The impact of soil fauna on crop performance improvement relies on its role in improving soil physical properties, nutrient release, and their interaction with other soil organisms. Nutrient release due to soil fauna activities had a positive effect on crop (cowpea) performance improvement in a rehabilitated soil in the Sahel (Mando 1998). Termite activities enhanced nutrient uptake by cowpea by about 90.9 g kg^{-1} in termite plots compared to 15.6 g kg^{-1} *in non-termite plots for* N, 49.3 versus 0.9 g kg^{-1} *for phosphorus* (P) *and* 39.1 versus 7.12 g kg^{-1} for potassium (K) with the use of cattle dung as organic material. The genera of termites involved did not affect cowpea.

In the study on organic resources management impact on soil fauna dynamics and crop performance in the central plateau of Burkina Faso described above, it was shown that soil performance can be related to soil fauna diversity and can vary depending on the quality of organic resource used (Figure 6).

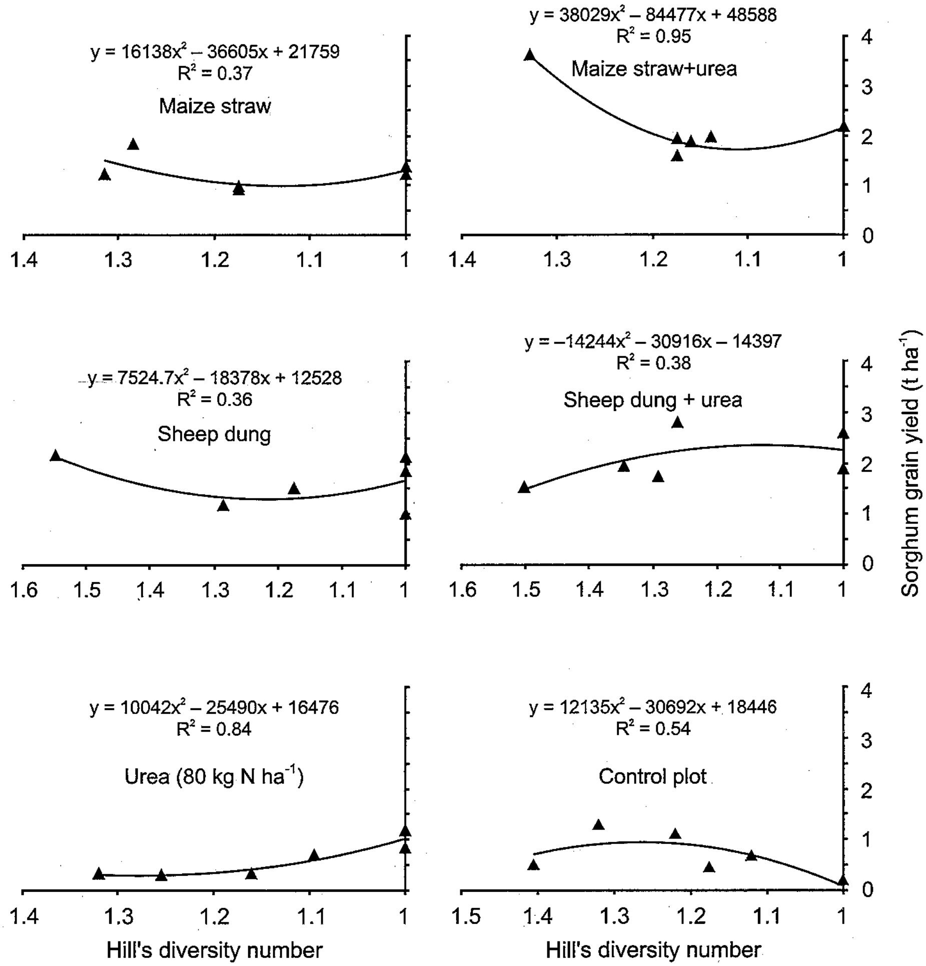


Figure 6. Treatments and correlation between Hill's diversity number and sorghum grain yield

The two extreme figures were the control plot, where crop performance decreased when soil fauna diversity decreased, and the high urea rate plot where increasing yield decreased soil fauna diversity. This showed that low external input agricultural systems rely on soil fauna diversity and the use fertilizer alone is not a solution for crop performance improvement, or for the maintenance of the beneficial contribution of soil biodiversity in the semi-arid conditions of West Africa.

With the single use of organic material together with urea at an equivalent rate of 40 kg N ha^{-1}, crop yield was correlated to soil fauna diversity. However, high diversity in these plots did not show significant increase in crop yield. High soil fauna diversity and high crop yield was only observed in the maize straw + urea plot suggesting that in this treatment increased diversity had a positive impact on crop performance improvement. This may be due to a balance between decomposer communities, ecosystem engineers, and their natural enemies (ants, arachnids, etc.). Maize straw obviously attracted more termites and their natural enemies, showing that high termite activities occurred first when they were attracted by maize straw and that this may have a positive impact on soil physical properties and nutrient release. Ants and arachnids were attracted by termites and this depressed the size of termite populations and may suppress the possible negative impact of some termite species on crop growth. This interesting area of study needs further investigation. However, Ouédraogo et al. (2002b) showed that combined maize straw/urea had a positive impact on crop performance depending on the soil N status. Added N should be sufficient to avoid nutrient immobilization when combined with maize straw.

Conclusions

Maintenance of soil functions in semi-arid areas is related to the sustainability and the maintenance of the beneficial contribution of soil fauna. Soil ecosystems are complex and have features that may transcend time-scale considerations. A network for soil diversity studies could provide a gateway to compensate for the lack of data in semi-arid areas of West Africa. Organic resources management is one of the important issues for crop performance improvement and the maintenance of soil biodiversity in these areas. Soil quality and crop performance improvement are a result of the interaction of different groups of soil fauna communities and abiotic soil conditions. Soil fauna population size is closely related to soil organic matter content in the prevailing semi-arid conditions in West Africa. Soil fauna diversity relies directly on organic resources quality and indirectly on the type of soil fauna attracted by a given quality of organic material. Combined organic material/fertilizer inputs should be promoted as warranted by their beneficial impacts on soil fauna diversity and subsequent crop production improvement. It will be important to strengthen studies on how soil organisms can improve soil functions maintenance, and crop performance. There is no doubt that human populations will rely on the maintenance of these above- and below-ground resource diversities for their livelihoods in the West African SAT.

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Managing and harnessing soil flora-fauna biodiversity in the tropics, for sustainable crop production

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Soil flora and fauna in relation to crop production

Soil is one of the most diverse assemblages of living organisms, and issues related to below-ground biodiversity are similar to, or more complex than, those related to the more visible above-ground biodiversity. A single gram of soil is estimated to contain several thousand species of bacteria alone (Giller et al. 1997). Of the 1.5×10^6 species of fungi that are estimated to exist worldwide, remarkably little is known about soil fungi, apart from the common fungal pathogens and the useful mycorrhizal species that improve crops' efficiency in taking up nutrients. Among the soil fauna some 1.0×10^5 species of protozoa, 5.0×10^4 species of nematodes, and 3000 species of earthworms are estimated to exist, in addition to other invertebrate groups. These other groups include animals, e.g., springtails and mites that are classified as mesofauna ('middle-sized', 0.1–2 mm long) and macro-fauna ('large-sized', 2–20 mm long), e.g., ants, termites, beetles, earthworms, and spiders (Hairiah et al. 2001). All the groups contribute to the way the ecosystem works and have been classified into several functional groups (Brussaard 1998) of which the nutrient recyclers form one. This paper draws from scientific and traditional knowledge about relevant soil flora and fauna and presents a perspective on harnessing their roles for sustainable crop production.

Strengths and weaknesses of conventional agriculture

High-yielding cereal varieties responsive to increased inputs of chemical fertilizers and pesticides fueled the Green Revolution and addressed the food needs of several countries, particularly those in Asia. However, after three decades, farmers are now experiencing difficulty in maintaining high yields, even with increasing levels of inputs. Second-generation issues, fall-outs of the Green Revolution have now surfaced. These include problems associated with soil quality, sustainability, and environmental degradation. Prior to the Green Revolution sustenance agriculture was relatively free from such problems, but it operated at a low level of productivity, that could not sustain the food needs of Asia's ever-growing population. Cultivars responsive to chemical fertilizers; and control of pests and diseases by chemi-

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cal pesticides played a key role in enhancing crop yield. Reports now suggest that if they want to continue harvesting high yields of cereals, farmers will need to apply higher inputs than ever before (Chand and Haque, 1998; Hobbs and Morris, 1996). There are more and more reports of chemical residues in food and feeds, and of insects developing resistance to routinely used pesticides.

Fertilizers are considered important inputs needed to attain high yields of different crops, particularly nitrogen (N) applied to cereals and non-leguminous crops. Response to nitrogenous fertilizers has been very apparent and farmers have adopted this technology globally. There is ample evidence of excessive and inappropriate use of N input, e.g., instead of the recommended 120 kg N ha^{-1} for rice and wheat, farmers were applying up to 180 kg N per ha to rice in Punjab, India (Sidhu et al. 1998). Such 'luxury' use of N-fertilizers may be responsible for the excessive nitrate found in well waters in some areas of the Indo-Gangetic Plains (Datta et al. 1997; Sachdev et al. 1977; Singh and Sekhon 1976). Nitrate pollution in England, that was restricted to only few areas until 1996, was found to have spread throughout the country when measured in 2002 (Figure 1). Information on the extent of water pollution or environmental degradation is scanty for Asia and needs to be collected and strengthened.

Pesticide use for plant protection is another input widely accepted as producing high yields. Residues of some chemicals in food are an important second-generation issue as they present potential health hazards (www.irlgov.ieldaff). Excessive levels of pesticide residues are widely reported from the developed world (Table 1). Again, the reports from Asia are scanty, except in the popular press. Both chemical fertilizers and chemical pesticides are vital inputs in maintaining the high productivity required to ensure food security for the growing masses in Asia

Table 1. Pesticide residues in food

Food item (country)	Residue	Excessive or not (level found)	Comments (reference)
Beef (Australia)	Endosulfan	+	Cattle fed on cotton gin trash (Pesticide News, June 1999)
Cabbage[1] (Ireland)	Demeton-S (methylsulphon)	+ (0.72)	Permissible level: 0.5
Pepper[1] (Spain)	Methamidofos	+ (0.35)	Permissible level: 0.01
Lettuce[1] (France)	Procymidone	- (3.9)	Permissible level: 5

1. Source: www.irlgov.ieldaff (2001)

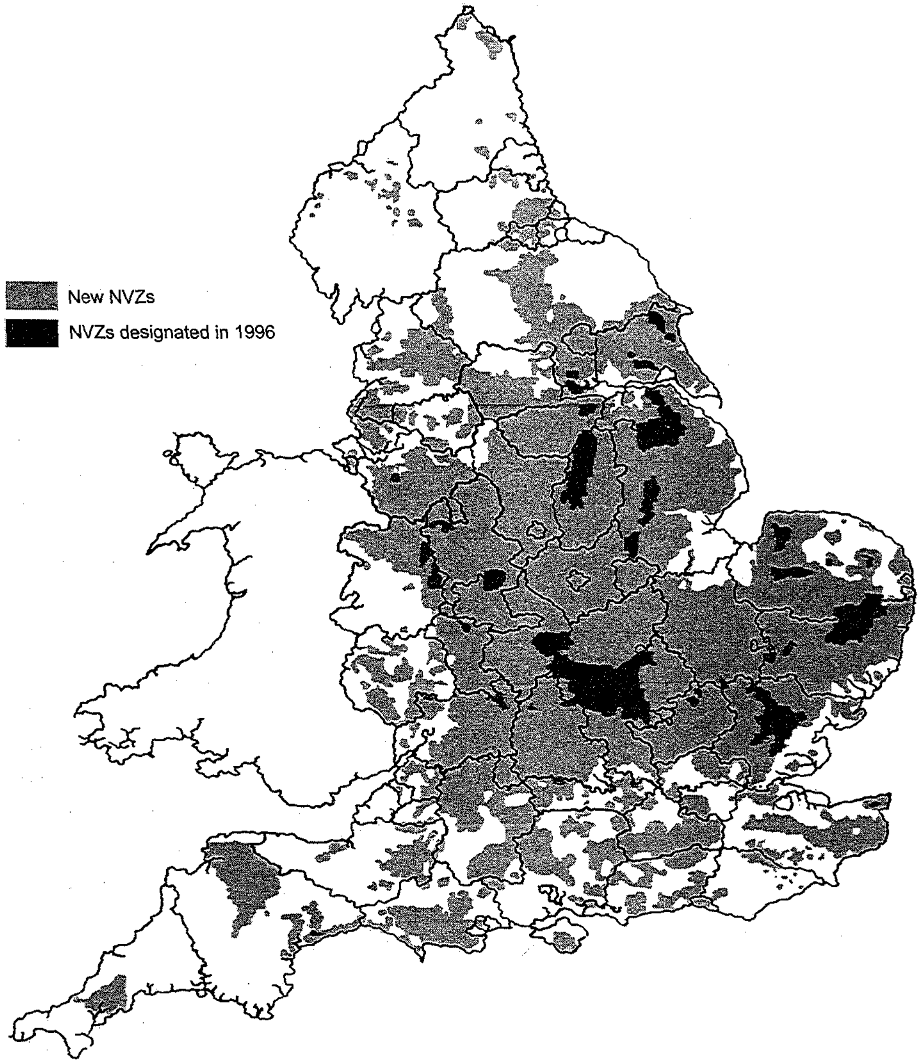

Figure 1. Nitrate-vulnerable zones (NVZs) in England, until 1966 nitrate pollution was restricted to a few areas, but by 2002 it had spread throughout most of the country

Source: www.defra.gov.uk/environment/water/quality/nitrate/maps.htm where the population has grown from 1.70 billion in 1961 to 3.72 billion in 2001, and is expected to reach 4.27 billion in 2025. However, there is plenty of scope to improve the management of such inputs so as to minimize ongoing land and environmental degradation. In this paper this scope is explained in the light of existing scientific information and the traditional knowledge of farmers.

Does alternative agriculture have solutions?

Ever-increasing attention is being paid to the environmental impact of conventional agricultural practices and in this context organic farming as an alternative is gaining recognition as a relatively environmentally friendly crop production system. Both the area and markets of organic produce are expanding every year. Based on a United Nations survey, at least 130 countries produce organic food commercially (International Trade Centre 1999). Total global area is now estimated at more than 7 million hectares while the market for organic food has swelled to an estimated US$ 22 billion per year (Brown et al. 2000). This expanding market seems to be prompting farmers to shift to organic agriculture the extent to which this system can meet the food needs of the ever-growing population from limited arable lands needs a comprehensive assessment. The authors are aware of two groups of Indian farmers, each of about 2000 farmers (one in Karnataka and the other in Madhya Pradesh) that have been growing food and fiber crops organically for at least 5 years. All these farmers are registered with companies who purchase their produce at prices generally 20–25% higher than the prevailing market price for a given product. Experts from the companies visit a certain farm regularly, look for evidence that chemicals are not used and certify the farm as 'organic' or otherwise. A book by Alvares (1996) lists 460 active organic farmers and promoters of this system of agriculture in India. Few of them visited by the authors had similar buy-back arrangements with non-governmental organizations (NGOs) or companies. Some were certified by such international certification agencies as Skal International (www.skalint.com), or Demeter International (www.demeter.net) [(both of whom have offices in at least 20 countries), or the Indian Organic Certification Agency (Indocert), indocert@vsnl. com].

In countries where organic farming has long been in practice, organic farms are usually associated with a significantly high level of biological activity (bacteria, fungi, springtails, mites, and earthworms). This is generally ascribed to a versatile crop rotation system (generally involving polyculture rather than monoculture), reduced or no application of fertilizers as crop nutrients, and a ban on chemical pesticides, resulting in lower leaching losses than those reported from conventional farms (Hansen et al. 2001). Also, the level of biodiversity (e.g., in flora, arthropods, birds) is higher on an organic than on a conventional farm (Stockdale et al. 2001). A team lead by McIssac at the University of Illinois, USA reported that the nitrate concentration in drainage water from organically managed fields was about half of the concentrations measured in conventionally managed fields. This information was indicated to have implications on the nitrate pollution in Illinois rivers and on State policies on its management (www.aces. uiuc.edu/~asap/research/stew_farm/sf-hom.html). Alternative agricultural systems have good potential to address issues of agricultural pollution associated with conventional agriculture.

There are several streams of crop husbandry generally called 'alternative agriculture'. Two such systems that follow strict protocols of cropping are 'biodynamic agriculture' and 'permaculture'. Common practice among them is that they disallow the use of bagged fertilizers and chemical pesticides. In this paper, alternative agriculture is considered to be any system that addresses the issues of environmental and land degradation and residues of harmful chemicals in the food chain.

Are high yields possible with alternative agriculture?

Crop yields on most organic farms are generally lower than on conventional farms. In Europe, yields of organically grown arable crops are 60–80% of those grown in comparable conventional systems. In developing countries organic farming practices have increased crop yields with minimal external inputs (Stockdale et al. 2001). This is perhaps due to improved crop nutrition from the combined use of chemical fertilizers and organic materials (particularly in fields low in organic matter), generally referred to as 'integrated nutrient management'. Some organic farmers have claimed to produce yields equal to or higher than those from conventional agricultural practices and to have maintained high soil quality (Reganold et al. 1993), but these studies were on orchard crops or on sheep ranches. A farmer in Japan claims to have grown crops (including wheat) organically for the last 40 years, and to have harvested yields at par or higher than those of his neighboring conventional farmers (Fukuoka 1978). In India some groups are also claiming to harvest high yields with organic farming practices (Table 2), but such claims are difficult to accept because they generally do not strictly follow scientific experimental protocols to allow dependable comparisons.

Most scientists, however, discard even the possibility of harvesting high yields following the application of such inputs as composts and green manures and non-chemical crop protectants. Even if it is possible to achieve high yields with quantitative applications of compost, there will not be enough plant biomass or animal dung available to meet the likely demand in such densely populated countries as India and China. Several experiments have indicated high yields can be achieved solely by applying with chemical fertilizers alone or in combination with composts. Despite applying large quantity of biomass (e.g., *Lantana* incorpo-

Table 2. Crop yields (t ha^{-1}) claimed by organic farmers in India[1]

Crop	Conventional	Organic
Sorghum	0.8–1.1	0.9–1.2
Cotton	1.7	1.8
Groundnut	0.3–0.4	0.4–0.6
Rice	3.6–3.8	4.4–4.6
Wheat	2.0	2.2–3.2

1. Source: Ahinsak Kheti (2002)

rated before sowing wheat @ 5 t ha^{-1} and its effects noted on the following maize crop, Table 3), or the farmyard manure (FYM) applied to pearl millet (Table 4), crops did respond to N-application suggesting that the applied organic matter did not meet the N-needs of the different crops. Such data suggest the need to use fertilizers to attain high yields, and also indicate the importance of plant biomass if sustainable high yields are to be harvested.

But some scientific data does give credence to the likelihood of harvesting high yields using alternative agriculture techniques. For example, plants without applied fertilizer-N attracted fewer pest attacks, and polyculture systems (another important feature of alternative agriculture) have higher predation ratios of natural enemies to herbivorous insects than those in monocultures (Andow 1991; Russell 1989). There are reports of low disease incidences in polycultures, e.g., intercropped *Phaseolus* beans had less severe angular leaf spot infection than those that are sole cropped

Table 3. Yields (t ha^{-1}) of maize obtained from plots receiving biomass[1] and nitrogen treatments, mean of 2 years (1996/7–1997/8), Himachal Pradesh, India

	N levels				
Treatments	0	60	90	120	Mean
Control	0.73	2.77	3.48	4.08	2.77
Lantana	1.31	2.60	3.92	4.45	3.20
Eupatorium	1.31	3.16	4.01	4.50	3.25
LSD (P = 5%)		NS			0.206
Mean	1.12	3.01	3.80	4.34	
LSD (P = 5%)		0.235			

1. 5 t ha^{-1} *Lantana* or *Eupatorium* incorporated into soil with residue of previous wheat crop
Source: AICRP (2000)

Table 4. Yields (t ha^{-1}, 20-year means) of pearl millet obtained with combined applications of FYM and nitrogen in a long-term experiment (1967–86), and organic carbon (mean %) in top 45 cm of soil profile (October 1987), Hisar, Haryana, India

	Pearl millet yield (t ha^{-1})				Organic carbon (mean %)			
FYM	N applied (kg ha^{-1})				N applied (kg ha^{-1})			
(t ha^{-1})	0	60	120	Mean	0	60	120	Mean
0	1.60	1.96	2.38	1.98	0.21	0.25	0.27	0.24
15	1.81	2.00	2.81	2.21	0.30	0.37	0.41	0.36
30	2.13	2.32	2.95	2.46	0.41	0.43	0.45	0.43
45	2.20	2.46	3.04	2.57	0.41	0.44	0.48	0.44
LSD[1]		NS		29.0		NS		0.05
Mean	1.94	2.18	2.80	0.33	0.37	0.40		
LSD		0.79				NS		

1. LSD (P = 5%): FYM (F) = 0.29, Nitrogen (N) = 0.79, F × N = NS
Source: Gupta et al. (1992)

(Boundreau 1993). The addition of composts and plant biomass provides important sources of nutrients since these materials provide all the nutrients a plant may need, without the imbalances (particularly N) generally associated with the application of large quantities of artificial 'bag' fertilizers. Compost and crop residues are important raw materials that enhance the activity of soil flora and fauna as indicated by the enhanced activity of the soil enzymes that are required to mineralize nutrients and make them availabe to crops (Nannipieri et al. 1978; Ross and Cairns 1982). But, low levels of some nutrients (e.g., N) may retard plant growth unless composts and crop residues are supplemented. Organic farmers generally green manure their crops with legumes to enhance soil N.

With the exception of a few niches, large quantities of organic materials are not available to farmers at present. Farmers in some areas of four Asian countries continue to burn large quantities of crop residues, e.g., in the Punjab 12 million t of rice and wheat straw that could serve a good source of soil organic matter is burned annually (Sidhu et al. 1998). In other areas such strategies for on-farm production of biomass as growing multiple-use tree species on farm boundaries have to be considered. Some organic farmers mix annual crops with orchard or agroforestry crops that provide a ready source of biomass for composting.

Foliar application of nutrients, particularly N, can boost crop growth and yields (Moursi et al. 1980; Turley et al. 2001). In a mini-experiment conducted at ICRISAT, Patancheru, in 2002 (different from that reported later in this paper), cotton plants without soil-applied urea, but following the application of large quantities of plant biomass and FYM, when sprayed twice with 1% urea at 147 and 173 days after sowing had chlorophyll activity [measured on third open leaf from the plant apex using a spadmeter (SPAD-502) from Minolta, Japan] similar to those receiving 80 kg N ha^{-1} with or without additional biomass. Such enhanced chlorophyll activity may improve crop growth. The tissue-N concentration in the urea-sprayed cotton was lower than that in the treatments receiving soil-applied N (80 kg N ha^{-1}), so was likely to be less damaged by insect pests. If this is improved, it may be possible to achieve high yields by spray-applying nutrients, particularly fertilizer N (e.g., 25 kg N applied as 5 sprays of 500 L ha^{-1} of 1% urea solution in water, against at least 80 kg N ha^{-1} applied to the soil). Farmers know crops grow well if they apply compost (particularly when it contains earthworms). Spraying a wash made by mixing compost in water (biosolution) should help to improve crop yields and attract fewer insect pests.

Even if high yields could be achieved, one of the most common criticisms of organic agriculture is its requirement of more labor than conventional farming. Offermann and Nieberg (1999) concluded that labor use is on average 10–20% higher on organic farms than on comparable conventional farms in Europe. Such information is not available for Asia. Talking to some farmers in India suggests that at present organic farmers are not worried of spending more on labor, if it makes economic sense. Perhaps they are satisfied with the savings from buying fewer chemical fertilizers and pesticides, and with the 20–25% higher than the prevailing market prices they receive for their produce. But, research managers and policy-makers responsible for food security (at a district or national level) must ensure yields comparable to those obtained by conventional agricultural practices, before supporting any alternative system.

