

STRESSED ECOSYSTEMS AND SUSTAINABLE AGRICULTURE



Editors

S.M. VIRMANI • J.C. KATYAL • H. ESWARAN • I.P. ABROL



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Amongst the various concerns on sustaining agriculture to meet the expanding food needs of the future, the question of maintaining and improving ecosystem quality has emerged as an important issue. Global changes due to human pressure on the resource-limited world are threatening to degrade the carrying capacity of land. Ecosystems that are degraded or those that have reached a stage of degradation such that their original biotic communities (or agriculture) cannot be supported any longer are considered as stressed. Degradation results when land-use requirements are not matched by land qualities.

Stressed environments occur mainly in developing semi-arid tropical countries where a web of inter-related reinforcing factors maintains rural poverty, unplanned population growth, expansion of farming into marginal lands, deforestation, soil erosion, water pollution, degradation of land and unsustainable agriculture.

An eminent group of scientists met in Hyderabad, India, in February 1993 to devise alternate systems of land management that would restore degraded lands back to productivity, optimize natural resource use, and stabilize dryland production. The set of 34 invited papers included in this volume attempt to provide insights in a holistic multidisciplinary approach on the constraints that undergird technologies for sustainable land-use in stressed environments.

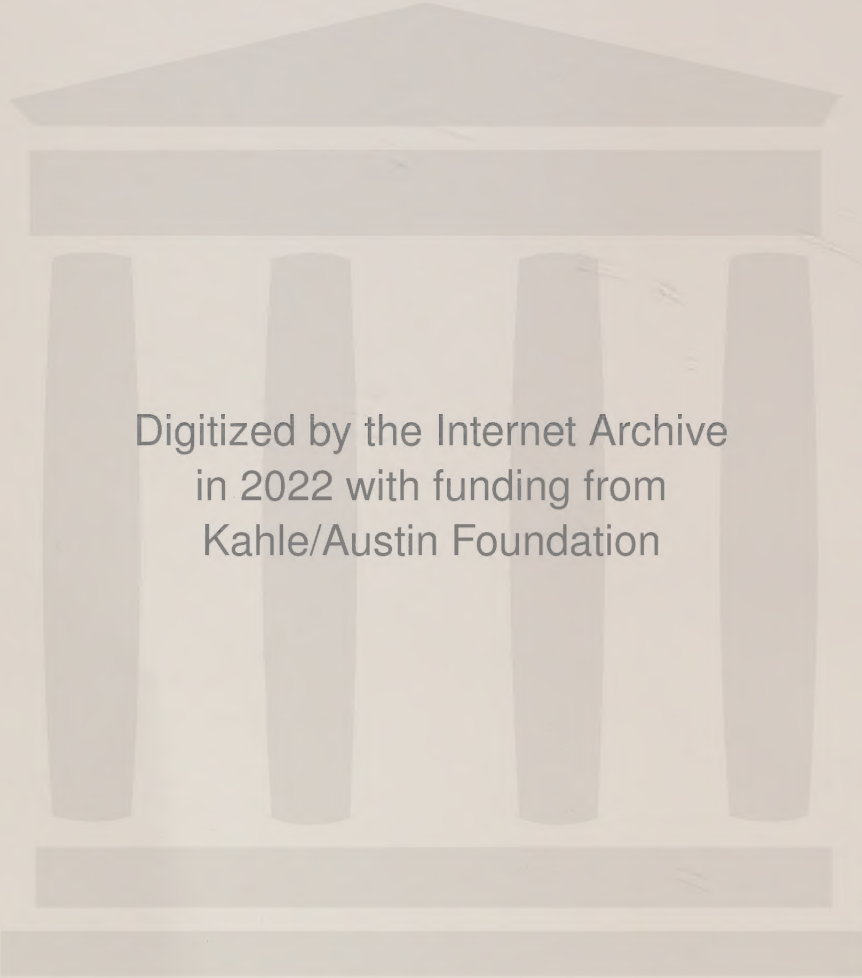
The Editors

Dr. S.M. Virmani, Principal Scientist of Agroclimatology in the Division of Soils and Agroclimatology at the International Crops Research Institute for the Semi-Arid Tropics is conducting research on soil and climate-related constraints to sustainable farming systems in the semi-arid tropics.