Experience at ICRISAT

Assuming that farmers following alternative agricultural practices are indeed harvesting high yields, it is worthwhile to explore why, so that such practices may easily be adopted by other farmers. At ICRISAT, an experiment with four treatments (T1–T4) according to the details given in Table 5 was initiated in June 1999 to determine the potential of harvesting high yields from crops that receive low-cost inputs. The major objective of this experiment was to learn if plant biomass (added to three of the four treatments) could be used as surface mulch instead of burning (a practice common in at least four Asian countries) and serve as source of crop nutrients. The experiment is on a deep Vertisol and is fully rainfed. The annual mean rainfall at Patancheru, the site of the experiment, is 783 mm that allows two intercrops or sequential crops to be grown in a year. To be certain of

Table 5. Treatments used in continuing long-term experiment[1] at ICRISAT, Patancheru India, June 1999 to April 2002

Inputs	Treatments[2]			
	T1	T2	T3	T4
Land preparation	0	0	Conventional (bullock-drawn)	Conventional (bullock-drawn)
Sowing	Bullock-drawn drill	Bullock-drawn drill	Bullock-drawn drill	Bullock-drawn drill
Biomass	10 t ha^{-1} rice straw as annual surface mulch	10 t ha^{-1} farm waste, stubbles, hedgerow foliage	0	10 t ha^{-1} farm waste, stubbles hedgerow foliage
Compost	1.50–1.77 t ha^{-1} annually	1.50–1.77 t ha^{-1} annually	1.8 t ha^{-1} Year 2 only	1.8 t ha^{-1} Year 2 only
Nitrogen (N)	0	0	80 kg ha^{-1} 2 split doses annually	80 kg ha^{-1} 2 split doses annually
Phosphorus (P)	20 kg ha^{-1} rock phosphate	20 kg ha^{-1} rock phosphate	20 kg ha^{-1} SSP[3]	20 kg ha^{-1} SSP
Plant protection	Biopesticides	Biopesticides	Chemical pesticides	Chemical pesticides
Weeding	Manual, weeds retained	Manual, weeds retained	Manual, weeds discarded	Manual, weeds discarded

1. Crops grown in all plots: Year 1 pigeonpea–chickpea sequential, Year 2 sorghum/pigeonpea intercrop, Year 3 cowpea/cotton intercrop
2. T1 = low-cost 1; T2 = low-cost 2; T3 = conventional agriculture; T4 = conventional agriculture + biomass
3. SSP = Single superphosphate

production these crops must be sown as intercrops during the rainy season, in June or July. Different crops were grown in each year of the experiment but were the same across all four treatments. This experiment provides an excellent field site for testing the hypothesis that treatments receiving high biomass as a source of nutrients (an important input in alternative agriculture) harbor high soil biodiversity and support high biological activity, and that these factors are associated with the high yields observed.

It may be noted that the experiment was essentially an unreplicated study conducted on large plots (0.2 ha for each treatment, total area 1.02 ha). The effect of insect pest management using biopesticides (bacteria in particular) observed as the effects on pests (*Helicoverpa* pod borer in particular) and their natural enemies and on earthworms were considered inappropriate on small plots. Therefore the plot sizes chosen were close to those of farmers' fields in developing countries. Such a protocol is not new (Guldin and Heath 2001, Guthery 1987) and seems an acceptable norm under the experiment circumstances. The study only provides some insights into potential effects of the treatments and should be interpreted accordingly. There were 30 plots each of T1–T4. Observations were made from each. Two of the four treatments (T1 and T2) in this on-going experiment receive plant biomass as their major source of crop nutrients and depend on herbal extracts and microorganisms as biopesticides. Crops in T3 plots received all inputs recommended for a given crop in the local area while those in T4 plots besides receiving all conventional agricultural inputs, also received the same quantity and quality of biomass as that applied to T2 plots.

While the data assembled in the first 3 years of the experiment is being thoroughly analyzed prior to publication, preliminary trends indicate that in two out of three years, higher yields were harvested from T1 and T2 than from T3. In year 2, the combined yield of sorghum/pigeonpea intercrop varied from 5.03 t ha^{-1} in T1 to 5.87 t ha^{-1} in T2, compared to 4.74 t ha^{-1} in T3 and 5.14 t ha^{-1} in T4. In year 3, the cowpea from the cowpea/cotton intercrop was used as a green fodder and to enhance soil fertility and encourage natural enemies of insect pests. The yields of cotton ranged from 0.90 in T1 to 0.95 t ha^{-1} in T2, while only 0.44 t ha^{-1} was harvested in T3, and T4 yielded 0.68 t ha^{-1}.

In both years 2 and 3, the high yields in T1 and T2 that were protected by herbal extracts, such as neem oil, and microbial pesticides, were largely attributable to their having suffered less insect pest damage than T3. There were higher populations of spiders and coccinelids (ladybird beetles), the natural enemies of insect pests, in T1 and T2 than in T3 and T4 (Figure 3).

The stover (plant parts other than those of immediate economic importance, e.g., grains or cotton seed in this experiment) yield in all plots was around 10 t ha^{-1}, i.e., the same quantity as that added to T1 and T2 as surface mulch but always higher in T3 and T4 than in T1 and T2.

It is widely accepted that only a portion (<10%, T J Rego, unpublished data) of N applied as biomass to a soil is recovered by the crop. In T1 and T2 recoveries of applied N and P were higher than those usually reported in published literature. One could therefore suspect that the soil in T1 and T2 would have been depleted of N and P. But, at the end of year 3, the level of total soil nutrients (N + P) in the top 60-cm soil profile in T1 and T2 improved by 3.7–7.6% over that at start of the experiment in June 1999. It therefore seems that after initial priming of the system

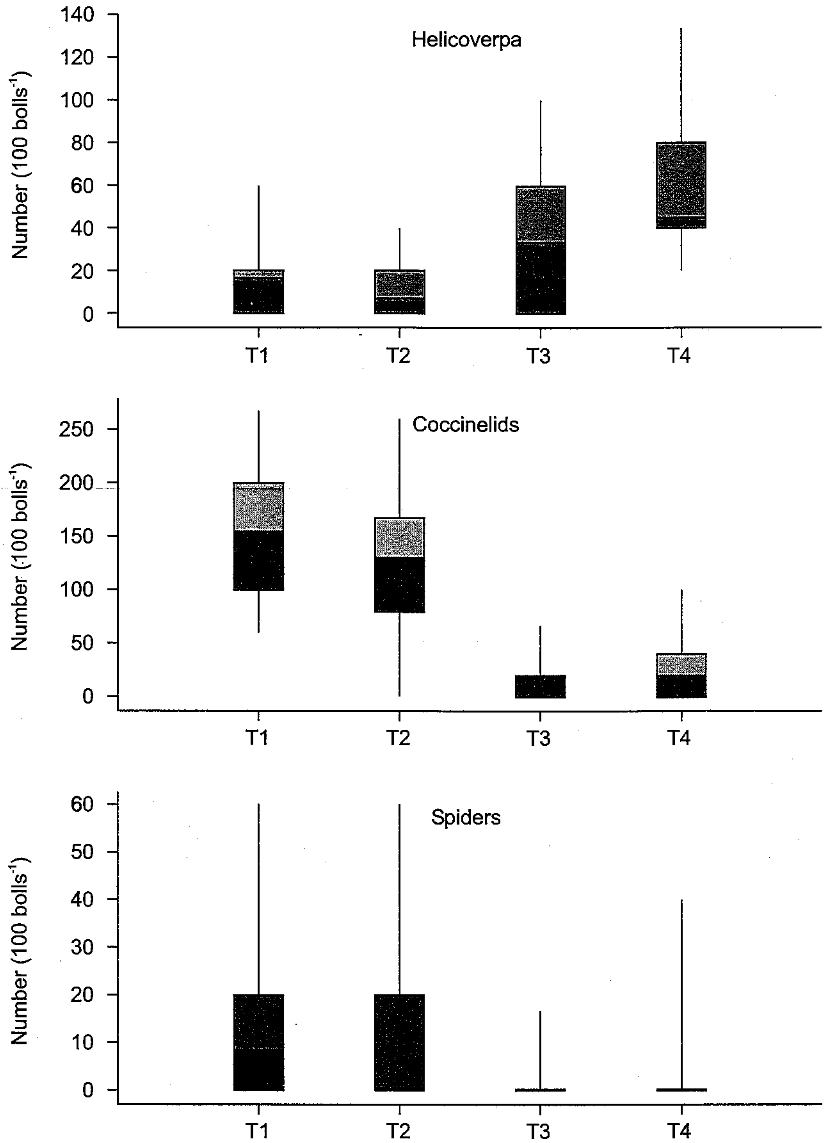

Figure 2. Trends in the number of coccinelids, spiders and *Helicoverpa* larvae per 100 cotton bolls[1] observed at 88 days after sowing in four treatments of a long-term field experiment, ICRISAT, Patancheru, 2001/2.

1. The young cotton bolls (squares) randomly selected for the observation were 1-cm diameter, 150–180 squares per treatment were observed (5 bolls $plot^{-1}$ X 30 plots $treatment^{-1}$) to collect the information

with plant biomass, the treatments (T1, T2 and T4) receiving plant biomass may be able to enhance and harness soil flora–fauna activity for crop production. It also appears that the four crop husbandry systems had very different compositions and abundance of soil biota – both invertebrates and microorganisms. Such differences influence the plant and soil processes differently and need to be investigated in order to develop management strategies capable of producing crops with sustainable high yields using low-cost inputs.

For the first 3 years of the experiment the yield of non-leguminous crops was invariably higher in T3 and T4 that received chemical fertilizers, supporting the widely held view that chemical fertilizers are a must for high yields of non-leguminous crops, including cereals. But the yield of legumes (relevant in year 2 in this study) was higher in T1 and T2 than in T3 and T4. As a result the annual productivity in T1 and T2 was higher (5.03–5.87 t ha^{-1}) than in T3 and T4 (4.74–5.13 t ha^{-1}) largely due to the lower levels of pest damage in T1 and T2.

Conclusion

It is widely believed that using plant biomass, composts and biopesticides for crop protection are more benign agro-practices than using chemical fertilizers and pesticides. But for these practices to be supported by farmers, scientists and policy-makers, high yields (particularly of cereals and non-leguminous crops) must be ensured. Learning from the experience described above and from the published literature, the authors believe that soil flora and fauna biodiversity increase with efficient management of plant biomass. Also, that there is potential to harvest high yields by strategically using the biomass available on a given farm in combination with chemical fertilizers. However, more work is needed to verify these observations. Crop husbandry protocols (Table 6), that could achieve high yields while enhancing the activity and biodiversity of soil flora and fauna through inputs of plant biomass, low doses of fertilizers and biopesticides, without sacrificing the productivity of a given piece of land have been proposed. An on-farm experiment to verify these protocols has been initiated in an intensively cropped, irrigated area (Karnal, Haryana, India) in the postrainy season 2002/3.

Table 6. Proposed protocol for high yield through eco-services, for a small to medium-sized farm

Activity	**Present practice**	**Suggested alternative**
Tillage	Bullock-drawn, tractor	Use of mulch, No tillage (except at sowing) crop residue incorporation and use of tractor in case of medium farm
Seed treatment	Thiram	Antagonistic bacteria
Weeding	Herbicides, interculture, manual (weeds discarded)	Manual (weeds retained as mulch) (interculture on medium-sized farms)
Nutrients	Chemical fertilizers (generally imbalanced use) microbial inoculants, legumes in system, compost application	Microbial inoculants, crop residues, legumes in system, composts and their **biosolutions**, and need-based amendments with chemical fertilizers
Insect pest management	Chemical pesticides, mechanical	**Non-chemical pesticides, micro-organisms, mechanical (shaking off insect pests from plants)**
Disease management	Disease-resistant lines, fungicides	Disease-resistant lines, **non-chemical pesticides**

1. Bold type indicates less formal research; rely on experience of farmers and NGOs

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Improving agricultural productivity and livelihoods through pollination: some issues and challenges

Uma Partap[1]

Introduction

With the ongoing shift in the focus of agriculture from subsistence systems to commercial agriculture in many developing countries, new challenges for improving and maintaining productivity are emerging. Among these challenges are crop failures due to inadequate pollination. This is caused by several factors, most important of which include the lack of adequate numbers of pollinators. In recent years pollinator populations and diversity have been declining due to several factors including: decline in wilderness and loss of habitat, land-use changes, monoculture-dominated agriculture, and excessive and indiscriminate use of agricultural chemicals and pesticides. Consequently, the need to ensure pollination particularly by conserving pollinators and incorporating managed crop pollination has increased and will increase further. This calls for a more intensive focus on the issue from the perspectives of policy, research, development, and extension. Policy reorientation, improving institutional capabilities and human resource development are key areas needing attention.

Based on studies on apple pollination and farmers concerns in Bhutan, China, India, Nepal and Pakistan (Partap 1998; Partap and Partap 2002; Partap et al. 2001), this paper presents a general picture of pollination issues in the uplands of semi-arid subtropical areas of the Hindu Kush–Himalayan region. It tries to analyze such issues as the decline in pollinator populations, its impact on agricultural productivity and implications for pollination management, the contribution of pollination to food security and improving rural livelihoods, and the challenges of integrating pollination as a necessary input to agricultural policies and plans in the light of available information. The need to conserve pollinator diversity to ensure pollination is emphasized, and at the same time an alternative perception to beekeeping – namely, 'to promote bee-keeping primarily for crop pollination with honey and other bee products as by-products' is presented. This new approach adequately combines the two benefits, but institutional reorientation in the context of policies, research, and extension might be necessary.

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Although much of the information presented relates to experience in the semi-arid subtropical region of the Himalayas, it nonetheless presents important lessons to farmers and institutions in the semi-arid tropics (SAT) because institutional and policy issues throughout the developing world are largely the same.

Pollination as an input to agricultural productivity and eco-services

For a farmer, the most desired goal in agriculture is to obtain the maximum possible crop yields from given inputs and ecological settings. Farmers also try to improve the quality of their produce, particularly fruit and seeds. It is particularly important to obtain a premium price for produce when farmers are engaged in cash-crop farming.

There are two well known ways of improving crop productivity. The first is by making use of agronomic inputs including such plant husbandry techniques as the use of good quality seeds and planting material, and practices to improve yields, e.g., providing good irrigation, organic manure, and inorganic fertilizers and pesticides. The second method includes the use of biotechnological tools, e.g., manipulating the rate of photosynthesis and biological nitrogen fixation, etc. These conventional techniques ensure the healthy growth of crop plants, but work only to a limited extent. At some stage, crop productivity becomes stagnant or declines with additional inputs, even if all known agronomic potentials of the crop have been harnessed (Partap and Partap 1997).

The third and relatively less-known (particularly in developing countries) method of enhancing crop productivity is through managing crop pollination using friendly insects, who in the process of searching for food provide this useful service to farmers (Partap and Partap 1997). Pollination is an ecological process based on the principal of mutual interactions or inter-relationships (known as proto-cooperation) between the pollinated (plant) and the pollinator. Pollinators visit flowers to obtain their food (i.e., nectar and pollen) and in return pollinate them. In many cases pollination is the result of the intricate relationship between plants and their pollinators, and the reduction or loss of either affects the survival of both. In recent years the Convention on Biological Diversity (CBD) has recognized pollination as a key driver in the maintenance of biodiversity and ecosystem functions (UNEP/CBD/COP/3/38).

The pollination process involves the transfer of pollen from the male part of the flower (anther) to the female part (stigma) of the same flower (self-polli-nation) or another flower of the same or another plant of the same species (cross-pollination). Pollination is vital to completing the life cycle of plants and ensuring the production of fruit and seed, whether by agricultural crops or natural vegetation/flora. This ecological process is an essential prerequisite for fertilization and fruit/seed set. If there is no pollination, there will be no fertilization – no fruits or seeds will be formed and farmers will harvest no crop. Pollination is therefore the most crucial process in the life cycle of the plants and is essential for crop production and biodiversity conservation. It also helps to enhance farm income and rural liveli-hoods. Figure 1 shows the relationship of pollination to improved livelihoods through enhancing agricultural productivity and biodiversity conservation.

Many cash crops are actually self-sterile and require cross-pollination to produce seeds and fruit (McGregor 1976; Free 1993). But it is not only self-sterile varieties that benefit from cross-pollination, self-fertile varieties also produce more and better quality seeds and fruits if they are cross-pollinated (Free 1993).

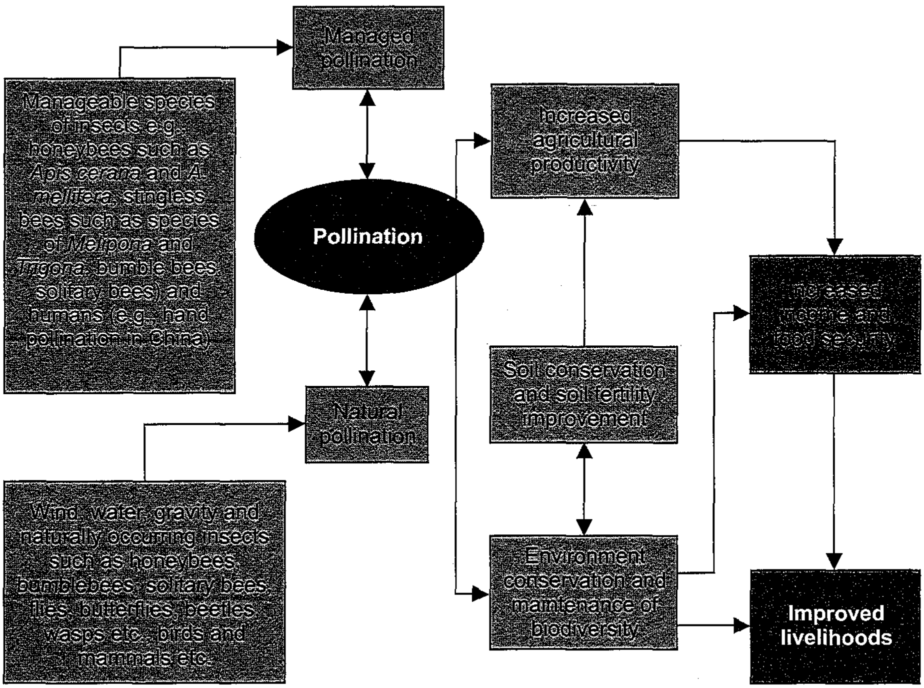

Figure 1. Contribution of pollination to enhancing agricultural productivity and improving rural livelihoods

Contribution of pollination to food security and enhancing livelihoods

Agriculture is the basis of the livelihoods of large parts of the rural population in developing countries. Most agricultural land is not only marginal in terms of potential productivity; its quality also appears to be deteriorating as indicated by declining soil fertility and crop productivity. As a result, many families face food shortages of varying degree and these are contributing to the chain reaction process of poverty–resource degradation–scarcity–poverty (Jodha and Shrestha 1993). This pessimistic scenario means that efforts should be made to explore all possible ways to increase the productivity and carrying capacity of such farming systems in order to improve the livelihoods of marginal households. This cannot be done by emphasizing the cultivation of cereal crops alone.

If poor farmers are going to compete favorably in the modern world, they must be given options and alternatives that are not already captured by competition. Cash-crop farming, i.e., growing fruit and vegetable crops suited to specific agroclimatic conditions, is one comparative advantage that could be exploited by these farmers. For example, in uplands of the semi-arid parts of the Himalayan region off-season vegetables and fruits provide a comparative advantage to farmers (Partap 1999). A variety of fruit crops including apples, peaches, pears, plums, almonds, apricots, grapes, and cherries are grown. Logically this increases the need for managed pollination. Equally interesting is the adoption of apiculture as a new enterprise by many people. Promoting bee-keeping to help pollinate cash crops will be of benefit to both the beekeepers who will receive money for the pollination services of their honeybees and will harvest honey, and to the farmer whose income will be increased through boosting crop productivity as a result of the bees' pollination services. This will help ensure food security and enhance the livelihoods of both the farmers and the beekeepers (Figure 1).

Inadequate pollination as a factor affecting agricultural productivity

Studies revealed that among several factors affecting agricultural productivity, pollination plays an important role, but that there are signs that the overall productivity of many agricultural crops is decreasing. Possibly worst-affected are such cash crops as fruit, particularly apples and pears, and off-season vegetables on which farmers pin their hopes of cash income, and that are underpinning development efforts (Partap and Partap 2002). This reduction in productivity is taking place despite intensive efforts at extension and information dissemination to support improvements in a range of management practices, and strong support for the introduction of successful commercial crop varieties. Evidence of this emerging pollination problem has been documented in a series of field studies across the Himalayan region (Partap 1998; Partap and Partap 2000; 2001; 2002; Partap et al. 2000). These studies investigated the state of inadequate pollination, its causal factors and its impact on crop productivity.

Pollinator populations and diversity at risk

It has been estimated that over 75% of the world's crops and over 80% of all flowering plants depend on animal pollinators, especially bees. Globally, the annual contribution of pollinators to agricultural crops has been estimated at about US$ 54 billion (Kenmore and Krell 1998).

However, in recent years pollinator populations and diversity are declining. The factors causing this decline could be the decline in habitat, with the accompanying decrease in food supplies (nectar and pollen) as a result of a decline in pristine areas, land use changes, increase in monoculture-dominated agriculture, and the negative impacts of modern agricultural interventions, e.g., use of chemical fertilizers and pesticides (Verma and Partap 1993; Partap and Partap 1997; Partap and Partap 2002). Earlier farmers grew a variety of crops that bloomed during different months of the year and provided food and shelter for a number of natural insect pollinators, so the pollination problem did not exist. Monocropping also requires pesticides to be used to control various pests and diseases. Thus, it not only reduces the diversity of food sources for pollinators, but also the pesticides kill many pollinators pesticides. Insecticides have contributed to the extermination of both the diversity and abundance of pollinating insects. Changes in climate might also affect insect numbers (Partap and Partap 2002).

Impact and implications of decline in pollinator population and diversity

The decline in pollinator populations and diversity presents a serious threat to agricultural production and conservation and the maintenance of biodiversity in many parts of the temperate, subtropical and tropical world. One indicator is that the decline in natural insect pollinators is decreasing crop yields and quality despite adequate agronomic inputs. Examples can be found in Himachal Pradesh in northwestern India, northern Pakistan, and parts of China where despite all agronomic inputs, the production and quality of such fruit crops as apples, almonds, cherries, and pears are declining. Extreme negative impacts of declining pollinator populations can be seen in northern Pakistan where neither farmers nor institutions understood the importance of pollination. Disappointed with the very low yields and quality of apples as a result of poor pollination, several farmers in Azad Jammu and Kashmir actually chopped down their apple trees (Partap 2001).

One implication of the decline is that it has created the need for managed pollination to maintain crop yields and quality. Cash-crop farmers in areas where pollinator populations have declined now are forced to manage pollination of their crops. For example, farmers in Himachal Pradesh, northwestern India are using honeybees to pollinate their apples, while those in Maoxian County in the Hengduan mountain area of China are pollinating their apples and pears by hand using human pollinators because beekeepers will not rent their honeybee colonies to farmers who use excessive pesticides, even while apples are flowering. A large part of these farmers' income is spent on in managing pollination.

The need to conserve, promote and diversify pollinator resources is pressing in several countries of the developing world. This calls for research and extension activities to be initiated and strategies to be developed to promote conservation and the sustainable use of pollinators. It will require a much wider understanding of the multiple services provided by pollinator diversity and the factors that influence them in agricultural ecosystems to secure sustained pollinator services.

Promoting use of honeybees: one option for managing pollination

Lack of pollinators is an important factor in inadequate pollination. Under such circumstances manageable species of honeybees such as *Apis cerana* and *Apis mellifera* assume importance and beekeeping is the most promising way to pollinate crops, especially cash crops. Although only 15% of the world's principal food crops are pollinated by manageable bee species (e.g., honeybees, bumblebees etc.), these crops make an immense contribution to increased food security and enhance livelihoods through generating cash income for farmers. The use of managed species of is the easiest and most readily available way to ensure crop pollination.

Honeybees are the most efficient pollinators of cultivated crops because: their body parts (including hair) are especially modified to pick up pollen grains, they have potential to work long hours, they show flower constancy, and are adapted to different climates (McGregor 1976; Free 1993). *Apis cerana* and *A. mellifera* are valuable species because they can be kept in hives, and transported to fields to pollinate crops. Managed honey production, and beekeeping are part of the cultural and natural heritage of several communities in many (including developing countries).

In various fruit and vegetable crops, pollination by honeybees increases crop yield by increasing fruit and seed set and enhances fruit quality (shape, size, weight, color and taste) and seeds and reduces premature fruit drop.

The main significance of honeybees and beekeeping is pollination; hive products are of secondary value. It has been estimated that the benefit of using honeybees to enhance crop yields through cross-pollination is much higher than their role as producers of honey and beeswax. Morse and Calderone (2000) showed that the annual value of honeybee pollination in the USA is US$14.6 billion. Similar annual estimates have been made for other countries: e.g., in Canada US$ 1.2 billion (Winston and Scott 1984), about US$ 3 billion in the European Union (EU) (Williams 1992), and US$ 2.3 billion in New Zealand (Matheson and Schrader 1987). Cadoret (1992) estimated that the direct annual contribution of honeybee pollination to increase farm production in 20 Mediterranean countries was US$ 5.2 billion – 3.2 billion in developing countries and US$ 2 billion in others.

Experimental research on the impact of honeybee pollination

A number of studies have been undertaken to show the impact of honeybees in enhacing crop productivity, but their role is not very well understood in developing countries, since most of the research work has been done in developed countries.

Limited research carried out in the Himalayan region has proved that bee pollination increases the yield and quality of apples (Dulta and Verma 1987; Gupta et al. 1993), peach and plum (Partap et al. 2000), citrus (Partap 2000a), kiwi fruit (Gupta et al. 2000) and strawberry (Partap 2000b) (Table 1). These studies have also proved that bee pollination not only increases fruit set but also reduces fruit drop in apple, peach, plum and citrus and reduces the percentage of misshapen fruits in strawberry. The results also showed honeybee pollination increases the juice and sugar content in citrus fruit (Table 1).

Studies have also shown that honeybee pollination enhances seed production and quality in various vegetable crops (Partap and Verma 1992; 1994, Verma and

Table 1. Impact of honeybee (*Apis cerana*) pollination on the productivity of fruit crops

	Fruit increase (%)			
Crop	Set	Mass	Size (length, diameter)	Reference
Apple[1]	10	33	15, 10	Dulta and Verma 1987
Peach[1]	22	44	29, 23	Partap et al. 2000
Plum[1]	13	39	11, 14	Partap et al. 2000
Citrus[1]	24	35	9, 35 Increased fruit juice by 68% and juice sugar content by 39%	Partap 2000a
Strawberry	112	48	Misshapen fruits decreased by 50%	Partap 2000b

1. Premature fruit drop reduced by bee pollination

Partap 1993; 1994) (Table 2). Scientific evidence also confirms that bee pollination improves the yield and quality of asparagus, carrot, onion, turnip, and several other crops (Deodikar and Suryanarayana 1977). Recent experiments in different parts of the Himalayan region show that honeybee pollination not only increases fruit set in rapeseed and sunflower, but also increases their oil contents (Singh et al. 2000).

Table 2. Impact of honeybee (*Apis cerana*) pollination on vegetable seed production

Crop	Increase (%)		
	Pod set	Seed set	Seed mass
Cabbage	28	35	40
Cauliflower	24	34	37
Radish	23	24	34
Broad-leaf mustard	11	14	17
Lettuce	12	21	9

Source: Partap and Verma (1992; 1994), Verma and Partap (1993; 1994)

The quality of pollination is determined by: the number of colonies per unit area, the strength of bee colonies, the placement of colonies in the field, the time of placement of bee colonies, and the weather conditions. Experiences from pilot experiments have shown that the best results are achieved by placing strong bee colonies free of diseases, and with large amounts of unsealed brood when the crop is at 5–10% flowering (Free 1993; Verma and Partap 1993).

Using honeybees to pollinate apples in Himachal Pradesh

Developed countries such as USA, Canada, Europe, and Japan have long been using honeybees to pollinate apples, almonds, pears, plums, cucumbers, melons, watermelons, and berries, but the developing countries lag far behind in using honeybees, use even though plenty of scientific evidence is now available that the practice of using honeybees to pollinate crops is beneficial. While in the USA the first colonies of honeybees were rented out to pollinate pears in Virginia in 1895 (Waite 1895) and apples in New Jersey in 1909 (Morse and Calderone 2000), in the Himalayan region the first colonies of honeybees were rented out for apple pollination only in 1996.

A survey carried in apple farming areas of Bhutan, China, India, Nepal, and Pakistan revealed that honeybees are being only used for apple pollination in Himachal Pradesh (Partap 1998). Here, some farmers keep their own honeybee colonies while others rent them from the Department of Horticulture or from private beekeepers. The fee for renting colonies of *A. cerana* or *A. mellifera* is In Rs.800 (US$ 16.4) per colony for the 2-week flowering period. This includes Rs.500 (US$ 10.25) as a refundable security deposit and Rs.300 (US$ 6.15) as rent. At present, Himachal Pradesh is the only place in the whole of the Hindu Kush-Himalayan region where a well-organized system has been established. This large-scale use of honeybees has led to the development of a new vocation in this small state where a number of pollination entrepreneurs now complement the official government services. Reasons for this enterprise include the existence of strong research and extension institutions and farmers associations.

The survey also revealed that in addition to increasing the number of insect pollinators by renting colonies of honeybees, some progressive farmers in Himachal Pradesh are also making efforts to conserve populations of existing pollinators by making judicious use of carefully selected less-toxic pesticides and spraying outside the apple flowering period.

Promoting stingless bees: another option for managing pollination

Like honeybees, species of stingless bees (*Melipona* and *Trigona*) are also kept in hives for honey production in Central and South America, particularly in Brazil and Mexico where beekeeping is a tradition and part of local culture. Traditional beekeeping with *Trigona* also occurs occasionally in Asia, especially in Indonesia (Crane 1992). Stingless bees are very well adapted to tropical habitats. *Trigona* species occur in every continent except Europe, but *Melipona* does not occur outside the Americas (Crane 1992). In Brazil more than 250 stingless species are known and further new species are being discovered every year. Relatively few stingless species occur in Asia and Africa.

Stingless bees are important pollinators of such crops as sugar apple (custard apple), papaya, citrus, mango, guava, melons, pumpkins, sweet potato, cassava, chayote, coffee, cocoa, and macadamia. Although quantitative data on the impact of pollination by stingless bees are scanty, there is information that these bees are very efficient and effective pollinators of crops grown both in the field and in greenhouses. For example, native species of *Trigona* were reported to be more effective pollinators of macadamia than *A. mellifera* in Australia (Heard 1988; Vithanage and Ironside 1986). The sustainable use of stingless bees as pollinators needs to be mainstreamed into the agricultural system.

Promoting conservation and sustainable use of non-honeybee pollinators: the sustainable option

Over 25,000 species of bee are found globally, where they pollinate over 70% of the world's cultivated crops. Non-honeybee pollinators are estimated to provide annual pollination services worth US$ 4.1 billion to US agriculture (Prescott-

Allen and Prescott-Allen 1990). About 15% of the world's 100 principal crops are reportably pollinated by manageable species of domestic bees, while at least 80% are pollinated by wild bees. However, as explained earlier the populations of these pollinators are declining in several intensively cultivated areas, so there is need to develop strategies to conserve and promote their sustainable use. This will require much wider understanding of the value of pollinator diversity, the multiple services they provide, and the factors that impact on them.

Many species of bumblebees (*Bombus* spp.) and solitary bees, *Amegilla, Andrena, Anthophora, Ceratina, Halictus, Lasioglossum (Evylaeus), Megachile, Nomia, Osmia, Pithis*, and *Xylocopa* can be reared on a large scale and managed for crop pollination. In many developed countries various insect pollinators, including some species of bumblebees and solitary bees, are being reared and managed commercially to pollinate various crops, particularly those that are not effectively pollinated by honeybees. Bumblebees, for example, are used to pollinate potatoes, tomatoes, strawberries and other crops grown in greenhouses, alkali bees and leaf-cutter bees are used to pollinate alfalfa, horn-faced bees to pollinate apples, almonds, and other fruit trees, and other species of solitary bees on cotton, mustards, lucerne, and berseem. In Japan the solitary bee *Osmia cornifrons* is being reared and managed on a large scale to pollinate about 30% of all the country's apple crops (Batra 1995; 1997; Sekita 2001).

There is good potential for the managed use of non-*Apis* pollinators in developing countries where there are thousands of hectares of cropped land that need cross-pollination. In cold and arid areas like Balochistan (Pakistan), Mustang (Nepal), and Lahul (Himachal Pradesh), where stationary beekeeping cannot be practised because of the prevailing cold dry climate and lack of forage during the larger part of the year, conserving and managing non-honeybees for pollination could be a good option. Conservation can be ensured simply by avoiding the use of pesticides during the period when crops and other plants are blooming. This could be of great help in saving pollinators whose adult lives coincide with crop flowering.

Even though both the need and the potential exist, the practice of rearing and managing natural pollinators is practically absent in developing countries, because most institutions do not have either the mandate or necessary expertise in this field. Development and use of these insects will take a long time, major research and extension efforts will be needed before insects can be reared and managed, but efforts towards the conservation of non-*Apis* pollinators could be initiated. The first step would be to save them from the harmful impacts of pesticides. For this, there is need to raise awareness about the harmful effects of agricultural chemicals and pesticides and to train farmers and extension workers to make safe use of carefully selected less-toxic pesticides outside the crop blooming period.

Hand pollination

Hand pollination using human pollinators is another, but highly unsustainable, way to manage pollination of cash crops in intensively cultivated areas. This method is prevalent in the Maoxian valley of China where large areas of apples and pears are pollinated by hand to ensure that each flower is properly pollinated (Partap and Partap 2000). Maoxian farmers fully understand the value of managed pollination, but have a serious problem because pollinators have been killed by the overuse of pesticides. Even though beekeeping is common in the area, the practice of renting honeybee colonies for pollination is surprisingly absent and it is not promoted because beekeepers will not rent their honeybees in case they are killed. Therefore, hand pollination, promoted by the local government, is a common practice and all family members – men, women and children are engaged in a community effort to pollinate apple flowers (Partap and Partap 2000; 2002).

Various cooperative mechanisms among farmers have evolved to share labor and skills. Farmers with larger orchards generally employ laborers to pollinate. Manual pollination provides employment and income-generating opportunities to many people during the apple flowering season. Even though it is the most reliable method of ensuring apple pollination today, it will not be sustainable as a long-term solution, largely because of the increasing labor scarcity and rising costs. In areas where agriculture is diversifying to new cash crops, there is a need to raise awareness among people and local research and extension systems not only about the significance of managing pollination, but also the use of bee pollinators as an alternative to manual pollination. The risk of pesticides could be minimized through judicious use and adopting integrated pest management practices (Partap et al. 2001; Partap and Partap 2002).

Challenges in ensuring crop pollination

The development and use of insects other than hive bees in the developing world will take a long time and need major research and extension efforts. This section discusses the issues and challenges in ensuring crop pollination through using manageable species and promoting the conservation and sustainable use of natural pollinators as a sustainable solution to enhance agricultural productivity. Figure 2 presents the challenges of integrating pollination with farming systems and enhancing rural livelihoods through promoting managed pollination and conserving pollinator populations. The main constraints are lack of awareness and understanding among farmers, extension workers, planners and policy-makers about the importance of pollinators and pollination, lack of integrating pollination in agricultural development packages, scarcity of managed colonies of honeybees, and lack of knowledge about conservation, rearing, and use of pollinators and their pollination behavior.

Raising awareness

With a few exceptions among farmers in those areas where there is a pollination problem, people are not aware of the value of honeybees (or other pollinators) for agricultural production. This is because beekeeping has always been promoted exclusively as an enterprise for honey production, and because cash-crop farming is a new activity in many developing countries, so there is no indigenous knowledge on the need for managed crop pollination to enhance cash crop production. Raising awareness is the first step in development efforts.

Including pollination as a technological input to agricultural development packages

Pollination has been overlooked in agricultural development strategies and is not included as a technological input. High-value agriculture is being promoted in several areas and extension institutions offer packages of practices for each type of crop, pollination to achieve higher yields has been overlooked. Farmers have no way of knowing how essential it can be. This weakness in the agricultural extension system needs to be addressed.

Since pollination is essential, it should be included in agricultural development packages by promoting beekeeping as a 'double benefit approach'. Developing strategies to conserve, promote, and use other pollinators will also be helpful.

Influencing thinking about bees and beekeeping

Traditional thinking is that beekeeping is for honey production; its role in crop pollination is rarely considered. Today, most government agencies only promote beekeeping for honey production, e.g., by introducing *Apis mellifera*. There is a need to change the general 'mindset' about honeybees and beekeeping, and to raise awareness about the importance of managed crop pollination.

Strengthening research and development institutions

Managed crop pollination is a relatively new area, so there are few institutions with explicit mandates or expertise for its research and extension. Most

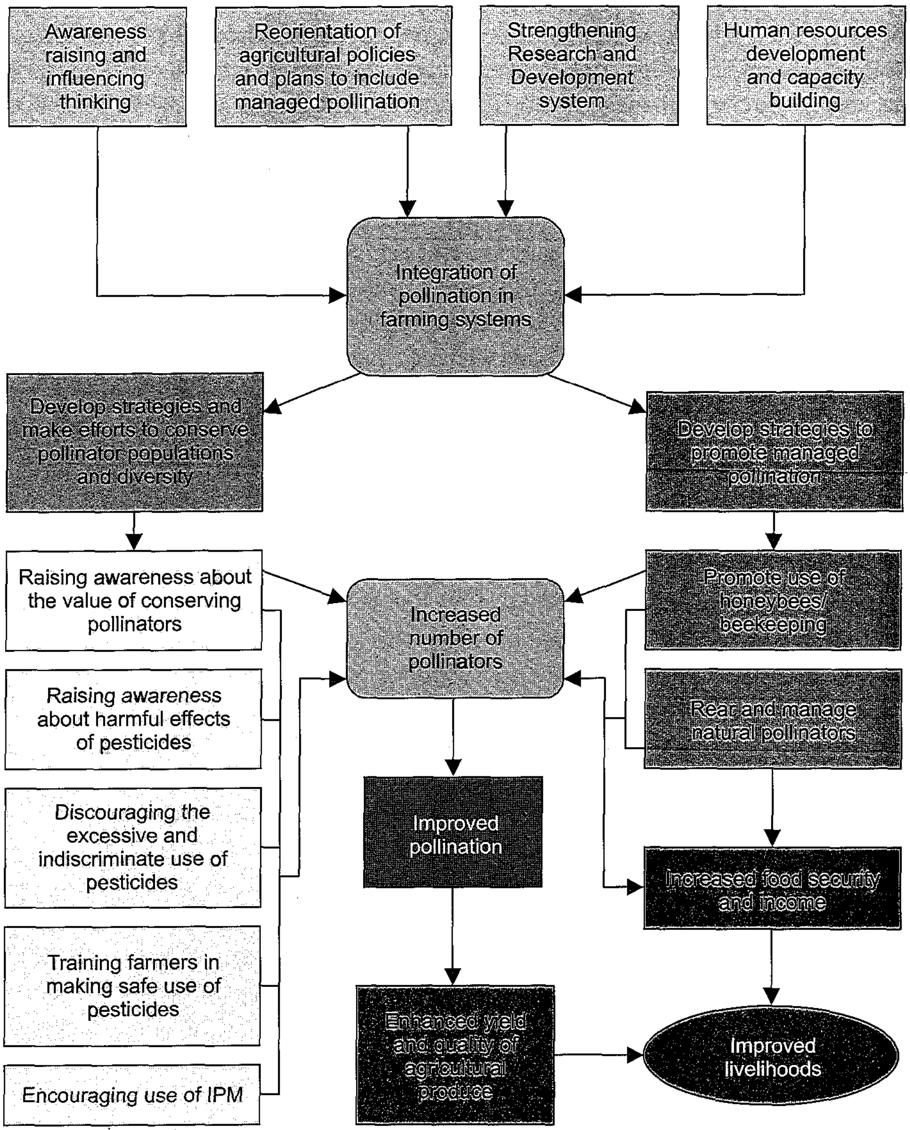

Figure 2. Awareness raising, reorientation of agricultural development policies and plans to include managed pollination as an input, strengthening R&D Institutions, human resources development and capacity building are necessary to integrate pollination in farming systems and enhance agricultural productivity and livelihoods of rural people

institutions only promote beekeeping as a cottage industry to increase family income through the sale of honey. Promoting honeybees as reliable pollinators of agricultural crops will require special efforts to strengthen research and extension systems. Such issues as declining pollinator populations and the need to conserve them need to be addressed by research institutions.

Human resources development and capacity building

Lack of knowledge among farmers is another constraint hindering the use of honeybees. Even those farmers who know that they can use honeybees to increase apple pollination and yield, do not always know how to manage the bees. Linked to institutional strengthening, greater focus is required to build the capacities of individual farmers, development workers and the farmer-led organizations that are the agents of change. There is a need to train farmers and beekeepers in managing bees to pollinate crops. There is also a need to develop human resources and build their capacities in a conserving, rearing, and using pollinators.

Crop pollination investment prospects

The inputs of pollinators in agriculture husbandry and biodiversity conservation have not been recognized by policy-makers, planners, development workers, and farmers. There is no conceptual clarity and recognition of the value of pollinators. A change in thinking at all levels is needed. The initial thrust of pollination programs should be to raise awareness about their significance and to generate knowledge and information to facilitate the formulation of strategies to ensure the wider use of honeybees primarily as crop pollinators, and secondly as honey producers. Changes in research and development investment policies may be needed to encourage this. It is also necessary to evolve strategies to promote investment in research and development that will enhance the use of pollinators. This means developing area-based approaches, and making full use of the existing diversity among pollinators.

Gender concerns

Women play an important role in agriculture and food production in several developing countries. They are the dominant labor force in agriculture and make a crucial contribution to all agricultural activities from soil preparation to postharvest operations. The development of rural women and encouraging their full participation as equal partners in the social and economic mainstream is one of today's greatest challenges.

Conservation, management, and sustainable use of pollinators have a direct impact to improving women's lives in terms of increasing both economic and food security, and reducing their drudgery. Information on the role and significance of women and how their livelihood is affected by the failure of pollination and through better management of crop pollination, is presented here to show why future strategies relating to managing pollination should give due attention to gender roles and capacity building.

Better pollination leads to increased agricultural production resulting in increased family income, and enhanced food security and livelihoods. This ensures better health, nutrition, and education for women. On the other hand, declining crops yields caused by inadequate pollination increases drudgery as women have to work extra hard to achieve food security. Women are key to the successful management of pollinators (Partap 1998; Partap and Partap 2000; Partap and Partap 2002; Partap et al. 2001). In Himachal Pradesh, women farmers manage bee colonies for use in their own orchards and for rent (Partap 1998; Partap and Partap 2002). There are numerous local women farmers' associations in Himachal Pradesh, known as *Mahila Mandals* that are actively engaged in beekeeping, renting out bee colonies, and encouraging their members to do so. As a result, a number of women beekeepers groups are evolving. This has increased the income of these women-headed pollination entrepreneurs who also benefit from honey sales. In the Hengduan mountain areas, Chinese women are the backbone of the hand-pollination process. Strategies to improve their skills are needed.

It is necessary to encourage the involvement of women in management of pollinators and pollination in other countries by creating conducive environments through extension and demonstration activities, and empowering women through training, research, and involving them in projects at national and international levels. While designing training programs and formulating policies on pollination and conservation, special consideration should be given to training women and building their capacities to bring them into the mainstream of development.

Conclusion

Like soil, water and nutrients, pollination is a limiting factor in crop productivity. A decline in agricultural productivity can be attributed to a number of factors, but pollination plays a crucial role. Such plant husbandry techniques as the use of better-quality seed and planting material and the provisions of all agronomic inputs including irrigation, organic and inorganic fertilizers, and biocides can be used, but without pollination, no fruit or seed will be formed.

The pollination issue is a relatively new problem that merits early attention. Since pollinator scarcity is the main cause of inadequate pollination, solutions lie in increasing pollinator numbers. This can be done by: conserving populations of natural insect pollinators, promoting integrated pest management, and making judicious use of chemical fertilizers and pesticides. At present, in the Hindu Kush–Himalaya region a more practical and preferred solution would be by promoting manageable species of honeybees. There is need to formulate policies that include pollination as an integrated input to agricultural production technologies. Other challenges include strengthening research and extension institutions and human resources development.

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Seed sense: strengthening crop biodiversity through targeted seed interventions

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Introduction

Seed whether true seed or vegetative planting material has multiple functions. It is both an essential input for all crop-based farming systems, and the primary harvested product of many but not all crops. The genetic information carried by the seed allows farmers to use plant genetic resources in a sustainable way and to conserve them over time. Seed is also used to deliver new varieties to farmers. Given the importance of seed, much attention has been devoted to developing new varieties, controlling seed quality, and setting up seed systems to serve the needs of farmers; but the impact of seed systems on crop and crop-associated biodiversity (C-CAB) is a strangely neglected subject.

Biodiversity has been neglected in agriculture (Vaughan 1998), and seed systems have been neglected both by biologists and many public-sector plant breeders. This is not the case with private-sector breeders who depend on functioning seed systems for their livelihoods. Smallholder agriculture in marginal areas – especially in sub-Saharan Africa (SSA) – is in crisis, and conventional approaches to agricultural research and development are being challenged. This is particularly noticeable in publicly funded crop improvement programs targeted towards crops that are important to the needs of the rural poor. Such programs are perceived to have had limited impact. The question is, what alternatives exist?

Several trends are evident in the area of plant genetic resources; enhancing the role of C-CAB in agriculture and the use of more participatory approaches in plant breeding, the application of biotechnology for crop improvement, and addressing seed-system constraints largely through policy change. All of this is taking place in an increasingly globalized economy with the private sector being the engine of growth, and governments withdrawing from service provision – especially in agriculture – and concentrating on providing an enabling environment within which the private sector can operate.

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An understanding of C-CAB and its management is seen as one avenue to a more sustainable agriculture that will maintain agroecosystem health, and pro-vide livelihood benefits to the rural poor of the semi-arid tropics (SAT). However sustainable agriculture and agroecosystem health are difficult concepts to define and measure, and are still subject to scientific discussion. Biophysical scientists in promoting more environmentally sustainable practices tend to ignore the incentives for farmers to adopt such practices. This is particularly the case for natural resource management technologies where the incentives are commonly lower than incentives to simply extract natural resources. The value of an additional dollar of output today is worth far more to most small-scale farmers than the value of much higher production levels in the distant future. If sustainability is to be pursued through promoting the adoption of new technologies, these investments must offer higher near-term payoffs than alternative demands on scarce land, labor, and capital. How often are relative returns to investments in agriculture evaluated with alternative farm investments or investments off-farm? (Freeman et al. 2003). The challenge for agricultural researchers interested in C-CAB is to learn from the mistakes of the past, and to approach C-CAB in a more holistic way. This paper examines some of the links between crop improvement research, seed systems, and globalization in the context of C-CAB.

Existing seed systems

Two types of seed system are commonly recognized; the informal seed system – sometimes referred to as the farmer seed system – and the formal seed system. The latter is increasingly operated along commercial lines and all commercial seed systems can be classified as formal, although not vice-versa, as there are examples of formal seed sector operations that are subsidized and are not necessarily commercially viable. The relative importance of the different systems depends on several factors including the degree of agricultural commercialization, and the types of crops being supplied. Both systems will be described and compared to illustrate how these systems differ, and their relative importance to poor farmers in semi-arid ecosystems.