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**Stressed Ecosystems
and
Sustainable Agriculture**

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S.M. Virmani

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H. Eswaran

I.P. Abrol



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Foreword

Global environment, economic growth, and global agriculture are our major concerns even in the present milieu of diminishing budgets and other priorities, and we have a commitment to improve all of them. Both the Brutland Commission in 1976 and Agenda 21 of the United Nations Conference on Environment and Development, held last year, have challenged us to look beyond the obvious and to harness our strengths to make this a better world for all of us.

The emerging stresses on natural resources and environment are generally population driven. In 30 years, food production has to be doubled to meet the needs. For the first time, mankind is faced with the challenge of not only increasing productivity but also preserving the resource base to achieve intergenerational equity. The benefits of the 'green revolution' have not come without environmental costs, and agricultural resources in several countries have been severely degraded. Signs of agroecosystem stress, and even its breakdown are visible in many countries of the world. In our efforts to enhance production, we have inadvertently reduced the world gene pool of many animals and plants as we emphasized monoculture for development. The challenge to maintain biodiversity is critical and is affected by national and international policies.

Finally, we must add that there are many indigenous systems, particularly in India, where sustainable agriculture is traditionally and historically practised. We have much to learn from this indigenous knowledge.

Unsustainable crop yields, unacceptable rates of soil erosion, excessive deforestation, loss of germplasm diversity, and poor farmers who do not know what to do next to eke out a living on land appear to continue in many parts of the world.

We are searching for answers to these and other issues. What is evident is that we need a fresh look. We need to change our way of thinking. We need new approaches. We need innovative ideas and solutions. This is our challenge and this monograph on "Stressed ecosystems and sustainable agriculture" provides a fresh look at some of these issues and suggests options for research and development considerations. It provides new directions for international funding agencies to consider, and we hope some of them will be acted upon.

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Preface

Ecosystems that are degraded or those that have reached a stage of degradation such that they cannot support their original biotic communities (or agriculture) in the absence of relatively high inputs are considered to be stressed. It is becoming very evident that agriculture is one of the main factors causing ecosystem stresses and degradation results, when land-use requirements are not matched by land qualities.

A workshop was held at Hyderabad, India, during 15–20 February 1993, to assess the issues and to recommend research and development initiatives to reduce or manage stresses so that sustainability could be approached and equity becomes tangible.

This synthesis report brings together the major findings of the workshop. As the different chapters and the discussions show, the subject is complex and a holistic, multidisciplinary approach utilizing indigenous knowledge, tailor-made to the socioeconomic context appears to be the most promising solution in the quest for sustainability.

The editors would like to thank the many funding agencies and collaborators who made the workshop possible. The financial and logistical support of the following is gratefully acknowledged:

- Indian Council of Agricultural Research (ICAR)
- International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)
- Central Research Institute for Dryland Agriculture (CRIDA)
- Soil Management Support Services (SMSS) of the US Agency for International Development (USAID)

Finally, this synthesis report and proceedings which are being published as a book is the result of the painstaking typing, editing and reviewing of many persons. Our appreciation to all of them is sincerely recorded.

S.M. Virmani
J.C. Katyal
H. Eswaran
I.P. Abrol

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I. A Synthesis

A Synthesis

Introduction

Development of new agricultural technologies and a better appreciation of the existing but underutilized knowledge of resource management will be crucial in meeting the ecological needs and in achieving the anticipated food demands of the growing population in the future. The greatest challenge for the coming decades lies in the fact that the production environments are unstable and degrading, and the balance between intensive and extensive agriculture is precarious. Experience over the past 20 years has shown that mismatch between crop production methods and resource characteristics has led to decline in soil fertility, increased soil losses, disturbed hydrological balance, and a buildup of pests and diseases. The sustainability of agriculture in developing countries and particularly under stressed semi-arid tropical environments is thus under a serious threat.