In commercial agriculture, farmers routinely purchase seed from commercial seed companies. The choice of seed of different crops and varieties is a commercial decision based on the needs of the market, and what will grow well on a particular farm. Farmers learn about the suitability of different crops and varieties through experience, and from other sources including: promotional material from seed companies, independently run trials conducted by government agencies, commodity associations, and other institutions. Seed produced by the formal seed sector is differentiated from grain by the way in which it is managed from sowing through to the point of sale. Countries with a formal seed sector have established standards (enshrined in seed legislation) that must be adhered to if the product is to be marketed as seed rather than grain. These standards are designed to ensure that seed is of acceptable quality in terms of varietal integrity (i.e., will the plant that grows from the seed be true to types) and physiology (germination percentage being most commonly used to determine whether the seed is viable or not). Farmers purchase seed in the knowledge that the variety being sold will be true to type, and that the seed will germinate. If this is not the case, the farmer can resort to law and obtain compensation. There is a strong incentive for commercial seed companies to understand the needs of end-users (both farmers and markets), the environmental constraints to production, and to maintain rigorous quality standards from multiplication through to marketing, otherwise their business will fail. The formal seed sector is also dependent on research and development for the supply of new varieties.

Throughout much of the SAT the majority of farmers sow their own saved seed. The amount of seed saved is determined by several factors including the size of farm to be sown in the next season, the type of crop, and the need for multiple sowings where stand establishment might be affected by drought, pests, diseases, or a combination of factors. Seed is not differentiated from grain through the application of established standards, but by individual farmers who may select certain plants in the field for harvesting specifically as seed, and/or by separating grain to be used as seed at some stage after harvest. Seed production is integral to crop production, whereas in the formal seed sector seed production is carried out separately from grain production. If farmers do not have their own saved seed, a range of acquisition methods are used to acquire seed including begging, purchase/barter, and loan. Seed can be acquired from several sources including relatives, neighbors, friends, and/or local markets. When seed is acquired from local markets, the quality of seed is determined by the buyer, otherwise it tends to be regulated by 'good neighborliness' rather than any formal certification system as in the formal seed sector where seed is only acquired for cash through commercial channels. Farmers, relying on the farmer seed system, may acquire new varieties from the formal seed sector, by local selection, through social networks, from traders introducing grain into an area, and from humanitarian agencies.

Understanding the demand for seed

Tripp (2001a) has categorized seed demand from farmers into four major types. The first type of demand originates from emergencies, including drought, flood, and/or civil disaster that can result in lack of seed availability. The distribution of seed by humanitarian agencies following disaster has been widely adopted in the past decade to assist in agricultural rehabilitation. For example, in southern Somalia between 2000 and 4000 metric tons (t) of cereal and legume seeds have been distributed on an annual basis since 1991 (Longley et al. 2001). The second type of demand is caused by poverty. Farmers may not harvest sufficient grain to be able to set aside their seed requirements for the coming season, and/or there is a necessity to sell or consume all stocks to meet short-term needs. Sperling (2002) differentiates between acute and chronic seed insecurity where acute insecurity is brought on by distinct short-duration events, and chronic seed insecurity is the result of long-term structural problems that affect specific groups of farmers. Because poor farmers tend to be chronically seed-insecure, this will be elaborated further. The third type of demand stems from the desire of farmers to acquire quality seed. Quality is a subjective term, and is used when referring to different aspects of seed, causing considerable confusion for those who are not fully conversant with seed terms. Farmers growing hybrid crops purchase fresh seed every season because the use of recycled seed results in both yield depression and lack of uniformity as a result of segregation. Formal-sector seed is generally considered to be 'quality' seed because its production is controlled and inspected, and where market standards exist that require the production of grain to meet strict grades and standards farmers tend to use such seed. Other examples include vegetables that are not normally grown for seed and where seed production is less than straightforward. Finally, there is the demand for seed from farmers wanting to obtain a new variety.

The failure to clearly understand the different types of seed demand has hindered the development of sustainable seed delivery systems that can potentially increase C-CAB. This will be expanded upon in the following sections.

Cropping systems

Over the last half-century smallholder development has achieved notable successes through the application of Green Revolution technologies that include agricultural mechanization, improved crop cultivars and management, and the use of fertilizer and pesticides. As an illustration of this success wheat yields in India have quadrupled and rice yields in Indonesia have tripled – achievements that have made a strategic contribution to wider processes of economic development.

An important element supporting this Green Revolution has been the formal seed sector that encompasses research, production, distribution, and marketing. In India this has evolved from being primarily a government-dominated sector to one where both government and commercial seed enterprises compete for business as a result of seed regulatory reform. Commercial seed companies have gravitated towards the marketing of hybrid crops including pearl millet, sorghum, maize, and rice where economic returns are the highest leaving the less-profitable crops such as groundnuts – that have a low seed multiplication rate and are bulky and difficult to store – to state seed enterprises.

Globally 90% of our food requirements come from 15 plant and eight animal species although over 10,000 plant species have been cultivated over time. Will this process accelerate or is there the likelihood that the number of species used in agriculture will expand? To try to answer this question, it is interesting to examine some of the 'orphan crops' that are important to smallholder farmers in marginal areas, and then to speculate whether these can be elevated to a higher status through a breeding approach similar to that which has been so successfully used for Green Revolution crops. One such crop is pigeonpea (*Cajanus cajan*). India is both the world's largest producer and consumer of pigeonpeas, but until recently conventional breeding approaches had failed to deliver substantial productivity increases, and farmers had shifted out of pigeonpea production into more profitable crops. Unique among the legumes, the first hybrid pigeonpea which yielded 30% more due to heterosis was developed and released in 1996 (Saxena et al. 1996). However, the technology could not be commercialized until a practical way to produce hybrid seed was identified. This problem has now been solved and private seed companies have started to invest in the crop because they see the potential for profit from repeat sales of hybrid seed. In Africa ICRISAT is working on developing *Guinea* sorghum hybrids, a process that is being facilitated through the application of genomics. Hash et al. (2002) report the development of improved pearl millet hybrids that have better resistance to downy mildew disease because of the greater understanding of heritability gained through genomics research.

Many involved in development in marginal areas of the SAT would be quick to dismiss hybrid technology by stating that smallholder farmers are too poor to buy seed, but there are some successful examples of farmers doing just that. In Niger the national agricultural research service has multiplied small quantities of a locally adapted sorghum hybrid, NAD 1, and found that farmers were willing to purchase this on commercial terms. A private input supplier has now started seed production of the same variety that will be marketed through his own chain of agricultural input shops. The fact that hybrid technology is working in one of the poorest countries in the world where crop cultivation is marginal at the best of times, suggests that the commercial seed sector can find a profitable niche in which to operate.

In zones where the Green Revolution has been profound, discussion now focuses on post-Green Revolution challenges that include sustainable water use; dealing with soil problems and pest complexes with growing pesticide resistance; and weaning farmers off the subsidies – notably electricity, water, and inputs – which underpinned the Green Revolution. Here biotechnology in the form of transgenic crops is beginning to have an impact. In India the Government had to accelerate the release of Bt cotton after farmers got hold of experimental seeds and were amazed at how effective the Bt technology was in reducing pest damage. In much of SSA farmers have stopped growing cotton because of the poor returns, but there is renewed interest in the crop from the textile industry that has preferential access to US markets. South African smallholder farmers report similar success with Bt cotton and its use is likely to spread as other countries try to compete in this lucrative business.

Globalization

Globalization is already having far-reaching consequences on agriculture. Globalization is a broad concept, but one feature of relevance to agriculture is the emergence over the past decade of a global agri–food system. This process is being driven by: the creation of the World Trade Organization (WTO), the declining cost of transport and communication, the urbanization of the planet, and the rise of a global middle class (Busch 2002). Increasingly end markets are dominated by large retailing firms (supermarkets) that compete among themselves on: continuing minor innovations in products and packaging, maintaining strict quality criteria, and price. These retailer-dominated supply chains require producers to be able to:

- Meet exacting quality criteria, covering such matters as size, color, texture, pesticide residues, and taste
- Adjust production volumes rapidly to meet short-term market trends
- Track minor product innovations by changing planting material, planting methods, and packaging
- Keep up with cost-reducing technical progress, in a context in which the partner retailer and its competitors have multiple sourcing (Kydd 2002).

In eastern Africa this is clearly seen in the development of the horticultural sector where producers are linked to end markets dominated by supermarket chains in the United Kingdom and Europe. Although the bulk of horticultural production is exported, similar trends are taking place in both domestic and regional markets for such traditional commodities as rice. In Kenya, one rice miller processes and packages five different rice varieties in response to demand from local supermarkets and wholesalers. Rice varieties are sourced locally, regionally from Tanzania, and internationally from Pakistan. Within each variety, the product is further differentiated based on grades, with hand-sorted grains at the premium end of the market and broken grains at the opposite extreme.

An initial assessment suggests that globalization will further reduce the range of cultivated crops, and hence reduce C-CAB. One factor mitigating against this trend is the desire among consumers for new products that add variety and excitement to the diet. Consumers in the developed world, thanks to cheaper transport and more efficient supply chains, now have access to a much more diverse range of foodstuffs than in the past. If crops that are important to farmers in marginal areas can find a niche in such markets, this will stimulate their commercial exploitation by farmers. C-CAB with good marketing and research targeted not only at increased productivity but also at postharvest processing technologies has the potential to elevate the agrobiodiversity debate from one of ecological curiosity to hard business. Market demand will then drive sustainable seed delivery systems that are an essential pre-requisite to maintaining the exacting grades and standards of globalized markets.

So far this paper has concentrated on the more conventional end of seed delivery to illustrate that there is potential to change the existing status quo through more innovative approaches. Attention will now shift to more interventionist approaches that are less commercially attractive, and that require the development of strategic partnerships to assist farmers in marginal areas.

How appropriate are modern varieties

There are numerous examples of farmers trying out seed of modern varieties only to reject them. This is particularly the case in marginal areas where farmers use biodiversity to exploit environmental niches rather than using purchased inputs to overcome biotic and abiotic constraints. Ortiz (2002) has reviewed the different approaches for breeding under stress environments. These involve either increasing yield of broadly adapted genotypes (Rajaram et al. 1997), or exploiting genotype adaptation (particularly of landraces as at least one parental source), and fitting cultivars to the specific target environment (Ceccarelli 1997; Cleveland, 2001). Because cultivars – typically landraces – are highly adapted to a specific environment there is less adaptability for evolutionary change, which appears to be essential for sustained crop improvement, by both farmers and professional plant breeders. This need for adaptability necessitates a compromise between the two strategies described above. The important point is that to be effective in marginal, low-input, stressful environments plant breeding will have to become decentralized away from a central breeding station to local undertakings in targeted agro-ecozones for each crop. This new plant breeding paradigm will require new institutional arrangements if the results from such efforts are not to remain in the hands of few farmers, but are to have wider impact across the targeted agro-ecozone where the breeding work has been undertaken.

Emergency/relief seed

The demand for relief seed resulting from emergencies was briefly mentioned in the previous section, but will be expanded here through a case study of the present food crisis in southern Africa because it illustrates how C-CAB is largely ignored in such situations.

The present food crisis in several countries of southern Africa has resulted from the widespread lack of food availability at household, national, and regional levels. Poor households are the worst affected because they lack the necessary resources to access whatever food is available, and are therefore forced to utilize food resources that are inadequate to sustain a healthy life. Under such circumstances there is a need to import and distribute free food to targeted households to avoid famine. Even as relief operations start and food aid is provided, attention turns to assisting rural households in resuming farm activities. Seed aid is often combined with, or closely follows, food aid and tends to be treated in a similarly logistical way, even though there are important differences between food and seed.

What is seed? In the countries of southern Africa where there is widespread food insecurity the majority of farmers use their own saved seed. When a crop is harvested, farmers give first priority to safeguarding their seed supply, not only to ensure that there is sufficient seed for sowing, but also because they attach a strong value to the genetic information that is contained within that seed. If households are unable to set aside seed a range of sources may be used to access it. These include: obtaining seed from relatives, friends and neighbors, from local grain markets, and from commercial seed retailers. A critical feature of cropping systems in marginal environments is the broad biodiversity both within and between crops, and the ability to access seed through multiple channels is an important factor in helping farmers to maintain this diversity. From the farmers' perspective, seed is more than just 'certified seed' available from the formal seed sector, it includes grain of locally adapted crops and varieties.

Do farmers lose seed following drought? There is a tendency to assume that farmers eat their seed if they are short of food. For cereal grains, which dominate the cropping systems of the region the seed needs are only a fraction of the household grain requirement, and so there is little to be gained from eating seed. Surveys in the most drought-prone areas of Zimbabwe following the 1990/1 drought that was the worst in 100 years, found that only one quarter of farmers lost their seed stocks but that seed was still locally available (Rohrbach 1997). Similar findings have been reported for Mozambique and several other countries in Africa, confirming that farmers place a high value on preserving seed stocks even in extreme adversity. It is incorrect to assume that all farmers will have lost seed because of drought. Such assumptions have grossly overestimated seed requirements in previous droughts.

Is seed available? An absolute lack of available seed is only likely to be a problem where crop production has not been possible over wide areas for multiple seasons. In southern Africa there has been a very significant decline in crop production due to a combination of factors, but there has not been total crop failure over widespread areas. Under such circumstances, the problem for farmers affected by disaster is having the necessary resources to access seed, rather than the unavailability of seed per se. The seed needs of isolated areas of limited or no crop production are easily met by local traders who play an important role in moving seed from surplus to deficient areas. Seed of locally adapted crops and varieties will be available in most communities, and so relief seed should only be used to supplement local seed shortfalls rather than meeting the total seed needs of communities.

Is commercially available seed superior? The long-term development of agriculture in southern Africa necessitates the development of input markets that are responsive to the needs of farmers. Over the past two decades the public seed sector has been privatized as a result of structural adjustment policies, with seed production and marketing being undertaken by commercial seed companies. The success of the commercial seed sector will ultimately depend on whether these companies can market seed of the crops and varieties that are wanted by farmers. The question as to whether commercially available seed is superior has to be determined in the marketplace. Unfortunately, the distribution of large quantities of emergency seed biases the development of commercial seed markets and sharply reduces incentives to develop retail trading networks. Companies prefer to sell large quantities of seed from centralized depots in capital cities with the result that general merchandise retailers have little incentive to stock seed. As a result most farmers have no access to seed in rural markets in either good years or bad. Farmers should be allowed to choose the seed of the crops and varieties that they require. This includes seed that is locally available from other farmers, and commercial seed.

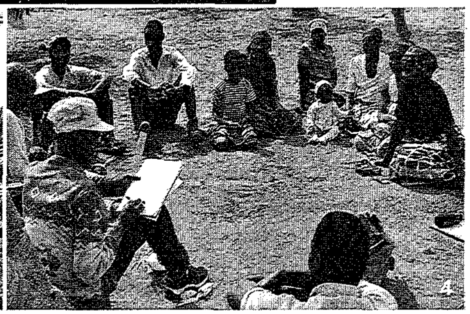
Which crops and varieties should be provided to farmers? This is the most frequently asked question by humanitarian agencies planning emergency seed programs. More-realistic questions to ask include; what seed is available now?, is it locally adapted?, and do farmers like it? Most countries in the region have lists of crops and varieties that have been officially released, and these should be consulted. However it is important to realize that farmer varieties are not included, and that 'official release' does not always equate with farmer acceptance. Following the 1990/91 drought in Zimbabwe, seed of recently released early-maturing sorghum and pearl millet varieties was provided to farmers as emergency relief, and these are still being grown on 25–40% of the national sorghum and millet hectarage today (Rohrbach 1997). On the other hand thousands of tons of early-maturing cowpeas have been distributed season after season in Mozambique, and yet very few farmers continue to grow them. This problem can largely be avoided by letting farmers decide which crops and varieties they require. An unsuspecting humanitarian agency might accept the advice of a commercial seed company holding large stocks of a particular variety, but this is not always in the best interests of farmers. By letting farmers choose, the commercial seed company will start responding to the needs of farmers.

Rather than providing farmers with seed directly, they can be provided with resources so that they can acquire seed from alternative sources. One approach that has been extensively tested is that of 'seed fairs' where farmers are provided with vouchers that can be redeemed for seed (Remington et al. 2002). The advantage of this approach is that farmers get to choose the seed of the crops and varieties that they need, rather than having a third party determine what they need. In countries where a formal seed sector exists, commercial seed companies are encouraged to participate in such fairs, a process that will ensure they start responding to the needs of farmers.

Seed interventions. One of the four categories of seed demand described earlier is that made by farmers wanting to obtain a new variety. Although much of the seed used by smallholder farmers in marginal areas is their own saved seed or seed accessed through social networks and other arrangements, farmers are keen to try out new varieties, and even to purchase small quantities of seed with which to experiment. Tripp (2001a; 2001b) has advocated the sale of small seed packs as a way to foster this process, and emerging experience in several parts of Africa has confirmed that there is a demand for such seed. An illustration of how this can be implemented is the partnership between CARE Somalia/southern Sudan and ICRISAT (see photographs page 140).

Most of Somalia is arid and not suitable for crop production, but there is a small southern area where rainfed crop production is successfully practiced because of the heavier soils and slightly higher rainfall. Longley et al. (2001) estimated that 90% of the rainfed area is sown to sorghum with the remaining 10% being divided between cowpeas and maize. The traditional sorghum varieties are tall long-duration types with compact 'goose-necked' heads and are valued both for their fodder and because the grain is well adapted for long-term storage in underground pits. In 1999 CARE decided to embark on a sorghum seed production and distribution project instead of just purchasing local grain and redistributing it as seed. Because there is no central government or functioning research service in the country they requested advice from ICRISAT on potential sorghum varieties to multiply, and then requested ICRISAT to supply 1 t of foundation seed divided between the six varieties selected to initiate the production process. At the same time that the seed was being multiplied, informal discussions with market women in Baidoa uncovered a network of small seed traders, all women, who specialize in marketing seed in addition to grain.

1. Fields of improved sorghum grown by a Community Seed Production Group in southern Somalia
2. A farmer in southern Sudan inspecting drying heads of sorghum that will be used for seed
3. Women trader in Somalia selling fresh sorghum grain that is used as a source of seed in times of shortage
4. Focus group discussions in Mozambique help to understand farmer seed management practices
5. Small pack of improved sorghum seed grown for sale by women traders in Somalia and procured from a Community Seed Production Group

These female petty traders buy grain at harvest time from farmers in the surrounding villages and pay a premium of about 20–50% for good quality seed (described as freshly harvested, properly dried, pure in color, and with large healthy grains). In some countries local traders do not differentiate seed from fresh grain but in southern Somalia the distinction is important because grain stored in underground pits rapidly loses viability and cannot be used for seed. The traders therefore store the seed separately in 200-L drums, keeping varieties separate. The importance of local seed marketing is thought to relate to the relative frequency of localized drought, the difficulties of storing seed over more than a few months, and the consequent demand for off-farm seed.

Rather than distributing the improved sorghum varieties free to farmers as relief seed, ICRISAT suggested to CARE that some seed be packed into 2-kg packets and sold to women seed traders on a wholesale basis so that they could then retail it to interested farmers. After just 3 weeks, the 32 traders who participated in this exercise had marketed all 10 t of seed. The use of small seed packs has been successfully piloted in southern Africa with a modern open-pollinated sorghum variety, but in this case a commercial seed company undertook the work and was surprised at the demand. The approach has now expanded to West Africa where it is being piloted with both sorghum and groundnut seed.

A critical lesson from this work is that researchers need to be far more proactive in getting germplasm into the hands of farmers. Unfortunately this is easier said than done, as many countries have seed regulatory systems that discourage this type of activity, since they require several years of formal testing before a variety can be marketed. Such systems are justified on the basis that farmers need to be protected from unscrupulous seed sellers who will be tempted to make a quick profit by marketing fake seed. It is debatable whether commercial seed companies are willing to engage in this type of initiative, and there is justification for the public sector to support seed production of small quantities of new varieties to get these into the hands of smallholder farmers. Tripp (2001b) stresses the need to provide information to farmers to accompany new varieties so that they can make more informed decisions, and also to speed up the diffusion process.

On-farm trials with farmers serve much the same purpose as small seed packs in that, once farmers have grown and harvested a crop, they then serve as a source of seed to other farmers. Jones et al. (2001) have reported how a single on-farm trial with a modern pigeonpea variety resulted in 68% of farmers growing the variety within a period of 12 years. Maurya et al. (1988) showed how farmer participation in breeding quickly produced many varieties of rice that yielded on-farm twice as much as the 'locally-adapted' traditional varieties.

Conclusions

This paper opened by comparing formal and informal seed systems. Each of these was then examined separately, and opportunities identified where strategic interventions can be made for improvement. Formal seed systems are increasingly dominated by the private sector, which necessitates that they operate along commercial lines. Commercial seed companies have tended to focus their efforts on marketing hybrids, and seeds of other crops where there is a consistent demand not easily met by farmers through their own efforts. By understanding the decision-making process that drives the commercial sector, there are opportunities to redirect crop improvement efforts to produce products that provide both real benefits to farmers, and commercial incentives to private-sector seed companies. As globalization proceeds, farmers will increasingly have to respond to the needs of end-users. Although farmers in marginal areas might not themselves be involved in these vertically integrated supply chains, they will be affected indirectly as agricultural produce moves more freely in response to consumer demand. The desire amongst consumers for greater variety in the range of foodstuffs consumed can potentially provide markets for crops that have largely been neglected, but exploiting these opportunities will require efficient and dynamic seed supply systems to support farmers, otherwise the farmers will risk becoming marginalized in the global economy.

There are new insights into crop improvement that necessitate a shift away from centralized breeding to localized efforts targeted towards specific agro-ecozones. This new breeding paradigm will require a different approach to seed supply that builds upon the strengths of informal seed exchange mechanisms whilst overcoming some of their deficiencies. The present regulations surrounding release of new varieties and certification of seed that exist in many countries can block farmers' access to new varieties. While some controls are vital for plant sanitation, the current situation in which farmers are told which germplasm to grow and where, needs to change to one in which farmers evaluate and multiply promising materials themselves (Witcombe et al. 1999).

Free seed distribution through relief schemes has not been particularly useful, except in the rare cases where there is an absolute lack of available seed. Procurement of relief seed from the formal sector fails to strengthen existing seed systems because the seeds supplied are often inappropriate and hence rejected by farmers. An alternative approach is to first understand what problem exists, and then to address the identified problem. If the problem is one of households not having sufficient resources to access available seed, it is better to provide resources to farmers so that they can make their own choices about which crops and varieties to grow.

Much can be done to enhance C-CAB through seed-supply interventions. There are now well documented experiences on the range of seed interventions described, and the time is right to develop a coordinated and focused plan of action involving multiple stakeholders to improve the livelihoods of smallholder farmers in marginal areas.

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Sustaining agricultural productivity and enhancing the livelihoods of rural communities through promotion of neglected crops and their associated biodiversity in semi-arid agroecosystems (Summary)

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Global food security and rural incomes are at risk due to their excessive dependence on a declining number of plant species. To conserve and use the world's plant genetic resources (PGR) for the development and welfare of present and future generations, there is need to enhance the use of PGR and to promote greater awareness of the important role that neglected and under-utilized species (NUS) play in securing the livelihoods of people around the world. Hundreds of such species are still to be found in many countries, representing an enormous wealth of agrobiodiversity that has the potential to contribute to improved incomes, food, and nutritional security.

Of the 850 million undernourished poor people in the world today, the majority still live in rural areas, and in adverse environments. Many NUS are nutritionally rich and are adapted to low-input cultivation. Their use could contribute to both the food security and the wellbeing of the poor. The contribution of NUS in combating vitamin and micro-nutrient deficiencies is seen as essential, particularly in marginal rural areas where these species are sometimes better adapted to the prevailing environment than major crops.

Growing demand from consumers for diversity and novelty in foods is creating new market niches for which NUS could generate additional income. Designer foods with balanced amino-acid and micronutrient profiles can be developed through appropriate blends of major cereals and NUS. Marketing opportunities, processing, and adding value to NUS would create demand and encourage farmers to grow and consume them.