It is with this background that the Indian Council of Agricultural Research (ICAR), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Soil Management Support Services of US Agency for International Development (USAID), organized the International Symposium on **Agroclimatology and Sustainable Agriculture in Stressed Environments** at Hyderabad in India during 15–20 February 1993.

The issues of sustainability are well enunciated in the countless publications and meetings held globally and thus there is a general understanding (and some misunderstanding) of the challenges. The generic causes of unsustainability and the difficulties of implementing programs to institute sustainability are also well debated and elaborated in this book. There is however, a significant knowledge gap in rates and magnitudes of degradation resulting in stresses and consequently early warning indicators for mitigating the stresses so as to prevent their onset, are hampered. Sustainability requires a holistic approach to agriculture: one that considers both temporal and spatial variations. This then demands information and knowledge of rates and magnitudes of degradation processes, along with indicators and threshold values for not only the impending collapse of the system but also for the diagnosis of system impairment; the response of the system to ameliorating measures; and the resource-specific technologies required to halt or reverse the unsustainability trends. The Symposium was designed to address several of these issues.

The objectives of the Symposium were to:

- identify and evaluate stressed agricultural ecosystems including land management factors that induce stresses.
- evaluate technologies that ensure sustainability including those which manipulate the resilience characteristics of the already stressed systems.

- recommend research and development needs to reduce knowledge gaps and aid in rational policy decision.
- suggest needs and approaches for international collaboration to address sustainability in stressed environments.

To accomplish these objectives, 110 distinguished scientists met at Hyderabad and discussed specific themes in five technical sessions. Five working groups also discussed and provided suggestions for the course of future research and developed recommendations. This 'Synthesis' provides an overview of the Symposium contributions.

Global Issues

A major global issue in the debate on sustainability is the conflict between economic development and environmental enhancement or the choice between short-term economic goals and long-term ecological considerations. N.C. Brady aptly observed that the major challenge to agriculture is to not only minimize these conflicts but to bring synergism between development and environmental enhancement. It is well perceived that developmental and environmental goals are competitive and the scientific community has therefore the duty to allay these fears by ensuring that enhancement of one complements the other and that equity is only attained by directing attention to both. V.L. Chopra, referring to the Indian context, called for a new paradigm in the approaches to sustainability related research. He suggested that in our future research approaches the socioeconomic realities of the farming systems in different agroecological zones must be considered, and the potentials and limitations of the resource base should be given due importance. He envisaged that attainment of the goals of sustainability will require that technologies generated and promoted have the full involvement of the people.

Needs and approaches to sustainable agriculture were considered from three viewpoints. J.R. Anderson of the World Bank considered it from a donor's perspective, particularly in the context of diminishing financial resources to support agricultural research in the developing countries. A recent strategy of the Bank includes investment in knowledge generation and transfer, a more explicit concern for the environment, and greater attention to the role of the private sector in agricultural development. N.C. Brady, from the perspective of the United Nations Development Program, examined the changing emphasis in international assistance programs and defined new thrust areas as follows:

Biophysical

- genetic enhancement of selected crops and plants
- integrated pest management
- efficiency in use of water and plant nutrients

Socioeconomic

- policy change options at both international, national, and local levels
- small holder aspirations, culture, and potential

J.G. Ryan provided ICRISAT's strategy which is focused around concerns for efficiency, equity, and sustainability as explicit hallmarks. The goal of the Institute's research thrust is to provide farmers in the semi-arid tropics with low cost sustainable agricultural technologies based on an understanding of three broad sets of determinants: physical such as soil, water, and climate; biological such as diversified cropping systems and agroforestry; and socioeconomic, such as equity, gender issues, and profitability.

Finally, I.P. Abrol of the Indian Council of Agricultural Research, dealt with the problem facing the Indian subcontinent, an area confronted with an environment where stressed ecosystems are the rule rather than an exception. He called for a new paradigm in the future approaches to research which must consider explicitly the socioeconomic realities of the farming systems and match these with the potentials and limitations of the natural resources. He advocates a holistic approach, with the 'whole' not only considering all components of the biophysical resource base but also ensuring that the technologies are developed, validated, and implemented with a full involvement of the farmers at all stages. Research must adopt the farmer-back-to-farmer approach to have acceptance and impact.

Resource Base and Related Stresses

A variety of definitions and concepts were presented during the course of the Symposium. S.M. Virmani called attention to climate-induced sustainability issues. The short- and long-term variability of climate including the spatial dimensions were identified as the major controls of farming in the arid and semiarid parts of the world. Attention was drawn to recent developments, particularly with the use of tools such as Simulation Models and Geographic Information Systems which enable better synchronization of farming events. It was pointed out that land degradation is not only the loss of utility but also the degradation of ecosystem diversity. Rehabilitation required an understanding of the resilience characteristics of land and the manipulation of these characteristics. The latter requires an analysis and quantification of the stresses. F.H. Beinroth stressed that although identifying the causes, nature, and degree of severity of stressed ecosystems and developing techniques for control and rehabilitation is crucial, it becomes a futile exercise if political and socioeconomic conditions prevent their implementation. One of the first specific situation where a national strategy that includes plans to alleviate stresses, was presented by Y.K. Alagh with his example of the recent five year plan of India. S.M. Virmani felt that there is an urgent need to create a user-friendly packaging and delivery system for agroclimatic information. A framework which can be used for organizing and conducting agricultural development programs based on agroclimatic qualities of the land at various levels (international, regional, local) needs to be evolved. A long-term planning perspective has to be taken. It is necessary, that decision makers and planners take into account climatic resources, while attempting to alleviate the constraints to increase productivity and for introducing sustainable agricultural practices.

The challenge before the resource-related researchers in the future is two-fold: one, to relate future agenda for farming system research with a sustainability perspective, and two, to help decision makers recognize the long-term planning needs by supporting production systems that avoid further degradation of the environment and contribute to the restoration and enhancement of productive capacity of the available agroclimatic resources. The hard choice between preserving and upgrading scarce natural resources for future use or exploiting these now to meet current needs, is the key issue to be resolved by the people living in the stressed environments. The case studies of arid zones by J. Venkateswarlu further illustrated the current stresses in this agroecological zone and also projected stresses. Dramatic increases in human and livestock population coupled with decreases in grazing land resulting from increased areas of cultivation has diminished available fodder, and enhanced wind erosion. Ground water has also been depleted and the recently introduced canal irrigation has created the problem of waterlogging and salinization. The study suggested that the current land use is unsustainable; if steps are not taken towards rectification, it can lead to collapse.

S. Fujisaka observed in his studies of the Philippine villages that the farmers are generally well aware of the stresses and some solutions to improve them were given. The study clearly establishes that farmers' perceptions of stresses and remedial action are not too different from those of the experts. It would be extremely beneficial to work in consortium with the farmers in any resource management program.

Resource Management to Counter Stresses

Though management technology to counter stresses was dealt with respect to individual disciplines, the communality of principles and approaches was evident with respect to plant nutrients. P.L.G. Vlek introduced the concept of Integrated Soil Fertility Management (ISFM). Soil fertility and nutrient management should be based on soil resource conservation, biological nitrogen fixation and input efficiency. The ISFM concept aims at optimizing input use and stabilizing agricultural production in a given ecological and socioeconomic environment.

In semiarid environments, nutrient management is, in one sense, secondary to water management. B.A. Stewart showed that optimizing rainwater use is possible by three technologies. The first is to retain precipitation in situ by minimizing runoff; the second is to reduce evaporation by more intensive cropping systems and by maintaining a soil cover, and the third by the use of drought tolerant crops. A combination of these technologies with appropriate nutrient and pest management and in the context of the available land resources would enhance sustainability. To increase water and nutrient retention, the roles of organic matter and residue management are critical. As plant residues are the food for the ruminants, the residue management to enhance the physical, chemical and microbiological properties of the soil has remained a dilemma in the developing countries. This issue needs urgent consideration.