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The primary challenge in conserving and using the PGR of NUS is to secure their survival and environmental adaptation, while at the same time providing increased incomes for rural poor. Climate change and the degradation of land and water resources have led to a growing interest in crops and species that are adapted to such difficult environments as those with poor soils or degraded vegetation, drought-prone areas, and desert margins. In these areas, NUS could promote sustainable agricultural development based on environmentally sound management of natural resources and conservation of agro-biodiversity.

The use of plants has long been an intimate part of local cultures and traditions and many of the NUS play a major role in keeping cultural diversity alive. Their unique array of diversity in taste, color, texture, modes of preparations, and ritual uses represents a rich component of the cultural, food-based social language that make our lives more interesting and enjoyable. People should be encouraged to rediscover the cultural values of raising their traditional crops, by according social prestige to such traditions.

The promotion of NUS requires the combined understanding, inventiveness, and interaction of farmers, industrialists, agricultural scientists, educators, environment-alists, and health-care workers. The food security base could be broadened by including NUS in farming systems research programs. Such sustainable food production practices as integrated farming systems, ecotechnology, organic farming, and integrated nutrient, water, and pest management are all ways to enhance NUS productivity. Efforts to improve NUS production through yield improvement, higher-factor productivity, and better postharvest management should be accelerated.

Among the NUS are several forage species. Forage crops are often given low priority and are gown in degraded, low-productive wastelands, on poor and problem soils that are not suitable for food-crop production. Their productivity depends on the availability of good quality seed of improved varieties. As they are shy seeders with low harvest indexes that are subjected to frequent cutting, opportunities to produce large quantities of quality seed are limited. Concerted efforts are needed to augment the seed production of cultivated fodders, range grasses, and pasture species to sustainably improve forage production. There is need to address various aspects of forage seed production and to overcome other constraints to production. Genetic improvement and organized seed-supply systems need to be implemented based on specific requirements and available infrastructure if future improvement is to be made in the forage resources of the semi-arid tropics.

Improving productivity and livelihood benefits of crop–livestock systems through sustainable management of agricultural biodiversity in the semi-arid tropics

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Introduction

Agricultural biodiversity as used in this paper and following Cromwell et al. (1999) consists of all components of biological diversity of relevance to food and agriculture. It includes the variety and variability of plants, animals and microorganisms at genetic, species, and ecosystem level that are necessary to sustain key functions in the agroecosystem [see also Convention on Biological Diversity (CBD) 29 December 1993].

Agricultural biodiversity provides the building blocks for the evolution or deliberate breeding of useful new crop varieties and animals. It provides biological support to production through soil biota, pollinators and predators, and such wider ecological services as maintenance of soil fertility, water and air quality.

The purpose of this paper is to explore the links between agricultural biodiversity and crop–livestock production systems in order to highlight management strategies and policies that can be used to increase the productivity and livelihood benefits of these systems through sustainable conservation and use of agricultural biodiversity. The emphasis is on crop–livestock systems as these systems provide the best opportunity for diversification, poverty alleviation, and sustainable management of agricultural production in the semi-arid areas. This exploration begins with the identification of the types of crop–livestock systems that are important in the semi-arid tropics (SAT).

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Classification and importance of crop–livestock systems in the SAT

Livestock production systems can be categorized in several ways: by species, agroecology, land use, and management strategy. Seré and Steinfeld (1996) using a two-step approach classified world livestock production systems into 11 categories (Figure 1). First, based on land use and degree of integration with crops, four livestock production systems were identified namely: landless, rangeland (areas with minimal cropping), mixed rainfed (rainfed cropping combined with livestock), and mixed irrigated systems (cropping under irrigation with livestock). In a second step, the rangeland and mixed systems were further broken down by agro-ecological potential in terms of length of growing period (LGP) and temperature into 3 zones: the highland/temperate zone defined on the basis of temperature, the arid/semi arid zone defined as having LGP of <180 days and the humid/sub-humid zone with an LGP of ≥180 days.

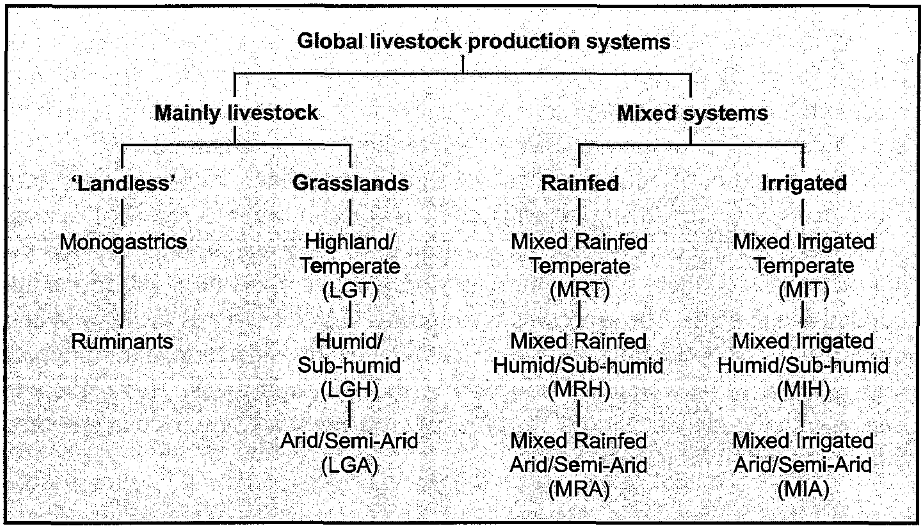

Figure 1. Classification of livestock production systems

This classification scheme provides a useful starting point for discussion of the interlocking nexus of biodiversity, crop–livestock systems and sustainable livelihoods in the SAT. Although a continuum of livestock production systems ranging from landless (urban and peri-urban), rangeland, mixed rainfed, and mixed irrigated can be found in the SAT, the main focus of this paper is on the rangeland i.e., livestock grassland systems in arid/semi-arid (LGA), and mixed rainfed crop–livestock systems in arid/semi-arid (MRA) zones in sub-Saharan Africa (SSA) and South Asia. The extension of cultivated area and cropping into range-lands in both SSA and South Asia primarily as a result of human population pressure and low agricultural productivity, and the implications of this for biodiversity necessitate the consideration of rangeland production systems as part of the crop–livestock systems discussed here.

The rangeland and mixed rainfed crop–livestock systems occupy about 40% of the total land area in SSA and 35% of South Asia (Table 1). These systems carry about 56% of the total tropical livestock units (TLUs) in SSA and 30% in South Asia. They provide direct livelihood benefits, including food, employment and income to about 200 million people in SSA and 310 million in South Asia, out of which 97 million in SSA and 130 million in South Asia are poor people eking out a living on less than US$ 1 day^{-1}. These statistics highlight the importance of these two livestock production systems and show why they merit considerable attention in the biodiversity–livelihoods debate.

Table 1. Agricultural and economic indicators for sub-Saharan Africa (SSA) and South Asia by production systems

	SSA[1]			South Asia[2]		
Indicator	**Total**	**LGA[3]**	**MRA[3]**	**Total**	**LGA**	**MRA**
Land area (million km^2)	24.1	6.3	3.4	4.4	0.3	1.2
Proportion of total land area (%)	100	26	14	100	7	28
Tropical livestock unit[4] (million TLU)	230.8	76.1	52.4	306.0	13.6	76.2
Proportion of total TLU (%)	100	33	23	100	5	25
Human population, 2000 (million)	627	42	157	1337	19	290
Proportion of total human population, 2000 (%)	100	7	25	100	1	22
Number of poor people, using US$ 1 day^{-1} poverty threshold, 2000 (million)	279	18	79	542	6	124
Proportion of total poor people, 2000 (%)	100	6	28	100	1	23

1. SSA includes countries spread across West, Central, southern and eastern Africa.
2. South Asia consists of: Bangladesh, Bhutan, India, Nepal, Pakistan and Sri Lanka.
3. LGA = Livestock only, rangeland-based arid/semi-arid; MRA = Mixed rainfed arid/semi-arid
4. One tropical livestock unit (TLU) = an animal of 250 kg live weight
Source: Thornton et al. 2002.

Links between agricultural biodiversity, crop–livestock production systems and sustainable livelihoods

In order to determine how agricultural biodiversity can be optimized to improve productivity, sustain livelihoods, and enhance ecosystem health, the first necessity is to establish the links between agricultural biodiversity, crop–livestock systems, and sustainable livelihoods. Figure 2 provides a schematic framework to illustrate these links. It adapts the sustainable livelihoods framework described in Carney (1998) and the agricultural biodiversity and sustainable livelihoods schema developed by Cromwell et al. (1999) to summarize some of the key features of the relationship between agricultural biodiversity, crop–livestock systems and sustainable livelihoods.

In terms of biological taxa, agricultural biodiversity includes:

- Higher plants: crops – domesticated and managed wild plants, trees, rangeland plant species
- Higher animals: domesticated animals, wildlife, fish
- Arthropods: insects, including:
  - Pollinators, e.g., bees, butterflies
  - Pests, e.g., grasshoppers, greenflies, ticks
  - Predators, e.g., wasps, beetles
  - Insects involved in the soil cycle, e.g., termites, dung beetles
- Other macro-organisms: e.g., earthworms
- Microorganisms: e.g., rhizobia, fungi, etc.

The mix of agricultural biodiversity in any one agroecosystem is determined by a set of human-controlled factors and the underlying natural conditions. Cromwell et al. (1999) listed factors determining levels of agricultural biodiversity in production systems as including:

- Underlying agro-ecological conditions
- Farmers' skills in on-farm agricultural biodiversity management
- Farmers' access to useful agricultural biodiversity off-farm (through neighbors, adjacent wild areas, formal-sector plant and animal breeding schemes) that is partly determined by population pressure, local knowledge, access, and contacts
- Farmers' access to other capitals that can substitute for natural capital, e.g., new technologies, agrochemicals that is significantly influenced by prevailing policies and incentive schemes.

By actively managing through the use of labor and other household resource endowments the mix of agro-biodiversity assets present in the ecosystem, farmers can

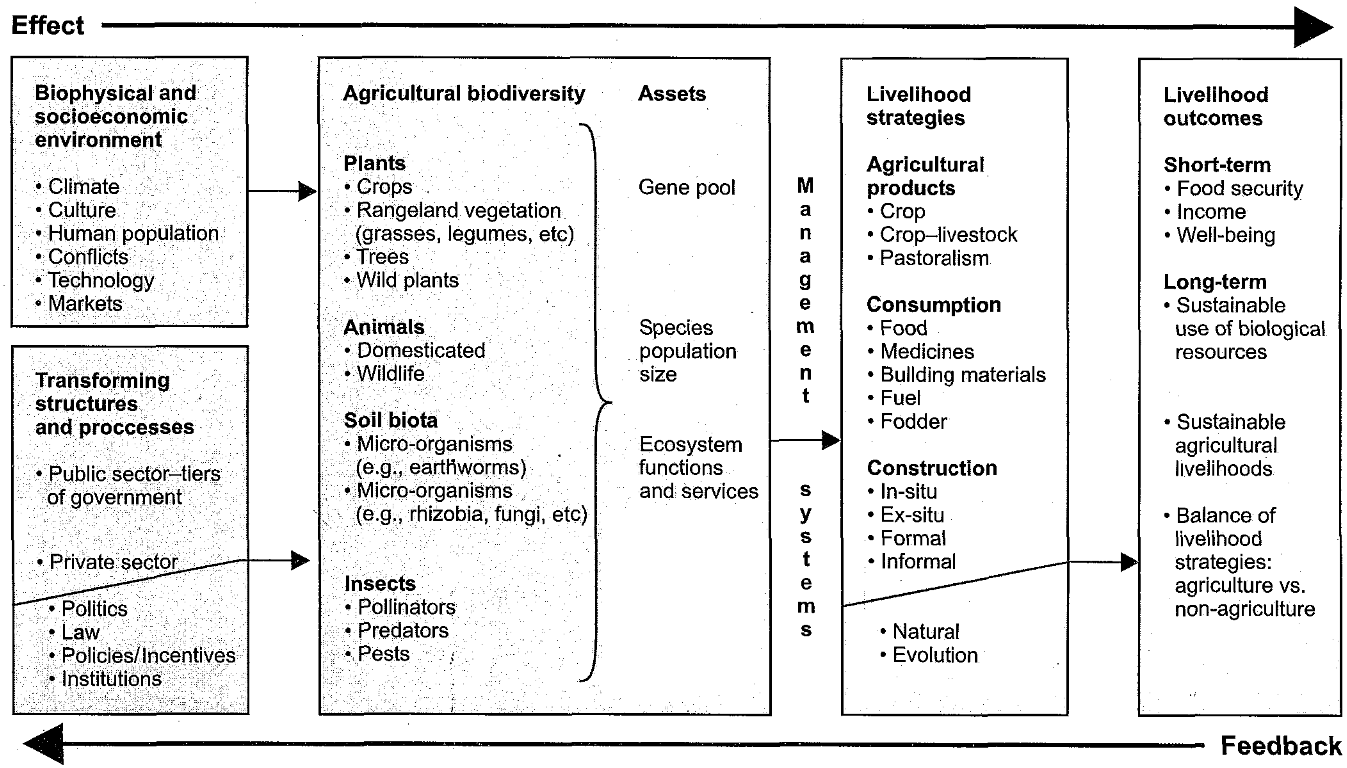

Figure 2. Links between agricultural biodiversity, crop–livestock systems, and sustainable livelihoods

develop livelihood strategies involving production, e.g., crop–livestock systems, consumption, and conservation of biological resources. Through this manipulation farmers can derive goods and services that contribute to sustainable livelihoods and also improve the productivity of production systems, while maintaining ecosystem health.

Management of agricultural biodiversity can contribute directly to sustainable livelihoods in crop–livestock systems through effects on production (food of crop and animal origin, medicines, soil nutrient recycling, pest predators, etc). It can also contribute to crop–livestock systems' sustainability through the provision of important ecosystem functions and services, e.g., soil fertility maintenance, pollination, pest and disease control, watershed protection, etc.).

But there is a feedback loop. Agricultural biodiversity is significantly affected by *natural conditions and processes of evolution* as well as by *the production*, consumption, and conservation strategies of farmers and the transforming structures and processes. Given the focus of this paper, the impact of crop–livestock systems on agricultural biodiversity in semi-arid West Africa is used to illustrate the potential positive and negative impacts of a production system on agricultural biodiversity.

Figure 3 shows the multifarious impacts of crop and livestock production on agricultural biodiversity in a semi-arid ecosystem. Complementary use of biological resources by crop and livestock and the flows of nutrients they generate enhance the productivity of the agroecosystem. Livestock graze non-arable lands, fallows, stubbles and weeds and recycle part of the nutrient intake from these pastures on cropped lands through corralling and manuring managed by farmers. The activities of soil macro- and microorganisms, e.g., dung beetles, earthworms, fungi, etc., on manure accelerate organic matter decomposition and the release of nutrients to plants. The transfer and recycling of nutrients from rangeland to cultivated fields create islands of higher soils fertility, which serve to enhance ecosystem heterogeneity and provide niches for more-productive high-value food and cash crops. The by-products and residues left after crop harvest, i.e., stalks, haulms, etc., provide feed for livestock, particularly during the long dry season when feed availability is low (Williams et al. 1997). Livestock also provide draft power for farm operations serving to conserve fossil fuels that are non-renewable and at the same time reducing environmental pollution.

Rangeland vegetation (pastures, trees, and browses) provides feed for grazing livestock. Grazing has been described as the cheapest way of feeding ruminant livestock and is the most efficient in optimizing feed selection by animals offered poor-quality feed (Westoby et al. 1989). The impact of livestock on agricultural biodiversity depends upon a complex set of interactions involving selective plant

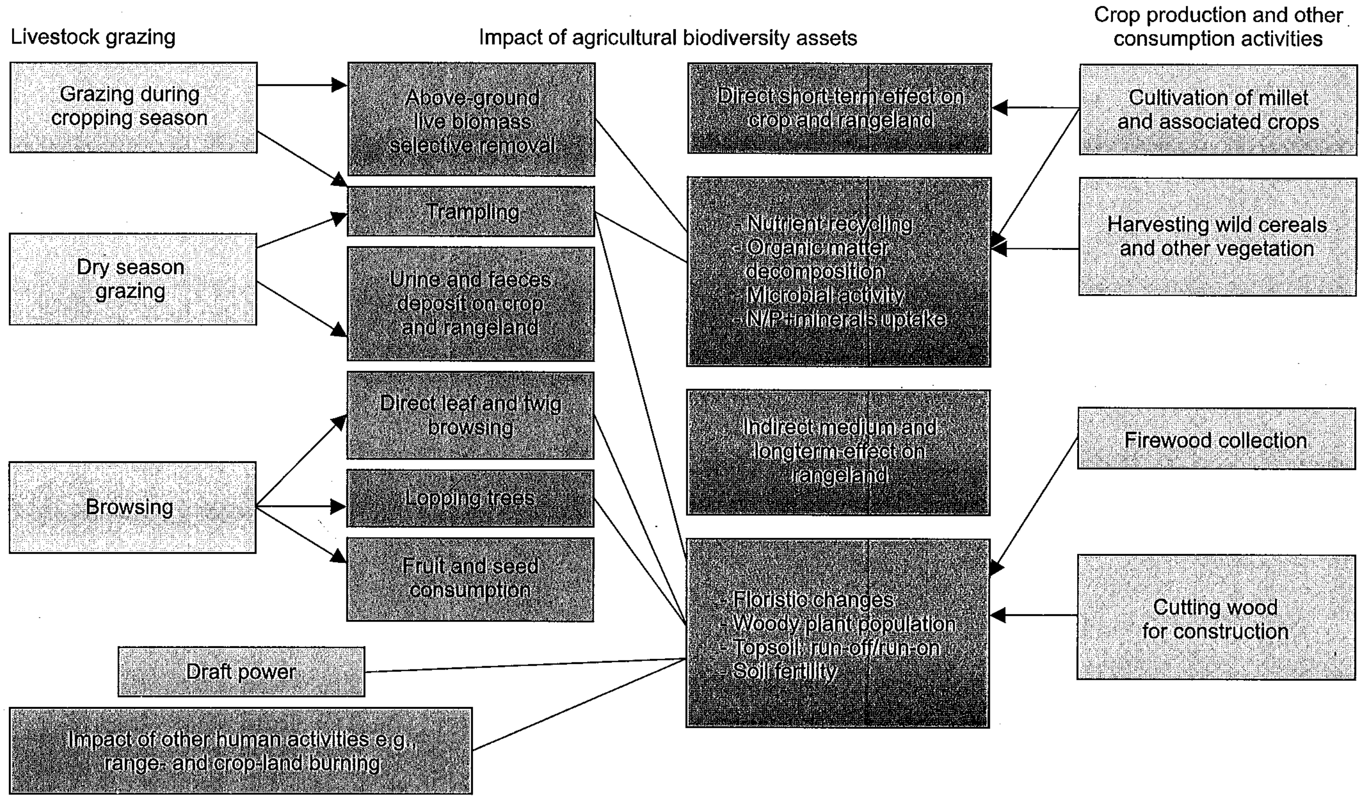

Figure 3. Impacts of crop and livestock on agricultural biodiversity in a West African semi-arid ecosystem

Source: Hiernaux (1996)

defoliation, soil trampling and manure deposition. The importance of each of these processes depends on the intensity, frequency, and timing of grazing, soil texture, terrain slope, and duration of the rainy season (Hiernaux 1996). Moderate grazing enhances within-patch diversity and reduces between-patch heterogeneity at the landscape level (Hiernaux 1998). Continuous heavy grazing leads to a reduction in species richness and changes in the composition of the vegetation. The density of palatable herbaceous plant species fall as they are replaced by less-palatable ones, because their competitive ability declines (Hiernaux 1996). Another consequence of heavy grazing can be the spread of woody vegetation and the eradication of grasses. Trampling (on loamy soils) and reduction in soil herbaceous plant cover can add to the detrimental impact of heavy grazing on the productivity of the range.

Overall, crop–livestock production systems can support agricultural biodiversity, but may also constitute a source of pressure. More importantly, the discussion in this section clearly indicates the significant spillover effects and feedback loops that need to be taken into consideration in the sustainable use of agricultural biodiversity to enhance crop–livestock systems' productivity and livelihoods in the SAT. It also underlines the need to have in place a framework for monitoring the impact of agricultural production, including crop–livestock production systems, on agricultural biodiversity. Essentially, this would involve developing indicators to measure the status and changes in agricultural biodivers-ity. Countries that are members of the Organization for Economic Community Development (OECD) have already initiated discussions on the development of such indicators.

Factors limiting appropriate use of agricultural biodiversity to enhance crop–livestock systems

Devising effective means of using agricultural biodiversity to improve crop–livestock systems' productivity requires knowing the factors presently limiting better utilization of biodiversity assets. Proximate factors vary under different conditions, but generally those in the SAT pertain to the highly variable rainfall both between and within years, and inappropriate policies that induce resource degradation and loss of biodiversity. The more deeply underlying factors include high population growth, disparities in access rights to key biological resources, and the rise of industrial agricultural production systems that rely on uniform varie-ties and breeds and heavy use of agrochemicals.

Demographic pressures leading to expansion of farming into marginal areas previously used for grazing reduce the diversity of natural habitats and often lead to land degradation. Inequality in access to biological resources creates a disincentive for sustainable use of resources by poor people. Industrial agricultural production systems that emphasize maximum yield per unit of land and homogenization of breeds and crop varieties erode biodiversity in the ecosystem and lead to a reduction in the resources available for future adaptation. Local knowledge on biodiversity is also weakened as industrial agricultural technologies emphasizing uniformity predominate. Policies that promote intensive use of agrochemicals, e.g., pesticides, herbicides, fertilizers, feed supplements, indirectly harm beneficial soil organisms and jeopardize the long-term sustainability and productivity of farming systems. This is not to argue against scientific advancements or the use of modern inputs and new innovations, but rather to emphasize that such new technologies and interventions need to be oriented towards optimizing the management and use of agricultural diversity in farming systems.

Options for better management of agricultural biodiversity to enhance productivity crop–livestock systems and ecosystem health

Various entry points exist to strengthen farmers' ability to use agricultural bio-diversity to improve crop–livestock systems' productivity and ecosystem health. These will include promotion of integrated natural resource management approaches, training and access to new technologies, strengthening of local-level institutions, and adjustments to economic and policy environment.

Application of integrated natural resource management principles involving nutrient recycling and augmentation of soil organic matter can help enhance biodiversity on farms and increase productivity and intensification of crop–livestock systems. In a project involving ILRI, ICRISAT and INERA (Institut de l'environnement et des Recherches Agricoles) in Burkina Faso, compost from crop residues, feed refusals, and animal manure enriched with locally available rock phosphate was applied at the rate of 4 t ha^{-1} once every 2 years to fields of sorghum intercropped with cowpea in the villages of Dori and Saria. The application of compost increased soil organic matter content and crop biomass yields by 60–80%. In another on-farm trial in the village of Katanga in Niger, cattle were corralled to deposit manure on either bare soil (control) or on a bed of mulch made from leaves and twigs of *Aristida sieberiana*. Pearl millet was subsequently sown in the manured fields. Compared to the control, the association of manure with mulch increased grain yield by about 54–136% and stover yield by about 42–150% (ILRI 1998). In both examples reported here, locally available materials were combined with scientific and local knowledge to improve soil nutrients. This clearly shows that adapting production practices to build upon known successful methods and local knowledge could be a powerful approach to using biodiversity to improve the productivity of crop–livestock systems and meet livelihood needs while enhancing ecosystem health.

New technologies and scientific advancements that promote diversity in farming systems, e.g., multi-purpose as opposed to single productive traits and species, can help provide the building blocks for future productivity growth by increasing the pool of resources available for future adaptation.