R. Lal approached the subject of soil conservation in a different way. He emphasized the need for more quantitative assessments and an improvement in

the quality and reliability of observed data. To reduce the subjectivity of different approaches he recommended that the impact of accelerated erosion for example, be assessed in terms of erosion-induced loss in productivity. He also advocated greater use of new concepts such as soil quality, soil resilience, etc., in the context of sustainable agriculture.

Sustainable Resource Utilization

This session was launched with the paper on "Indicators of Unsustainability" by its leading proponent—N.S. Jodha. Unsustainability was evaluated by him from the point of resource base and resource use. His basic principle regarding restoration of sustainability is by understanding the mechanism which helps in reversing unsustainability trends. This approach required the identification, inventorization, and validation of the indicators of unsustainability. Another important principle of his approach is the need to better evaluate related secondary and tertiary sector activities besides the primary sector, to help enhance the range and quality of options, which is the essence of sustainability.

G. Uehara showed how system models could be used to evaluate sustainability. The biophysical aspects of productivity, stability, resilience, and socioeconomic equitability, are all measurable and could serve as indices for evaluating sustainability. However, data is frequently lacking and this poses the current parametric problem where there are many models but scarce data.

Many of the soils of the tropics are low in nutrients. Nutrient management systems are useful if there are nutrients in the soil to manage. If mining of the soil is the practice, without resupply in the form of fertilizers, there can be no guarantee of sustainability. In this regard, S.W. Buol is of a firm view that production can only be ensured with external inputs of the nutrients. N.S. Jodha, on the other hand subscribed to the view that too much reliance on purchased inputs could be an indicator of unsustainability. A similar debate exists on the use of chemicals for Integrated Pest Management (IPM). The fear of organic chemicals entering the food chain is the main rationale against their heavy or indiscriminate use. R.J. Rabindra proposed genetic engineering as a tool for introducing host plant resistance as the basis for any IPM program. Approximate mix of approaches such as cropping system, farming system, and cultural practices could all be enmeshed in such a way so that heavy use of chemicals is avoided. Similar views with respect to disease management were expressed by P. Trutmann. Apart from utilizing genetic variability, he recommended greater use of traditional systems.

Indicators and measurements of sustainability and nonsustainability were also discussed. The importance of information management technology to address some of these issues with a focus on new and improved technologies to manage natural resources to ensure sustainability were discussed.

Technology for Mitigating Stresses

Although a major objective of the Symposium, there was an apparent admission of the lack of adequate and stress-specific mitigating technologies. This has been

recognized as a major knowledge gap which has to be researched. Adequate information and approaches exist for individual technologies but the solutions to multiple stresses are still evasive. J.C. Katyal showed how research on resource use optimization in rainfed agriculture provided a number of land-use options. A most enlightening paper on "Efficient plant types" was submitted by K.S. Gill. Working on the premise that a substantial improvement in crop productivity per unit area per unit time is the key to negating the effects of increasing population, the focus of germplasm enhancement research, until recently, has been on yield increases. However, with the new environmental paradigms, objectives of crop breeding research, there is a need for change with a greater emphasis on producing efficient plant types for defined environments. Gill also emphasized the need for crop breeding work on nonfood commodities. A similar view was expressed by S.K. De Datta that the future agricultural research agenda should not only include breeding for more productive crop varieties but also management technologies that will better protect the natural resources and optimize use of soils and water. Such systems will cope better with the stresses. Levelling off or decreasing trends observed in rice yields in both upland and paddy systems requires new approaches to research. In addition there are also increasing concerns of rice ecosystems contributing to global climate change. This aspect of rice production needs to be addressed with indepth and holistic research. Some economic incentives may have to be provided to accelerate implementation of emerging technologies.

Recommendations of Working Groups

Agrometeorology

Climate is the major factor influencing agricultural productivity and sustainability in the stressed environments. There is a need to develop farming systems for different agroecologies that are weather sensitive, and sustainable and minimize the influence of climatic fluctuations on resource degradation.