Appropriate policy support and incentives can also help to ensure effective use of agricultural biodiversity to improve crop–livestock productivity. Elimination of subsidies for fertilizers, pesticides, and herbicides will encourage the use of more diverse and naturally occurring inputs and farming methods. The reform of tenure and property rights systems to ensure that poor farmers have rights and access to necessary biological resources, e.g., grazing land can help to improve their productivity and livelihoods.

Future prospects

Looking ahead to the next two decades, the demand for meat and milk in developing countries, including those situated in the SAT, is expected to more than double as a result of growth in urbanization and incomes (Delgado et al. 1999). This expected growth in demand raises a number of opportunities and challenges for optimal use of agricultural biodiversity to improve crop–livestock systems' productivity and thereby the livelihoods of the smallholders who derive sustenance from these systems without jeopardizing ecosystem health. These opportunities and challenges can be considered at three levels – farmers, policy, and research.

There is evidence to suggest that due to the considerable agricultural production risks faced by smallholder farmers in the SAT, they tend to actively manage agricultural biodiversity on-farm in order to improve productivity and household food security. They practice a system of mixed farming in which a large number of species are raised, with considerable genetic diversity within species, and good use also made of wild plant diversity and non-plant agricultural biodiversity to minimize risk and enhance livelihoods and ecosystem health (Matlon 1988; McIntire et al. 1992; Cromwell et al. 1999). For the future, a key requirement is to empower farmers to continue to do this through access to new technologies, education, and training.

Policy and institutional changes are needed to create the conditions that would permit smallholders to benefit from the multiple values of agricultural biodiversity. This will involve eliminating perverse incentives, e.g., subsidies, tax relief, below-cost resource pricing in the agricultural, energy, and transport sectors, and marketing and distribution restrictions, that encourage a narrower range of crop and animal species, varieties and breeds. It will also involve addressing issues surrounding access and use rights. Well defined and secure property rights (common, private, state) provide good incentives for sustainable use of natural resources as they give greater security over future use and allow for long-term planning. At present, biodiversity issues are rarely seen to bear any relevance to mainstream policy and decision-making. There is a need to develop and experiment with approaches and mechanisms that can help mainstream biodiversity issues into sectoral policies and integrate livelihoods perspectives into biodiversity policies.

At the research level, surveys and assessments of agricultural biodiversity and its importance to crop–livestock production systems and local communities should be conducted. These can bring to light specific opportunities for using agricultural biodiversity to improve livelihoods and reduce poverty. Research is needed to develop indicators to measure the status and changes in agricultural biodiversity, including the impact of crop–livestock systems on biodiversity, and the role of biodiversity in agricultural production and ecosystem processes. The emphasis should be on indicators that are practical and relevant to management and decision-making.

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Appendix 1

This draft background document on crop and crop-associated biodiversity (C-CAB) has been developed using elements from an internal unpublished paper produced by D Wood for FAO. It is presented here as unedited background material for information.

Appendix 1. Draft background paper on crop and crop-associated biodiversity (C-CAB)

A. Introduction

Increasing international attention is being given to biological diversity in agriculture, as well as to the value of biodiversity to agriculture sustainability. The productive management of agricultural biodiversity will be key to meeting future food needs while also maintaining and enhancing the other goods and services provided by agricultural ecosystems.

The objectives of this document are to:

1. Stimulate discussion related to the question of what roles biodiversity plays in agricultural ecosystems – with a particular focus on crop and crop associated biodiversity, its components and interactions, and
2. To identify areas and topics for further action and consideration.

An Ecosystem Approach

The Convention on Biological Diversity (CBD) defines 'ecosystem' as follows: 'a dynamic complex of plant, animal and micro-organism communities and their non-living environment acting as a functional unit'. The CBD has determined that the application of the Ecosystem Approach will assist in achieving a balance of the three objectives set out in the Convention: a) conservation of biological diversity, b) the sustainable use of its components and c) the fair and equitable sharing of the benefits arising out of the utilization of genetic resources. Decision V/6 (http://www.biodiv.org/decisions/) provides a description of the Ecosystem Approach as defined by 12 principles and operational guidance for the application of the Ecosystem Approach.

While this definition is meant to give the widest possible scope for discussions related to biological diversity, specific reference to *agricultural biodiversity* can be found in Decision V/5. However, in comparison to the rest of the CBD documents on biodiversity, this reference to agricultural biodiversity is brief and points out that there is a lack of sufficient methods and a lack of understanding of the larger role of biodiversity in agroecosystems:

"...Understanding of the underlying causes of the loss of agricultural biodiversity is limited, as is understanding of the consequences of such loss for the functioning of agricultural ecosystems. Moreover, the assessments of the various components are conducted separately; there is no integrated assessment of agricultural biodiversity as a whole. There is also lack of widely accepted indicators of agricultural biodiversity. The further development and application of such indicators, as well as assessment methodologies, are necessary to allow an analysis of the status and trends of agricultural biodiversity and its various components and to facilitate the identification of biodiversity-friendly agricultural practices...".

Furthermore, in reviewing the implementation of the programme of work, the Conference of the Parties to the CBD *noted* the need for emphasis and further action, on the wider understanding of the functions of biodiversity in agro-ecosystems, and the interactions between its various components, at different spatial scales (Decision VI/5).

The Global Plan of Action for the Conservation and Sustainable Utilization of Plant Genetic Resources for Food and Agriculture and the International Treaty on Plant Genetic Resources for Food and Agriculture

The Global Plan of Action for the Conservation and Sustainable Utilization of Plant Genetic Resources for Food and Agriculture promotes the conservation and sustainable use of genetic resources of actual and potential value for food and agriculture. More specifically, its Activity 11 promotes sustainable agriculture through diversification of crop production and broader diversity in crops. Although targeted at crops, the requirement for diversification will, of necessity, impact on the biodiversity of agroecosystems including crop-associated biodiversity.

The goal of the recently adopted International Treaty on Plant Genetic Resources for Food and Agriculture is the achievement of sustainable agriculture and food security. To that effect, Articles 5 and 6 of the Treaty promote an integrated approach to the conservation and sustainable use of plant genetic resources and the application of ecological principles.

The question is worth posing: to what extent do the concepts and theories of ecosystems and ecosystem management have utility in addressing agricultural systems? A consideration of crop-associated biodiversity (CAB) is one doorway into this larger domain of questioning.

B. Some Key Terms, Concepts, and Issues

Over the past three decades a set of themes that relate to ecosystems in general have evolved. An ecosystems view of nature calls for special attention to spatial and temporal scales of measurement; to hierarchical theories of organisation, structure and function; the potential for alternative stable states in ecosystems; a critical role for indirect effects, spatial heterogeneity in process and pattern; non-linear dynamics; the essential role of perturbations; and to the importance of managing for resilience in ecosystems.

1. Scales of observation

Many books have been written on the subject of ecological scale, but very simply put, "...scale pertains to size in both time and space; size is a matter of measurement, so scale does not exist independent of the scientists' measuring scheme" (Allen and Hoekstra 1992). Furthermore, material systems are *scale-dependent* (manifesting different structures and behaviours at different scales), while conceptual devices or constructs are *scale-independent* (see next point). This might seem to be a simplistic or obvious concept, but if we look at much of the science found in agricultural journals and especially industry-related work, we see that agricultural research has most often taken the road pointed to by parametric statistics— of focusing on single or few factors while trying to hold all else constant under tightly controlled laboratory and field situations. While this has without question yielded results, it has also tended to "uncouple" our objects of study from elements and processes that act at larger spatial and longer temporal scales.

Yet it is this relationship of elements and processes within a larger web of influence (opportunities, but especially constraints) that, in nature, provides for self-assembly and regulation of ecosystems. Agricultural systems, if looked at closely, show many of these same characteristics. Management *cannot remove* production systems from the opportunities and constraints imposed by the larger ecosystem (unless we grow everything hydroponically in glasshouses). Ignoring agroecosystem structure, function, processes and constraints— while attempting to substitute with a handful of nutrients, and control with a pharmacopia of toxins— has led to gross inefficiencies, cumulative degradation of resources, and pollution at global scales.

2. Ecological theories of organisation

One of the barriers that need to be overcome is an underlying general confusion regarding the meanings of, and relationships among the most basic ecological concepts. For example, if we begin discussing a 'tropical irrigated rice ecosystem', are we talking about a specific material system? If so, what are its boundaries? Is it meaningful and useful to talk about a generic 'class' of tropical irrigated rice ecosystem, and if so, what are the characteristics associated with this label?

The CBD points out that 'ecosystem' is not a term necessarily linked to any particular spatial or temporal scale. In this context the CBD is using the term 'ecosystem' to refer to a theoretical construct that has certain general characteristics – it is not making reference to a specific material system. However, once an observer steps into a specific material system, *the act of making observations sets the temporal and spatial scale* from which the system is then represented – *observations are dependent on the scales used by the observer.*

It is convenient to talk about 'an ecosystem', yet it is difficult to set precise physical boundaries to any particular material ecosystem. Some types of material ecosystems (e.g., lakes) are more easily defined in space than others (e.g., savannas). Yet regardless of the type of ecosystem, for any reasonable boundary line we might draw, there will *always* be elements that defy the boundary— e.g., nutrients from rainfall, individual organisms, and soil and water transport all moving across the boundary. This problem of "fuzzy borders" to any material ecosystem can be resolved if we consider two points:

1. that certain levels of ecological organization (e.g., 'ecosystem') are more difficult for human beings to perceive, or are less tangible than others (e.g., 'organism'). This does not mean that 'ecosystem' is any less 'real' than 'organism';
2. that 'ecosystem' is a construct or perspective more useful for some topics of discussion than for others. If we are particularly concerned with spatial delineation, then 'landscape' is perhaps a more appropriate tool or perspective.

To generalize from this, the ecological organizational terms *organism, population, community, ecosystem, landscape,* and *biome* can most usefully be considered as different *perspectives* or conceptual devices, having different sets of attributes, and asking often *qualitatively different types of questions* (Allen and Hoekstra 1992). It is **not** the case that these terms are hierarchically nested with the one above subsuming, either spatially or conceptually, the terms below. Once we understand the potential for this type of confusion, we can then make efforts to increase the precision of our dialogue.

3. Ecological context and mechanism

When an observer steps into a particular material system, and begins making observations, then at this point the scale is set by the nature and act of observing the system. Scientific research tends to be focused on relatively small-scale phenomena in time and space, and often related to *ecological mechanisms;* whereas those elements of the system that behave on a much larger spatial and temporal scale than the observer, can usefully be described as the *Ecological Context* within which the mechanisms take place. These ideas have bearing on the interpretation of ecological (and agricultural) experiments. When considering, for example, the nature of field trials taking place in agricultural field stations – the scale of the trials (almost always very small) and the ecological context of the research station and surroundings (shaped by its history of management) often have very little similarity to the material ecosystems managed by farmers, so research may lead to conclusions that are highly site-specific or just plain wrong.

Take for example a report from an industry pesticide trial for a new insecticide. The experiments are duly replicated on 100 m^2 plots, for which populations of parasitoids and predators are monitored over time. The results indicate that two weeks after spraying the plot is again inhabited by beneficial insects. The conclusion by the industry researcher is the 'fact' that their chemical was not harmful to beneficial insects. This conclusion totally ignores the issue of scale and behaviour of arthropods – that surrounding non-sprayed areas are most likely acting as a reservoir, leading to the rapid reintroduction of natural enemies into such small treated areas. Further, it ignores the larger question of where these beneficial insects will be coming from if the chemical is being sprayed by many hundreds of farmers over large expanses of landscape.

Generally, non-systems-oriented research in agriculture very rarely reports the nature of the ecological context: what are the patterns of landscape vegetation, soil management, water management, refugia, and history of chemical use in the immediate vicinity to the experiment. If we are serious about an Ecosystem Approach to agriculture, then 'ecological context', or some such designation, should be a necessary introductory section in published scientific reports, along with 'materials and methods'.

4. Direct and Indirect Effects

If we focus through the lens of community ecology we consider the interactions of organisms from different species whose web of interactions comprise both *direct effects* (e.g., *A* has a positive or negative effect on *B*), and *indirect effects* (e.g., *A* has a positive or negative effect on *B*, but only through the mediation of *C*). Direct effects include the action of one organism physically on another, such as predation, parasitism, some forms of mutualism and interference competition. On the other hand, more than 80 different types of indirect effects currently have been catalogued, and are clearly responsible for a vast wealth of system behaviour. In species-rich marine intertidal systems researchers estimate that about 40% of the strong interactions between species are indirect. Indirect interactions in communities will be central to our discussion of crop-associated biodiversity.

5. Stability

The term 'stability' causes confusion with many people. In a systems dynamics view of nature stability does not imply constancy in time. Stability 'domain' is perhaps a more appropriate term as it suggests an image of systems components whose parameter values move within a certain range. The range is predictable, the values at any point in time more than likely will not be. Stability is then seen to be a tendency of a system to 'move in the direction of...' a certain theoretical point in parameter space. In fact it never quite gets there – it shoots past and comes around again, and it may exhibit cyclic behaviour, or possibly chaotic behaviour.

In agricultural systems farmers are constantly 'resetting the system' by harvesting fields; preparing the soil, and preparing the system for another season. The living elements of the system then reorganise themselves along the lines set by their population characteristics and individual life histories (e.g., likelihood of invasion, types of resources consumed, reproduction, and dispersal) and along lines determined by their *community* ecological relationships (competition, predation, parasitism, mutualisms and a multitude of ensuing indirect effects). What emerges is a 'system trajectory' for a particular field, or a type of successional pattern of development, that is in large measure determined by management choices made in the very early season, and by the general ecological context for that system.

6. Perturbation (disturbance)

Disturbance is an integral part of the definition of an Ecosystem Approach. Some form of destruction is the inevitable endpoint of successional growth and development. It is part of what makes systems dynamic, and it plays a critical role in maintaining resilience (see below).

Some types of regional disturbances by definition take place at large spatial scales (e.g., drought, storms, glacial movements), others are local and always at relatively small scales (a tree falling in the forest). Some disturbances can span a wide range of spatial scales (e.g., insect and disease outbreak, fire, flood). One of the key tenants of ecosystem management theory is that the normal disturbance experienced by an ecosystem allows for new opportunities for growth and development through 'creative destruction' (Holling 1995) allowing for new resources (e.g., space, light, nutrients) that were prior limiting factors. In systems where humans have attempted to restrain disturbance as a management policy – for example, the attempts to control all forest fires in US national forests in the first half of the 20th century – we saw the inevitable shift of the system to a more *fragile* state, prone to extremely large perturbations, triggered by small events, and for which the outcome in terms of damage was beyond the historical experience of the system. For example, when the understory in such fire-protected forests builds up to such an extent that a small fire eventually and inevitably gets out of control, leading to an unprecedented (or at least very rare) large-scale burn that destroys vast areas and very large trees that would otherwise have survived the small burn.

In 'natural' systems, disturbance most often occurs at small scales and in spatially unpredictable patterns (patchworks) of destruction and subsequent regeneration, leading to spatial heterogeneity and ecosystem structure that itself is a type of 'resource'. On longer time scales there may exist slower variables that slowly accumulate over time (e.g., the accumulation of woody understory during a long drought period) that eventually reach a stage where a small perturbation triggers an event synchronised over a large spatial scale. Large-scale, but relatively infrequent, synchronised perturbations (e.g., large fires and insect outbreaks) are therefore also part of natural ecosystems dynamics.

Disturbance is scaled by magnitude and by rate. The time course for disturbance is almost always fast in relation to the time course for growth and development of the system. As a result, disturbance creates *pulses* in the system (e.g., a nutrient pulse following a fire). In this way a disturbance can be 'transmitted' through the web of interrelationships of the ecosystem (one way of at least conceptually defining the spatial extent of an ecosystem).

Agriculture is perturbation. People often argue that agriculture 'is perturbation', by its very nature. True, farmers till the soil, plant varying degrees of monocultures or 'oligocultures', and remove the unwanted species through the labours of weeding. Then, at the end of an 'unnaturally' short successional period, they uniformly cut and remove large expanses of vegetation— possibly returning some residues to the soil, but often not — and then start the cycle over when conditions are again favourable.

However, the issue is not that perturbation or disturbance is 'unnatural' in ecosystems, nor even that the magnitudes of disturbance are particularly severe (although this can be an issue), but rather that:

1. disturbance associated with agriculture often involves *negative long-term cumulative effects* (e.g., soil erosion, salinity build-up, nutrient mining, loss of refuge for natural enemies), for which there is, for one reason or another, no regeneration allowed for by the system management; and,
2. that the *scale of the disturbance* can sometimes be so large (e.g., synchronous harvests, or insecticide applications on thousands of hectares) that populations are drastically delayed in arriving, diminished in number, or which engender actual species lost from the system.

In the first instance, *system resilience is degraded over time*, in the second case, systems may be hit so hard that they *shift to alternative and less desirable stability domains.* This brings us to our next term.

7. Resilience

This is a key term that integrates much of what was discussed above. Two definitions for *ecological resilience* were originally put forward (Holling 1973). The first is an engineering definition in which resilience is defined as *the return time* *of a system to equilibrium after a disturbance.* This definition seems to have caught on, probably due to the influence of mathematical modellers employing differential equations. The second definition of resilience is *the degree or extent of perturbation a system can withstand before it shifts to an alternative stability domain.* This second definition is more appropriate to our concerns in agroecology (see below for examples).

Resilience is a system-level quality that, as a concept, carries with it the idea that ecosystems are dynamic and, after perturbations, reorganise and replenish themselves. Another way to think about the ecological sustainability in agricultural systems is to consider *ecosystem management as a strategy to maximize resilience.* One can go further and consider the resilience of the economic and social components of sustainability as well. Perhaps a better way to tie all this together is to define agroecosystems to include the mutual interaction of biotic and abiotic elements, farmers and their social and economic subsystems. In this way, managing for resilience can be seen to naturally span all three sectors of sustainability (ecological, social and economic).

8. Adaptive management

Adaptive management was first developed as a resource management tool in the 1970s (Holling 1978). Various definitions of adaptive management are available in the literature (Walters 1986; Parma and Management 1998; Callicott, Crowder et al. 1999), but the basic concepts are simple and appealing. Adaptive management tries to incorporate the views and knowledge of all interested parties. It accepts the fact that *management must proceed even if we do not have all the information we would like,* or we are not sure what all the effects of management might be. It views management and policy, not just as a means to achieve objectives, but also as a type of 'experiment' or a process for exploring the ecosystem being managed. Thus, *learning is an inherent objective* of adaptive management. As we learn more, we can adapt our policies to improve management success and to be more responsive to future conditions (Johnson 1999).

9. Farmer education

Adaptive management was first developed in the context of the large-scale, long-term issues of forest systems in the industrialised countries, but what about farmers in developing countries? Clearly farmers are the managers and the other parties to the issues involve extension, research and policy-makers at various levels. The need for effective communication with clear common language is even greater given that we are now talking about hundreds of millions of people. The task might seem daunting to the researcher, but there are a growing number of successful programmes throughout the developing world that combine both an Ecosystem Approach to agriculture and high-quality, scaled-up farmer training methods that lead to much more resilient and productive ecosystems. Rather than placing additional burdens on the researcher, research based on an adaptive management approach can facilitate better research through the interaction, enthusiasm and creative energies of the many actors. Adaptive management in agriculture leads to decentralisation, and decentralised research is at once more appropriate given that farmscapes are heterogeneous across wide spatial scales.

C. What is 'Crop and Crop-Associated Biodiversity'?

Vandermeer and Perfecto (1995) first suggested two basic categories of agrobiodiversity. *Planned biodiversity* includes the crops and livestock purposefully introduced and maintained in the agroecosytem by the farmer. *Unplanned biodiversity* includes all soil flora and fauna, herbivores, carnivores, decomposers and any other species that exist in, or colonise the agroecosystem. Figure 1 illustrates their important role in maintaining ecosystem functions.

According to the original idea of Vandermeer and Perfecto (1995), planned biodiversity has a direct effect on ecosystem function – for example, overstorey trees in an agroecosystem provide the opportunity to grow crops that do not do well in direct sunlight (direct promotion of ecosystem function), and also promote an environment that allows for the attraction of beneficial arthropods that help control pests (indirect effect, represented by the dotted line).

Altieri suggested a quite useful organizational chart in 1994 to show the overall relationship between CAB and management practices ('enhancements') that have some relationship with 'components' and 'functions' in the agroecosystem (Figure 2). The task remains, however, to determine the actual mechanisms that would lead to a predictive strategy for managing associated biodiversity.

Components and Interactions. In contrast to the long history of formal research and historical knowledge related directly to crops, the understanding of the mechanisms and importance related to unplanned or crop-associated biodiversity is only now being thought of in any systematic fashion. The research literature on terrestrial agroecological relationships goes back many decades, but some topics, such as the role of vegetative diversity in the promotion of improved pest suppression, and the related question of how diversity relates to stability, remain controversial due to a lack of understanding of general mechanisms. Soil ecology is a relatively new discipline, but one hindered by the size and vast numbers of the organisms involved. Both components are hindered by the general problem of understanding and representing highly complex systems.

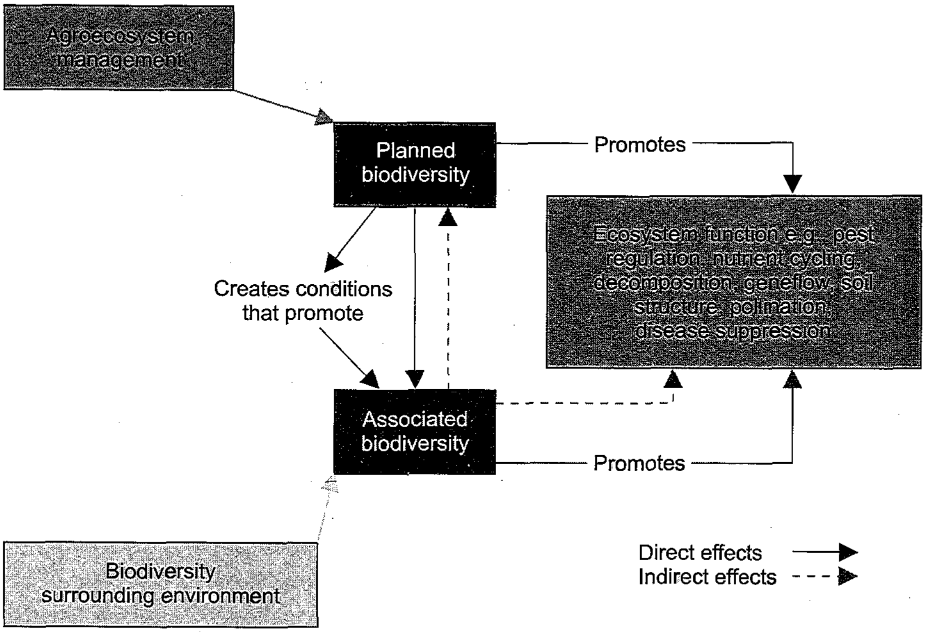

Figure 1. Planned and associated biodiversity

Source: Adapted from Vandermeer and Perfecto (1995)

Swift and Anderson (1994) conceive of CAB as divided into three types: *productive, beneficial*, and *destructive*. *Productive* biota includes crop plants and livestock, producing food, fibre, or other products for consumption. *Beneficial* biota contribute positively to the productivity of the system as pollinators, plants of fallows, soil biota controlling nutrient cycling, arthropod predators and parasitoids, and more. *Destructive* biota includes only weeds, pests, and pathogens. This classification underpins management – the role of farmers and agricultural scientists in increasing crop and animal production by encouraging productive biota and discouraging destructive biota.