With this background, the following recommendations were made:

- Develop methodologies to optimally use the products available from the meteorological services for economic and environmental benefits through agricultural planning and management.
- A model program is needed to demonstrate that international, national, regional, meteorological and dryland research centers can come together in consortia to deliver advice to farmers that will help them sustain their production at acceptable risk levels. This program should serve as a model for technology transfer and should focus on an important crop in stressed environments (e.g., groundnut).
- International collaboration in research, human resource and infrastructure development be strengthened in the areas of agrometeorology such as crop modeling, modeling weather effects on pests, and diseases. Monitoring of global climatic change and its impact on sustainable agricultural production system and enhancement of quality of environment for future generations are important agricultural research objectives.

- Quantification of plant behavior in controlled and field environments for developing appropriate farming systems/subsystems based on physical, biological and socioeconomic settings in different agroecological zones should receive top priority.
- Standardization of agroclimatic databases, their documentation and use is essential.

Assessment and Monitoring of Stressed Agroecosystems

This was a major point discussion. The consensus arrived at was:

- Although there are many definitions of sustainable ecosystems which differ in detail, there is a general consensus that the attainment of sustainable agroecosystems is a desired goal. It was agreed that conceptually an agroecosystem use, that matches the state of the soil quality results in sustainability. In a similar manner, where the soil quality does not match the use, then a stressed agroecosystem exists.
- The concept of soil quality was considered to be a function of individual soil attributes. Soil qualities of importance to productivity include the soil's ability to:
 - accept, hold, and release nutrients
 - accept, hold, and release water
 - promote growth and sustain productivity
 - resist degradation
- It was agreed that determination of dynamic changes of soil quality was crucial to the development and implementation of policies designed to improve soil quality and enhance sustainable agroecosystems. A dynamic change of soil quality is a function of the cumulative changes of state of individual soil attributes throughout a time period of interest. The change of an attribute from time zero to a new time period requires estimates of the reference state and the selection of an appropriate timeframe for its measurement of change.
- It was agreed that the resilience in soil quality is one way of evaluating soil management systems for degrading or aggrading processes. In systems where dQ/dT is greater than 0, the sustainability of the system is improving.
- The challenge for the scientist is to select land attributes that are significant indicators of an agroecosystem's quality and are related to the processes affected by the various land management practices. In a like manner it is necessary to identify biological response indicators associated with the changes of ecosystem quality.
- It was felt that the indicators of change are of two types:

Qualitative indicators—those associated with rather easily observed changes occurring on the land. They are associated with day to day awareness and experiences. People observe changes in the crop performance; they detect salt, crusts, or surface sealing of soils; they note the sediment load in streams; they recognize declining yield trends; etc. What we should learn is how to utilize this common knowledge in our efforts to scientifically backstop and develop quantitative indicators of sustainability of agroecosystems.

Quantitative indicators—dynamic changes in agroecosystems must be science-based and should be capable of providing reliable assessments of the consequences of land management practices. Such indicators must rely on the scientific knowledge of relationships supported by theory and experimentation. It is a never ending search for meaningful and practical ways of efficiently and effectively assessing and evaluating changes. The operational approach suggested basically consists of (i) a careful selection of observation/test sites, (ii) setting up of validated standards, (iii) definition of 'present' base level status to serve as a 'benchmark', (iv) decisions on the periodicity of monitoring, and (v) setting up a framework for coordination of research and information gathering.

- It was recognized that the scale of observations and the aggregation of information may lead to different conclusions regarding change. As an example, observations of biological responses in land areas of a few hectares may overlook the interactions of (e.g., land x water) processes throughout a catchment of a few tens of hectares.
- Decisions must be made about the units of study and the hierarchy of information integration. If we monitor quality of different agroecosystems (pastures, crops, agroforestry) the information could be aggregated by agroecological zones, subregions and regions which are physiographically defined. The basic unit of monitoring was suggested to be the agroecological subregion (in the Indian context) with 100 sampling sites per unit. The principal sampling unit would vary from one hectare or so to complete watersheds. The approaches would also vary from a simple measurement of selected physico-chemical properties to the monitoring of consequences (e.g., crop yield/biomass, etc.) followed by an examination of various production processes including soil variables. After an initial survey of the vegetation, monitoring of the vegetation cover at 5–10 year intervals, using remote sensing techniques, was considered adequate in most cases.
- It was agreed that information readily available from other sources should be utilized in every way to minimize the data to be collected in a monitoring program. Examples are crop statistics such as area sown, harvested, yields and associated input practices. Often such statistics are reported by political subdivisions rather than natural landscape units.
- Although physical indicators can be collected, monitored and assessed for dynamic changes it is essential to have real cost economics of the consequences of the land management practices. Modeling was recognized as a valuable assessment tool and the indicators selected should also be appropriate to facilitate simulation models. Feedback and communication among all involved in assessment and monitoring is essential.
- Details of biological response indicators were not specifically discussed, however several quantitative measures were mentioned. These included normalized yields, net primary production estimates, sustainable yield indices, and sustainable value indices. It was noted that combining information from individual agroecosystems into larger geographic areas would require innovative techniques of analysis and presentation.

- The group identified a total of 28 parameters considered important for the assessment and monitoring of a stressed ecosystem. Perceptions differed markedly about whether a given parameter should be monitored on a short-term or a long-term interval basis. The most commonly used indicators are:
 - available nutrient status
 - organic matter
 - soil depth
 - pH and EC and
 - water-holding capacity

Recommendations

- As sustained increases in agricultural production are crucial for the well being and survival of mankind, it was recommended that monitoring and assessment programs be promoted and undertaken as a national program. Strategic planning with careful review and its revision is essential to the success of any such undertaking. Existing programs should be useful to assist in developing plans specific for a country and to facilitate standardization of methodologies.
- It was recommended that customer involvement, especially for qualitative monitoring of ecosystem changes, be carefully considered in strategic plans for assessment and monitoring. This would foster awareness of the quality of the environment and improve the adoption of quality enhancing practices. It may involve the use of interviews, questionnaires etc., to identify participants, solicit their assistance, and more essentially, obtain people's inputs into the process.
- Soil quality classifications be developed for use in different ecoregions. Although national and international standards are needed for consistent and meaningful comparisons, local comparisons are also useful for awareness and implementation of land management practices.
- It was recommended that consideration and information sharing means be established to ensure transmission of assessment information to the appropriate audiences.

Research Needs for Mitigating Biotic Stresses

The working group identified components of pest management compatible with sustainable agriculture and also suggested several strategies that fall broadly under the following categories:

General diversity

Natural control and biological control

Pesticide management

Knowledge of indigenous systems and cultural practices

The current constraints to addressing these strategies were listed and research needs were formulated to overcome the constraints.

Genetic diversity

Constraints

- Policies related to seed production, cultivar release and maintenance. Some issues mentioned were cultivar release procedure, seed-certification standards that describe phenotypic variability/uniformity, and demand for phenotypic uniformity within a cultivar by the private sector.
- Demand for uniform crop/grain/product quality.
- Lack of knowledge regarding how diversity promotes stability.

Recommendations

Devise and support approaches and policies, which encourage genetic diversity of crops for durable pest management.

Research needs

- To find a relationship between crop diversity and stability of resistance to insect-pests and diseases.
- To understand pest-plant-environment interaction (epidemiology) of diverse ecosystems.
- To devise methods of utilization of indigenous genetic material in breeding programs.
- To understand the mechanisms to maintain durable resistance for its application in more pest-plant situations.
- To develop methods to characterize variability in pests and to determine shifts in their population. Recombinant DNA technology was suggested as a powerful tool in this case.