Soil Ecology – The 'Last Frontier'? In almost any imaginable agroecosystem the vast majority of biodiversity will be below the soil surface. There has been rapid recent growth in our knowledge of the identities and functional relationships of this biodiversity in recent years with the development of new molecular marking techniques. Clearly this diversity is critically important for agroecosystem through the variety of decomposition and nutrient mineralization pathways. These include historically well-known mutualistic relationships between plant roots and groups such

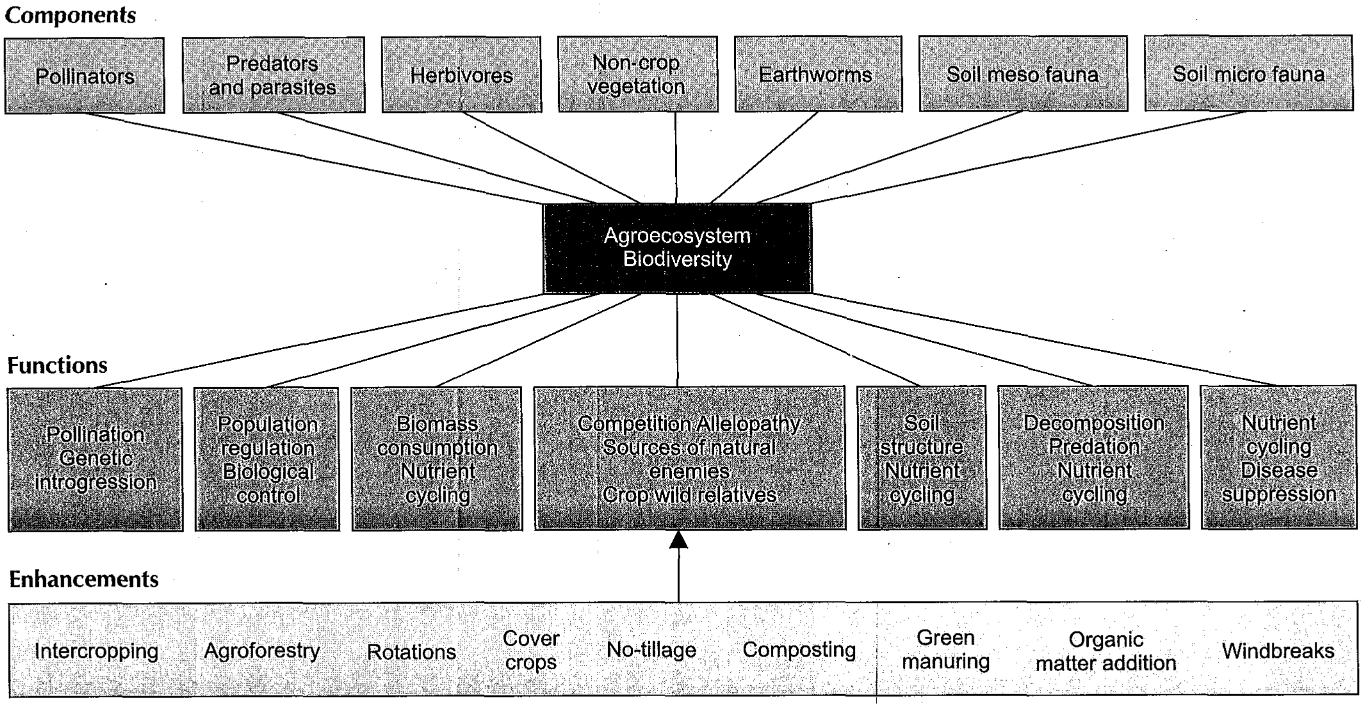

Figure 2. Overall relationship between CAB and management practices as described by Altieri

Source: Biodiversity and pest management in agroecosystems New York: Haworth Press 1994 as the mycorrhizal fungi, who facilitate the uptake of nutrients such as highly-immobile phosphorous in return for sugars from the plant. Recent developments are showing a much broader and more diverse set of mutualistic relationships between plant roots and microbes than has previously been suspected (R Sikora, University of Bonn, pers. com.), and is an area ripe with exciting research topics.

In spite of the vast diversity and concomitant complexity one generalization seems clear— within the current conditions of most agricultural systems, an improvement in the addition composted materials or recycling of crop residues helps productivity of soils and crops for a broad range of reasons. One topic of particular interest is that of '*suppressive soils*' in which the cultivation of a well-structured, organically rich soil not only serves to facilitate nutrient storage and retrieval, but also facilitates protection of the roots from pathogenic soil organisms who suffer a decreasing likelihood of host invasion due to the presence of the multitude of mostly saprophytic microorganisms, who facultatively are able to attack pathogens.

On the other hand, (Wardle, Giller et al. 1999) note: 'The extent to which soils can be abused, and yet still continue to produce yields indicates the robust nature of below-ground biodiversity. How much of this below-ground biodiversity is needed to guarantee the provision of nutrients and a favourable physical environment for root growth is yet to be determined.' The question of the relationship between species diversity and the continued maintenance of ecosystem function has been prominent in the scientific literature under the heading of *functional redundancy*, or the diversity – stability debate.

The *high resilience* of any component of an agroecosystem is in part a function of what processes are being measured (carbon and nitrogen cycling may be a more resilient function than, for example, the suppressive ability of soils), and the scale of measurement (function may deteriorate over time-scales outside that of the experiment).

D. Is Management of Crop-Associated Biodiversity Possible?

The CBD Decision V/6 Principle 2 states that:

"Management should be decentralised to the lowest appropriate level.

Rationale: Decentralised systems may lead to greater efficiency, effectiveness and equity. Management should involve all stakeholders and balance local interests with the wider public interest. The closer management is to the ecosystem, the greater the responsibility, ownership, accountability, participation, and use of local knowledge."

Yet, if crop-associated biodiversity refers to, by definition, *unplanned* biodiversity, acting to provide ecosystem services through *indirect* pathways, how can we consider that farmers actually *manage* it?

Three points are of interest here: *who* manages CAB, *how* it is managed, and *what* is required to make this management effective.

Who, How, and What?

Clearly farmers manage directly the agronomic factors related to the crop. These factors, in turn, are the "Ecological Context" for, and have impact on the CAB. Farmers manage soil amendments, water, synthetic inputs and all manner of crop-related factors (plant variety, spacing, patch size, overall vegetative patterns and diversity, timing, residue management, etc.). All these factors, which are managed directly for the benefit of the crop (not to say they are all beneficial), have strong direct and indirect effects on the CAB.

The point to note here is that **farmers indirectly manage CAB, *whether they realise this fact or not.*** The obvious corollary to this point is that **unless farmers have knowledge about the nature and function of CAB, they cannot *effectively* manage it**. More than 15 years of experience with participatory farmer training in IPM in Asia clearly shows the possibilities and the necessity of farmer training to include both Crop and Crop-Associated Biodiversity.

One of the clearest examples of the importance of farmers understanding the role of CAB and the importance of indirect effects is the wide-spread problem of insecticide-induced resurgence (Figure 4). Without knowledge of how insecticides destroy native pre-dators and parasitoids and often fish, birds and amphibians, farmers are prone to use pesticides as a type of 'insurance'. In many countries,

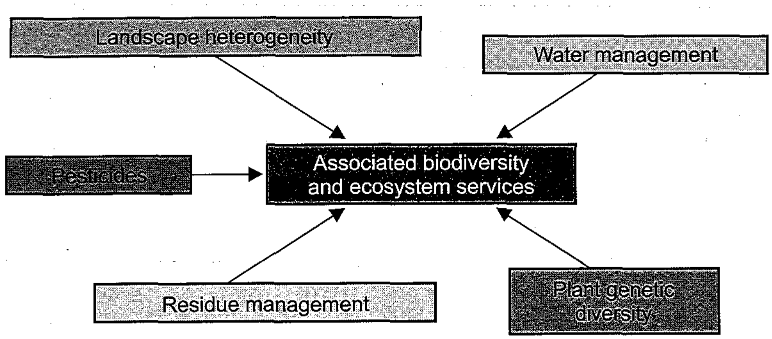

Figure 3. Indirect management: farmers, knowingly or unknowingly, manage large-scale factors in an ecological context, which in turn affect the associated biodiversity and ecosystem services

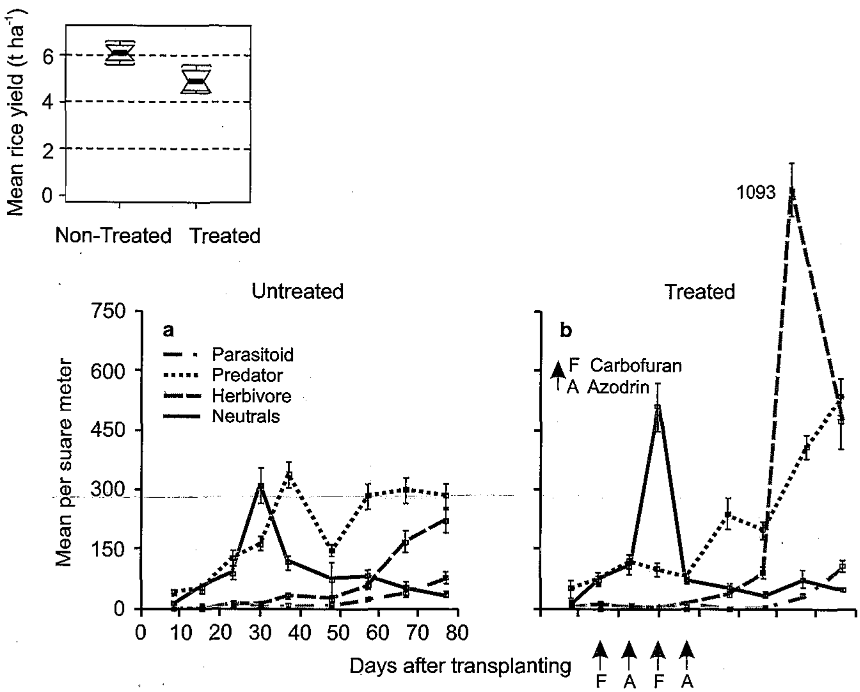

Figure 4. Experiments in tropical irrigated rice in Indonesia showing insecticide-induced pest resurgence; a. untreated rice plots have high levels of predators in the early part of the season because they are feeding on 'neutral' populations i.e., abundant populations of detritivore species; So, b. a typical insecticide application regime, during the early season, leads to suppression of the predator populations and resurgence of the pest (mostly rice brown planthopper and stemborers) more than one month later. The resurgence of the 'neutral' populations, supports the hypothesis that detritivore populations help build populations of generalist predators early in the growing season

Source: Settle et al., 1996

regardless of level ofeconomic development, farmers put pesticides on crops early in the season – whether they see a need for them or not – to try and avoid pest problems. Unfortunately for everyone but the chemical companies, this action constitutes a type of chemical perturbation of the ecosystem. If the perturbation of the system is not too widespread and long term, and depending on the nature of the toxins, the CAB that is responsible for effective biological control of pests (i.e., predators and parasitoids) may show sufficient resilience and rebound quickly and thus avoid having problems in *resurgence* of pests. However, if the toxic load is widespread, long-term and sufficiently toxic, then existing agroecosystem 'defences' will be suppressed (while pests escape through a variety of mechanisms) and pest populations then soar. Despite this being a well-tested and well-understood phenomenon in almost every agroecosystem, *farmers are still mostly unaware of the mechanisms and therefore the nature of the problem.* Moreover, for pollinated crops, these practices could lead to the destruction of pollinators and yield decline.

Detritivore Foodwebs as Alternative Pathways. In addition to illustrating the value of CAB in the well-known scientific examples of insecticide-induced resurgence, Figure 4 also illustrates a less well-known function for CAB— that of detritivore foodwebs acting as alternative pathways for energy. In brief, for tropical irrigated rice systems, soil organic matter feeds an aquatic foodweb whose top consumers (chironomid midges), together with arthropod detritivores feeding directly on the organic matter (principally collembolans and ephydrid flies) are available as an abundant source of food for omnivorous predators in the plant canopy (Figure 5). This early season boost of energy ensures abundant and well-distributed populations of predators throughout the season, and greatly increases the effectiveness of biological control of crop pests.

The example comes from tropical irrigated rice, but is probably a more general phenomenon than has been previously suspected, and is another fruitful avenue for research. The research further tested and found a strong correlation between inputs of organic matter (crop residues) and abundance of important predator populations (see Settle et al. 1996 for details).

E. Biodiversity for sustainable agriculture and sustainable agriculture for biodiversity – topics for actions and research

The Convention on Biodiversity COP 5 Decision V/5 states: "There is also much information about resources that provide the basis for agriculture (soil, water), and about land cover and use, climatic and agro-ecological zones. However, further assessments may be needed, for example, for microbial genetic resources, for the ecosystem services provided by agricultural biodiversity such as nutrient cycling, pest and disease regulation and pollination, and for social and economic aspects related to agricultural biodiversity. Assessments may also be needed for the interactions between agricultural practices, sustainable agriculture and the conservation and sustainable use of the components of biodiversity referred to in Annex I to the Convention."

The following is a list of possible topics related to C-CAB. These are offered as a starting point for discussion on possible areas for consideration and actions, but certainly more can be added.

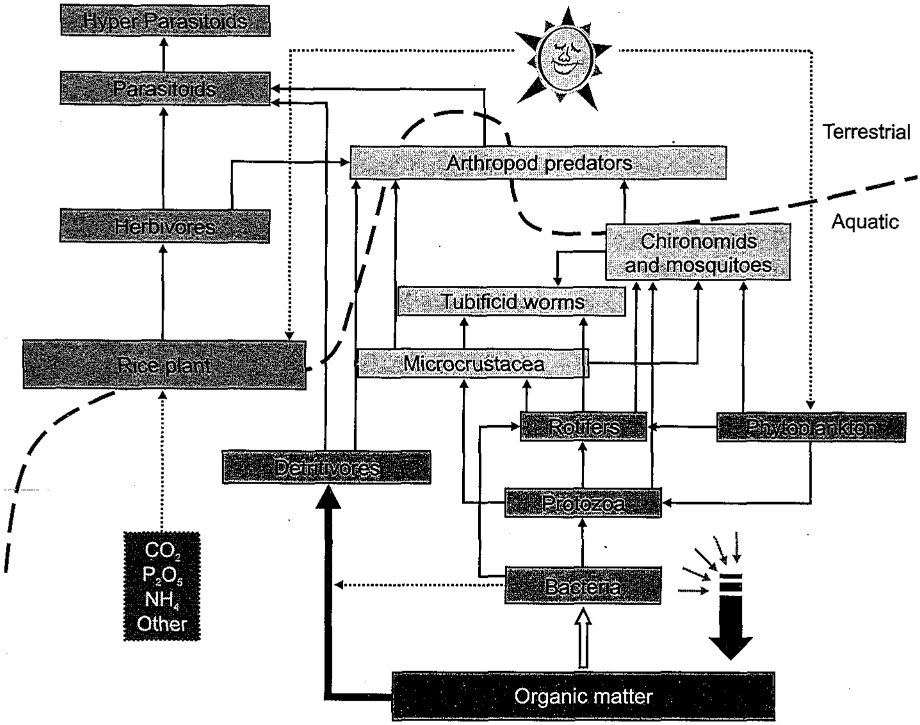

Figure 5. Tropical irrigated rice foodweb showing pathways from organic matter to terrestrial arthropod predators that support strong biological control of rice pests

Source: Settle 2001

Crop biodiversity

- **Genetic base and co-evolved pests and diseases:** Many early crop introductions must have originated from a narrow genetic base. Yet a narrow genetic base often sufficed, as in the case of fife wheat. Examples from plantation agriculture include the early narrow base to coffee and to oil palm (the original introductions of which are still growing in Bogor, Indonesia). Mangosteen (*Garcinia mangostana*) throughout the tropics is thought to be a single clone. But are these successful, but narrow-based, introductions 'living on borrowed time' until co-adapted pests rediscover them in their new location?
- **Varietal movement:** Most of the varieties grown by any farmer will have come from off-farm, introduced as a response to changing socio-economic conditions.

Adaptive management by continued access to varieties through seed flows of all kinds is probably the single most important issue for crop diversity globally

- **Varietal innovation:** Most concern in the past has been placed on the rate of varietal *loss* and how to prevent it by in-situ conservation. A quite unexplored area is varietal *gain* – the routine selection of 'off-types' (recombinants and mutations) as new varieties by farmers. Yet with some understanding and promotion, varietal innovation could perhaps outweigh varietal loss and lead to a net gain of varieties.
- **Neglected and underutilized crops:** There is a vast resource base for this and the need for much more effective approaches. This extends beyond farming to food-processing and marketing of novel foods.
- **Interface with the wild:** Wild food and other plant products can be a key resource in economically or ecologically marginal conditions. Yet there are numerous possibilities for social conflict and resource insecurity as concepts of ownership change (not least under the expanding system of strictly protected areas).
- **Crop transfers:** Many locally-important crops have never moved from their regions of origin, despite apparently suitable growing conditions elsewhere. Examples include the peach palm (*Bactris gasipaes*) and sago (*Metroxylon sagu*).
- **Phytosanitary measures:** While overcoming the bottleneck of crop introduction, continued effort is needed to exclude damaging pests and diseases. The current call for crop diversification places increased pressure on the international phytosanitary systems and prompts the need to enlarge the system and the knowledge base to include CAB associated with minor and unexploited crops.
- **The spread of invasive weeds:** is a specific and important topic related to crop introduction. There are particular problems with the intercontinental transfer of weeds which thereby escape their co-evolved enemies and flourish (in traditional agriculture, weed control has the largest impact of all farm operations on labour costs).
- **Varietal adaptation as a response to climatic change:** Long-term climate change has always been a feature of agriculture (indeed, the origin of agriculture itself may have been a response to post-glacial climate change). More knowledge is needed to choose between three hypotheses: a) varieties on-farm do not change over time (and as they progressively become dysfunctional, farming is abandoned); b) varieties adapt in-situ; or c) varieties are progressively replaced by varieties brought from elsewhere pre-adapted to the newer conditions.
- **Intensification and land management:** As agriculture intensifies globally, what are the direct effects of this on crop-associated biodiversity? For example, as fallows give way to continuous cropping, there may be two contrasting effects: a) biodiversity can no longer enter cropland seasonally from refuges in fallow; b)

there is no break in the cropping (or irrigation) to remove harmful organisms from the field. Also, are there benefits to biodiversity of nutrient enrichment (e.g. more biomass, more trophic cascades).

- **De-intensification and input substitution:** Socio-economic effects on C-CAB are highly important, as, very commonly, an economically unviable farm will be abandoned with the loss of all C-CAB. As farm income falls (food prices are at an historic low), external inputs will be reduced. This will increase the need for the management of C-CAB as a substitute for purchased inputs (for example, crop residues for feed, composting, crop diversification, IPM). If this is successful, farms will survive. A major challenge for farming is access to the knowledge-base to permit more sophisticated use of C-CAB for economic survival.
- **The socio-economic value of biodiverse gardens:** specifically relating to the economic complementarity of gardens with fields of staple crops.
- **Double and triple cropping:** supported by supplemental irrigation can extend the favourable season for on-farm biodiversity. This has been a feature of traditional 'tank' irrigation in Asia for millennia.
- **Perennial gardens in seasonally dry regions:** provide havens for crop associated biodiversity (and transient wild biodiversity).

Crop-Associated Biodiversity

- **Movement of CAB from surrounding systems into the environment of a newly introduced crop:** What are the differences between a swidden farmer in Borneo planting a half-hectare plot in the middle of a forest, with a Javanese farmer planting the same half-hectare in the middle of a vast rice production area on the island of Java, where rice has been grown for 3,000 years? Do different species come into play within similar functional groups?
- **Pollination:** Pollination is an essential ecosystem service, as it enables plant reproduction and food production for humans and animals (fruit and seeds), that depends to a large extent on symbiosis between species, the pollinated and the pollinator. In many cases, it is the result of intricate relationships between plants and animals, and the reduction and loss of either will affect the survival of both parties. Over three-quarters of the major world crops rely on animal pollinators. Pollinators provide over US$ 50 billion per year of services to agricultural and natural ecosystems. In order to secure sustained pollinator services in agricultural ecosystems, far more understanding is needed of the multiple goods and services provided by pollinator diversity and the factors that influence them. The involvement of farmers is also crucial in addressing this issue.

- **Soil-root interactions:** e.g., so-called 'suppressive' soils in which rich organically amended soils are correlated with reduced soil-borne diseases due to the activity of a multitude of microbial actors.
- **Below-ground linkages to above-ground biodiversity:** e.g., that enhance biological pest suppression (a new area of research).
- **Plant genetics interacting with CAB and implications for management:** For the past four decades agricultural research centers have been focussing on crop genetics without considering the relationship to CAB. This is changing in some interesting ways (e.g., breeding plants that when damaged, attract parasites of the pest doing the damage; grape leaves that have certain types of leaf hairs ('domatia') that house predatory mites and the non-pest alternative prey for predatory mites). These types of breeding programs, however, are still the exception. Breeders and agronomists during the Green Revolution failed to consider that CAB is the first line of defence against pests and pathogens. Developing resistant varieties while still promoting the use of insecticides led to rapid shifts in pest populations to be able to exploit the new varieties (so-called varietal "breakdown"); hence, accelerating the loss of very expensive and very valuable crop varieties.
- **Crop–livestock interactions/systems:** Grazing animals may determine the relative abundance of different species in a habitat. Part of this role is due to selection between the plants on offer in a pasture, both between species of plant and within species. According to Harper (1977), "a grazing animal tends to be a diversifier of a grassland community, creating locally different microenvironments for seedling establishment and the subsequent growth of plants, and continually initiating regeneration cycles on a small scale within the community." For instance, the further understanding of the complex and dynamic interactions between ingestive behaviour and diet selection by grazing animals and the stability and productivity of grazed areas might be required as well as the identification of strategies to improve the efficiency and sustainability of grazing systems.
- **Cattle and sheep removal of crop residues:** now that we are learning more about the multitude of valuable contributions made by plant residues to the sustainability of cropping systems, farmers need to be able to assess whether they want to feed, for example, rice or wheat stubble to cattle, or conserve the stubble for use as an organic amendment to conserve the function of soil and detritivore systems. Clearly, farmers in many places in India and Bangladesh have constraints placed on them by the needs of securing fuel and fodder. This requires looking at costs and benefits, opportunities and constraints of alternatives for cooking fuel as

well as alternatives for feeding cattle, possibly through improved legume forage crops.

- **Multiple-function perennials:** Use of non-crop perennial plants and tail-water recycling schemes for stopping soil erosion and for soaking up excess nutrient loads before they move into ground-water or streams. Further use of these plants can be made to attract beneficial organisms like parasitic wasps.
- **Cover crops in orchard and vineyard systems:** provide a multitude of beneficial effects including increased soil-water penetration, increased soil health, increased biological suppression of pests.
- **Increasing vegetative diversity for pest control:** does it work? The data are equivocal and the issue is controversial.
- **Evaluating the state of CAB in agricultural systems:** some agroecosystems are stable and sustainable. Others are degrading slowly over time due to nutrient mining, loss of habitat, changes in configuration of vegetative patterns; other systems are in a rapid downward spiral into ecological disaster and economic ruin. Can we derive methods and indicators to efficiently but rapidly evaluate the current state and likely short, intermediate and long-term trajectory of agroecosystems?

F. How to study CAB?

Studying CAB will be a new challenge for traditional agricultural researchers. Conventional methods of holding all factors constant and varying the one of interest in a controlled manner may be appropriate in some instances, but not as a general approach. One approach might be to follow the example of field ecologists who try to look at elements and processes across a transect of a particular ecosystem, or even across a transect of ecosystems within a certain classification level. For agricultural systems we might look at a particular class of agroecosystem (e.g., tropical irrigated rice, or rice–wheat cropping systems, etc.), but taking measurements across a transect of a particular cropping dimension (e.g., crop heterogeneity, input intensification, soil amendment practices, water control regimes, within-crop genetic heterogeneity, etc.). The following are several points that may be useful for some researchers interested in studying CAB:

- sample agricultural systems within-crop and across a continua of landscapes and management intensities
- seek to understand the range of mechanisms (both in terms of nutrient-flow and community dynamics) that support the "service" in question
- seek to understand how these mechanisms are affected by large-scale factors that underlie ecosystem function (the "ecological context")

- look to see how what the implications are for policy and management
- build capacity in countries
- take responsibility for educating people in an effective and practical way.

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Appendix 2

The outcomes of regional working group discussions for Asia and Africa that aimed to identify cross linkages and synergies of potential contributions of C-CAB to sustainable agricultural intensification. These are presented as 9 x 7 matrices, within which examples are shown in parentheses.

Appendix 2. Outcomes of regional working group discussions (Africa)

	Demonstrated benefits delivered by component	Demonstrated disruption caused by removing or compromising component	Interventions to enhance effect of component: a. Planned C-CAB b. Associated C-CAB
Soil ecology: macro-fauna	– Termites, ants, beetles effects on soil physical properties – Breakdown of soil organic matter (SOM) – Carbon sequestration – Improved soil health	– Impaired hydraulic properties – Soil compaction – Release of aflatoxin in ill-drained soils	– Provide organic matter (OM) supply • Cover crops • Organic residues • Wastes • Manures • Mulches – Create refuges
Soil microbial ecology	– N fixation and nutrient and water capture by mycorrhizae – SOM dynamics – Phosphorus capture by bacteria	– Non-inoculation of N-fixers associated with legumes – Storage and retention of N in system – SOM reduction	**Planned ABD** – Inoculate appropriate strains – Add appropriate compost microorganisms **ABD** – OM inputs that stimulate microbial activities
Pollination			
Crop–livestock	– Increased • Use of non-edible OM in cropping system • Diversification • Resilience • Investment • Draft power • Food security – Reduced • Risk	– Reduced • Area of crop cultivation • Plant diversity • Soil invertebrate diversity • Livelihoods	– Species diversification, possible effects on ABD (camels in northern Nigeria, goats) – Improved grazing management (NW Kenya, Burkina Faso) – Marketing (Somalia/East Africa, Kenya, Sudan) – Introduction of herbaceous legumes (Nigeria, Niger, Burkina Faso)
Seed sense and public/ private sectors	– Little impact of modern varieties on high-BD regions/higher impact in low-BD regions – Variety adapted to local conditions (increase productivity decreases risk?) – Diversification brings benefits • Livelihood benefits	**Wars, drought** – Loss of germplasm (groundnut in The Gambia) – Stop flow of germplasm (Mozambique, Somalia) – Reduced BD (Large commercial farms, Zimbabwe)	– ABD: N-fixing legume trees/inoculants (agroforestry) mycorrhizae – Planned ABD • On-farm trials – Gene banks • Small seed packs • Seed supply systems • Seed banks
Neglected or under-utilized crops (NUS)	– Variety adapted to local conditions (increases productivity, decreases risk) – Diversification benefits – Livelihood benefits (better nutrition) – Broadening genetic BD – Regional food security (Fonio, Bambara nut in West Africa) – Improved nutrition, improved soil fertility and NRM; domestic use + export	– Reduced livelihood benefits, particularly women (Fonio)	– Market potential (Bambara nut) – Supply/demand – Public/Policy market concerns
IPM: pathogen suppression	– Increased food and feed quality in groundnuts – Improved livelihoods (human and animal health)	– Decreased food quantity and income – Decreases quality reduces export potential	– Use of different varieties – Balance between toxic/non-toxic fungi in soil
IPM: arthropod predation	– Predation by community of 20–30 species in 4–5 function groups – Benefits: higher yields; better quality of cotton less honeydew from insects	– Pest population increases, inappropriate pesticide application	– FFS with local variations
Abiotic factors: land and water	– Reduced tillage (decreases labor and draft power) – Decrease in water use and residues	– Soil degradation, loss of topsoil, siltation of waterways – Affects lowland wetlands and ABD	– Introduce appropriate equipment sowing/ herbicides + crop diversify for biological plowing – Increase macro-fauna and micro-flora and water conservation

Appendix 2. Africa (contd.)

	Results: Production; Associated Changes; Risks	*Strengthening local communities' capacities to capture benefits;* **Building understanding and adapting tools**
Soil ecology: macro-fauna	**Results** – Better use of water-use efficiency (WUE) **Risks** – Increase rodents and reptiles in litter – Damage to exotic crops – High pH or soil brought to surface → chlorosis **Associated changes** – Use of mulch – Reduced need for tillage – Competition for OM	– Provide appropriate training and education [farmers field schools (FFS)]
***Soil microbial* ecology**	**Results** – Increased productivity – Suppression of *Striga* in nutrient-rich soils **Risk** – Quality control of inoculants	– Training and availability (storage, delivery...)
Pollination		
Crop–livestock	**Results** – Improved • Food security • Range productivity • Plant species composition • Income **Risks** – *Overgrazing* – Disease • Human, animal – Soil compaction – Increased unpalatable species and weeds	– Teach community livestock workers about introduced parasites – Train in livestock management – FFS on marketing (goats, chicken, cattle)
Seed sense and public/ private sectors	**Results/ Indicators** – New sorghum varieties (Somalia) – Income generation/ food security, livelihoods – Increased yield stability linked to variety release (groundnut, Nigeria) – Income generation (Malawi seed bank groundnut, CG7); C Somalia, Eritrea, sorghum + millet) – Improved livelihoods (Namibia: pearl millet Okashana) **Risks** – If narrow BD no resilience; collapse from pest and disease attack – *Inappropriate seeds (Afghanistan)* **Associated changes** – *Striga* (pearl millet, Eritrea) – Groundnut prone to rosette virus (Mozambique)	– Establish system to • Multiply breeder seed foundation seeds for farmers (groundnut, pigeonpea, Mozambique) • NGOs to produce small packs (OHVN in Mali) • FFS • Generate savings, credits (Coalition *'project intrants' – Niger)*
Neglected or under-utilized crops (NUS)	– Improved • Market recognition • Income (women, household)	– Establish market linkages – Processing and utilization – Production kit distribution to farmers
IPM: pathogen suppression	– *Quality produce* – Increased income and exports (oversupply to markets) – Improved health	– Create public awareness, farmers policy-makers, consumers – Promote on-farm/ participatory demonstrations
IPM: arthropod predation	– Increased yield, income – Decreased sickness	– Modify FFS to local culture/conditions
***Abiotic* factors: land and water**	– Increased production and WUE over time – Increased SOM **Risks** – More weeds and pests and fertilizers in initial stages – How to incorporate FYM → – Reduced herbicide efficacy	– Establish • FFS • Human capital/credit systems • Rural infrastructure

Appendix 2. Africa (contd.)

	Policy reforms to enhance ABD in agriculture; political economy of ABD	Research priorities and partnerships
Soil ecology: macro-fauna	– Control pesticide application (Fepernil for locust) – Need for soil ecotoxicological data – Regulate use	– Understand functional diversity of soil macro-invertebrates – Develop curricula, convey information to farmers
Soil microbial ecology	– Subsidise P fertilizers – Create market linkages – Stimulate demand for legumes (soya)	– Elucidate interactions between introduced and native microbial communities – Understand local seed systems, identify points of intervention
Pollination		
Crop–livestock	– Encourage livestock mobility – Control epizootics	– Market analysis of local demand – Encourage food safety and quality – Develop indicators
Seed sense and public/ private sectors	– Instigate variety release based on farmers choice, – Distinguish commercial/non-commercial crops) – Increase genetic diversity of seed available to farmers, ABD – Support seed fairs	**Research** – Farmer participatory selection – NRM practices – Research on ABD issues **Partnerships** – Public/ private sector – Local/ multinational – Farmers associations
Neglected or under-utilized crops (NUS)	– Encourage movement of germplasm in Africa (Bambara) – Create incentives for use	**Research** – Farmer participatory selection – NRM practices – ABD issues **Partnerships** – Public/ private sector – Local/multi-national – Farmers associations
IPM: pathogen suppression	– Establish • Grades and standards • Price incentives	– Adaptive research by farmers – Link technical, public health, and policy research on aflatoxin problems
IPM: arthropod predation	– Remove pesticide subsidies – Stop free distribution and credit – Remove pesticides from grant aid and discontinue World Bank loans for grade 1 and 2 – Strengthen regulation system – Invest in human capacity	– Host-plant resistance – Ineffective-ness of BT – Estimate returns, regulatory systems
Abiotic factors: land and water	– Provide incentives to encourage adoption	– Determine if herbicides can be substituted – Develop equipment and decrease labor use – Identify soil types and extra fertility generated

Appendix 2. Outcomes of regional working group discussions (Asia)

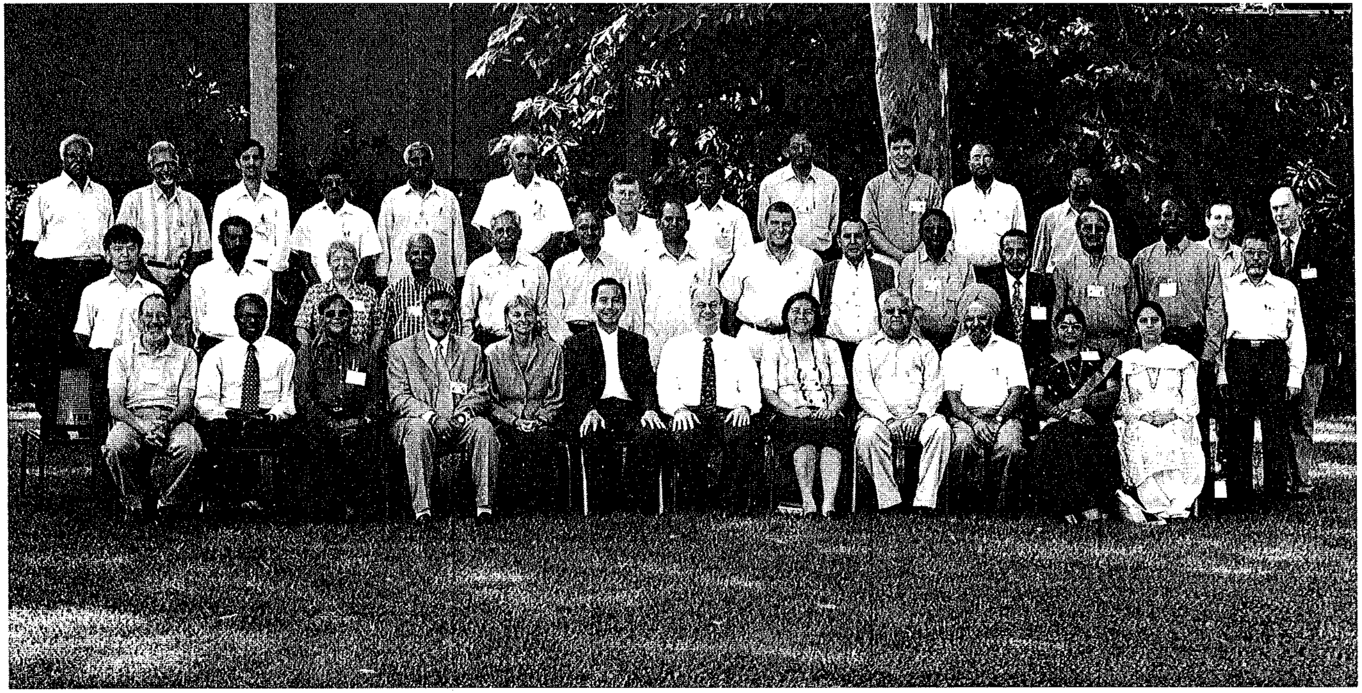
	Demonstrated benefits delivered by component	Demonstrated disruption caused by removing or compromising component	Interventions to enhance effect of component: a. Planned C-CAB b. Associated C-CAB
Soil ecology: macro-fauna	– Improved • Soil health • Plant growth • Productivity – Sustainable • Use of natural resources (NR) • Agro-ecosystem	– Adverse effects • Soil health • Plant growth • Productivity • Agriculture – Land degradation	– Add OM – Introduce useful/ beneficial macro- fauna – Reduce chemical fertilizers – Promote IPM, and IDM – Zero/minimum tillage
Soil microbial ecology	– Increased crop nutrients acquisition – Enhanced antagonists to control soilborne diseases	– Decreased soil quality, microbial life – Reduced nutrient acquisition – Increased soilborne diseases	– Increase application • FYM • Crop residues • Foliage from trees • Agroforests, field boundaries – Add *Rhizobium* and *Trichoderma*, etc.
Pollination	– Increased yield, enhanced quality (Himachal Pradesh, parts of China) – By-products – Employment	– Poor • Seed/fruit set • Yields	– Employ honeybee colonies – Manual pollination – IPM
Crop–livestock	– Recycling • Nutrients • Crop residues – Low-cost draft power – Increased income – Animal products – Diverse income sources	– Loss of soil fertility – Environmental degradation – Water and atmospheric pollution – Loss of • Complimentarity in crop–livestock systems • Income	– Manage FYM for biogas and soil fertility – Balance feed to reduce methane emission – Introduce legumes and fodder – Promote livestock–based local enterprises
Seed sense and public/ private sectors	– Increased productivity and quality – Improved • Livelihoods • Food security • Employment – Improved varieties grown more widely	– Lower • Yield • Quality • Food security • Income from agriculture	– Formal/informal seed production and distribution systems – Awareness of improved varieties – Seed quality control
Neglected or under-utilized (NUS) crops	– Broader food basket (rice-bean, in north-east India, buckwheat in Nepal, lablab in Indonesia) – Better nutrition (proteins, amino-acids and minerals) (chenopodium India; amaranth India, Indonesia; finger millet India, Nepal) – Low-input and marginal environments used – Livestock • Feed and fodder (kodo millet *Paspalum* – Madhya Pradesh, Gujarat)	– Loss of genetic diversity – Soil degradation (on sloping lands) – Malnutrition – Food security (Kalahandi, Orissa)	– Varietal improvement, production technology research (Amaranth in Gujarat) – Demonstrate improved technologies for NUS (on-farm demonstration buckwheat and finger millet in Nepal) – Processing, value addition, and new recipes (finger millet, amaranth in Karnataka) – Seed production
IPM: pathogen suppress-ion	– Reduced chemical use – Increased productivity – Better, safe environment – Healthy food products	– Reduced productivity – Enhanced chemicals use – Insect resistance	– Crop rotation – Intercropping – Application of OM/compost – Increase use botanicals and biocontrol agents
IPM: arthropod predation	– Less pest damage (*Spodoptera* on groundnut in Vietnam) – Increased production/ productivity – Enhanced environmental safety – Less disturbance to insect BD	– Increased • Crop damage • Use of chemical pesticides – Reduced • Populations of predators and parasites/ pollinators • Insect BD • Ecosystem stability	– Crop rotation, crop density, intercropping – Reduce chemical pesticides – Promote natural predators (birds)
Abiotic factors: land and water	– Increased • BD • Income • Yield – Enhanced quality (model watersheds, India, Pakistan, Thailand, China) – More land and water available	– Soil degradation – Water scarcity – Reservoir silting – Loss • BD • Income • Food security • Water quality	– Agroforestry – Promote NUS bund crop (Gujarat, *Glyicidia*) – Crop residue management – Rainwater harvesting and management – Soil amelioration

Appendix 2. Asia (contd.)

	Results: Production; Associated Changes; Risks	Strengthening local communities' capacities to capture benefits; Building understanding and adapting tools
Soil ecology: macro-fauna	**Results** – Increased BD – Stable and enhanced productivity, better quality – Better nutrient recycling and turnover **Risk** – Increased weed growth	– Awareness raising • Training (FFS) • Supply macro-fauna starter material (earthworms) – Community mobilization to preserve and promote of macro-fauna
Soil microbial ecology	**Results** – Increased soil health – Enhanced availability of crop nutrients – Less soilborne diseases **Risk** – Nutrient leakage (gentrification)	– Generate biomass on community lands – Local enterprises to produce agriculturally beneficial micro-organisms
Pollination	**Results** – Increased • Production • Quality • Income from by-products **Risks** – Insect stings – Varietal impurity in seed production	– Mobilize community awareness – Train and demonstrate – Provide bee colonies – Support bee enterprises
Crop–livestock	***Results*** – Increased • Soil fertility • Livestock productivity • Sustainable production system • Diversified sources of income **Risks** – Degraded grazing lands – Over-exploited land and resources	– Awareness of management and modern feeding technology – Train on outputs quality – Community management of grazing land and CPR – Diversify cropping systems
Seed sense and public/ private sectors	**Results** – High productivity, better quality (wheat, rice, India) – Development • Agro-industries (rice mills, threshers) • Seed industries (Maharashtra, Karnataka, Andhra Pradesh) – Employment generation **Risks** – Loss of local landraces/biodiversity – Increased genetic vulnerability to diseases and pests – Dependence on external supplier for seed – High cost of cultivation	– Increase awareness of improved cultivars, quality seed – Train farmers to produce seed – Supply seed of hybrids and varieties parental lines – Promote Seed Grower Associations (cooperative sector) – Encourage participatory seed production – Provide • Seed bank facilities at village level • Local varieties' seed
Neglected or under-utilized (NUS) crops	**Results** – Increased • Production • Productivity • Income for poor/tribal farmers – Better NRM – *Diversified production*	– Establish links between producer–consumer–procuring industries – Create awareness of crop nutritive values, other benefits – Provide • Marketing including exports • *Seed production*
IPM: pathogen suppress-ion	**Results** – Production • Increased • Pesticide residue-free – Reduced environmental degradation **Risk** – Increased populations of non-target pests	– Promote on-farm participatory IPM • Farmer-friendly literature on IPM – Village-level production of biocontrol agents – Mobilize community IPM projects
IPM: arthropod predation	**Results** – Improved production, quality (pesticide residue-free) **Risk** – Possible increase in non-target insect population	– Create IPM awareness IPM among communities – Teach IPM technologies
Abiotic factors: land and water	**Results** – Increased productivity crop and soil – Reduced soil degradation – Protected environment – Better health and nutrition **Risks** – Loss • Free grazing • CPR (Rajasthan) • Drinking water for urban population	– Develop participatory technology – Strengthen • Rural institutions

Appendix 2. Asia (contd.)

	Policy reforms to enhance ABD in agriculture; political economy of ABD	Research priorities and partnerships
Soil ecology: macro-fauna	– Incentives • Use earthworms, and other macro-fauna • Reduce chemical fertilizer/pesticides	– Elucidate roles of macro-fauna in cropping systems and agroecologies
Soil microbial ecology	– Policy support to produce beneficial microorganisms – Quality control standards – Training	– Promote • Enterprises to encourage better NRM • Rapid composting of crop residues instead of burning – Develop efficient biofertilizer/ biopesticides
Pollination	– Ban imported honeybees – Promote indigenous pollinators – Ban aerial insecticide sprays	– Identify non-honeybee pollinators
Crop–livestock	– Remove subsidies on non-renewable resources – Support • Area-wide linkages of crop/livestock system • Sustainable grazing – Promote • Cooperatives • Farmer societies • Marketing	– Develop feeds from farm waste/residues (now burnt) involves compaction and transport – Breeding • Dual-purpose crop varieties • Efficient breeds of animals – Develop • Easily digestible/ palatable, nutritious feeds and fodder • Efficient, diversified cropping systems
Seed sense and public/ private sectors	– Provide • Credit facilities to farmers • Seed-regulation policy • Government support to produce local variety seeds • In-situ conservation of indigenous BD • Implementation of farmers' rights	– Provide hybrid seed production technology – Maintain • Seed purity • Seed processing • Storage • Conserve local landraces in situ
Neglected or under-utilized (NUS) crops	– Develop • Policy to include NUS mainstream • Policy on alternate uses	– Promote • Alternative uses • Value addition • Marketing • Crop improvement and processing technologies – Develop • Seed production technology for forage crops (*Stylosanthes*) – Document indigenous technical knowledge on NUS and livestock
IPM: pathogen suppress-ion	– Create biopesticide registration policy • Enhance use of biopesticide	– HPR – New biopesticide – Mass multiply natural enemies – Conserve natural enemies – Develop stable effective biopesticides
IPM: arthropod predation	– High price for chemical residue-free products – Develop labeling and certification policy for biologically friendly products	– Identify effective predators to specific insect pests – Mass multiply predators/ parameters – Promote research on botanicals
Abiotic factors: land and water	– Promote • Watershed programs implemented by village *panchayats* – Develop rural agro-industry infrastructure • Market	– Develop technology for smallholders • Watershed management • Crop diversification • Land use diversification (crops and livestock) • Terrace farming research (China) • Indigenous knowledge of soil and water conservation



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FAO–ICRISAT Workshop
on Sustaining Agricultural Productivity and Enhancing Livelihoods
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with Emphasis on SAT Agroecosystems
23–25 September 2002
ICRISAT, Patancheru, India
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Acronyms

AAA	Asian Agricultural Association
ABD	associated biodiversity
AgREN	Agricultural Research and Extension Network (ODI)
AICRP	All India Coordinated Research Project
BARI	Bangladesh Agricultural Research Institute
BD	biodiversity
BGBD	below-ground biodiversity
CAAS	Chinese Academy of Agricultural Sciences
CAB	crop-associated biodiversity
CBD	Convention on Biological Diversity
C-CAB	crop and crop-associated biodiversity
CGIAR	Consultative Group on International Agricultural Research
CIMMYT	Centro Internacional de Mejoramiento de Mäiz y Trigo
CPR	common property resources
CRIDA	Central Research Institute for Dryland Agriculture (India)
DEFRA	Department of Environment, Food and Rural Affairs (UK)
DFID	Department of International Development (UK)
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária
EPTD	Environment and Production Technology Division (IFPRI)
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAS	Food and Agriculture Situation Reports (USDA)
FFS	farmers' field school
FYM	farmyard manure
GDP	gross domestic product
GO	governmental organization
GRN-SP	Gestion des Ressources Naturelles-Systèmes de Production (INERA)
HGCA	Home Grown Cereals Authority (UK)
HPR	host-plant resistance
IAEA	International Atomic Energy Agency
IARC	international agricultural research center
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ICIMOD	International Centre for Integrated Mountain Development
IDM	integrated disease management
IDS	Institute of Development Studies (UK)
IFPRI	International Food Policy Research Institute
IGFRI	Indian Grassland and Fodder Research Institute
IIED	International Institute for Environment and Development
IIM	Indian Institute of Management
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IMF	International Monetary Fund
INERA	Institut de l'Environnement et des Recherches Agricoles (Burkina Faso)

INRM	integrated natural resource management (CGIAR)
IOBC	International Organization for Biological Control
IPM	integrated pest management
IPR	intellectual property rights
IRD	Institut de Recherche pour le Développement (France)
ITC	International Trade Centre
ITDG	Intermediate Technology Development Group (UK)
IWMI	International Water Management Institute
LEST	Laboratoire d'Ecologie des Sols Tropicaux (France)
LGA	livestock grassland systems in arid/semi-arid zones
LGP	length of growing period
MRA	mixed rainfed crop–livestock systems in arid/semi-arid
NARS	national agricultural research system
NBPGR	National Board for Plant Genetic Resources (India)
NEPAD	New Partnership for Africa's Development (CGIAR)
NGO	non-governmental organization
NPPTI	National Plant Protection Training Institute (India)
NR	natural resources
NRL	Nuclear Research Laboratory (India)
NRM	natural resources management
NUS	neglected or under-utilized species
ODI	Overseas Development Institute (UK)
OECD	Organization for Economic Co-operation and Development
OM	organic matter
PANS	Pest Articles and News Summaries
PGR	plant genetic resources
PWAB	Programme of Work on Agricultural Biodversity (FAO)
R&D	research and development
RILET	Research Institute for Legumes and Tuber Crops (Indonesia)
RSA	Republic of South Africa
SA	south Asia
SAT	semi-arid tropics
SEA	southern and eastern Africa
SHG	self-help group
SOM	soil organic matter
SSA	sub-Saharan Africa
SSSA	Soil Science Society of America
TLU	tropical livestock unit
TSBF	Tropical Soil Biology and Fertility
UNCCD	United Nations Convention to Combat Desertification
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
USDA	United States Department of Agriculture
WSSD	World Summit on Sustainable Development
WTO	World Trade Organization
WUE	water-use efficiency

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ISBN 92-9066-457-6
9789290664574

ISBN 92-5-104942-4
9 789251 049426
TC/M/Y4681E/1/5.03/900

129-2002