Natural control and biological control

Constraints

- Lack of specific knowledge, for example, about ecology of biocontrol agents.
- Ease of availability and use of pesticides and their rapid action.
- Availability of initial seed money and long-term funding commitments.
- Unsure commercial viability (high cost of application).
- Lack of success of many experimental biocontrol agents.

Recommendations

There is an urgent need to support research to encourage pest suppressive environments by biological means.

Research needs

Research needs were perceived to be different for entomology and pathology because manipulation of biological control agents has so far been much more

successful in controlling insects rather than plant diseases. Constraints of biocontrol in entomology include knowledge gaps in taxonomy, population dynamics, biology, application and recovery, allelochemistry, etc.

In pathology the constraints identified were the lack of understanding of microbial ecology, mechanisms of action and methods of practical application.

Biological control of pests is an area which has witnessed an upsurge of research interests recently. Although research needs for biocontrol of arthropod pests are many, to better design biocontrol of pathogens a good understanding of microbial ecology and mechanisms of action of natural and introduced agents is required. Recombinant DNA technology would be an excellent tool in this study.

Pesticide management

Constraints

- Residues of pesticides in food and feed.
- Sustainable technology not always available.
- Availability of environment-friendly pesticides and new pesticides not easily available in developing countries.
- Difficulty of pesticide application in mixed cropping systems which prevail in stressed environments.
- Changing farmer and consumer habits are not perceived in advance.
- Technology to forecast pest outbreaks still not adequate.

Recommendations

Devise (a) better resistance management strategies so as to preserve susceptibility of pests to pesticides, and (b) cropping system based IPM to minimize pesticide use.

Research needs

- Devise novel technologies to apply pesticides at the most vulnerable stage of the pest's life cycle.
- To develop basic and applied research to exploit environment-friendly pesticides.
- Develop reliable and inexpensive monitoring and forecasting methods.
- Strive for methods to educate consumers, farmers, policy makers, etc., on issues related to IPM.

Knowledge of indigenous agroecosystems and cultural practices

Constraints

- There is a general failure to realize and appreciate the socioeconomic context in which a farmer operates.
- In the stressed systems, there is a great complexity of agroecosystems and therefore, specificities in agroecosystems prevent generalization.

Recommendations

Traditional agriculture systems require study and research to document their sustainable components and devise ways to adapting them to modern systems of agriculture. Conversely there is a need to integrate modern technologies with traditional practices. Such an approach will allow to build on traditional practices by increasing the scientific understanding of agroecosystems.

Research needs

Study traditional agriculture and cultural practices from systems and socio-economic perspectives to:

- Understand the interrelationships among and between the biological agents and management practices in different agroecosystems.
- Identify components of the system relevant to pest management.
- Recognize pest management practices that are indicators of sustainable agroecosystems.

Research Needs for Mitigating Abiotic Stresses

The group expressed concern at the widescale ecosystem degradation occurring in the semi-arid tropics as man and animals interact with limited land, water and vegetation. Delayed action will result in increased environmental and economic losses and much higher costs of later attempts at recovery.

The group recommends that there is an urgent need to launch a major holistic research effort to use rainwater efficiently in different agroecological zones for increased productivity and to sustain the natural resource base (land, water and vegetation).

Development of new technologies must be based on proper assessment of physical, economic, social and ecological factors. It is recommended that future approaches and strategies should be more location specific; multidisciplinary approaches would involve all relevant commodities and disciplines; a closer linkage between researchers, development agencies and farmers should be aimed at.

The Indian Council of Agricultural Research (ICAR) has already identified 20 major agroecological zones for the country. The group feels that these ecoregions and their subregions should be the focus of the technology development and application. The emphasis of research in these ecoregions should meet the specific needs dictated by abiotic stresses, current farming practices and economic, social and infrastructure settings.

For the semi-arid tropics the group identified abiotic stresses mainly due to moisture and nutrients per se or due to soil physical and chemical conditions. As the moisture and nutrient use efficiencies are interdependent, the group identified the following researchable components.

Water

- Harvestable water: amount, timing

- Means to harvest on-site and off-site water
- In situ water/moisture measurements
- Water balance: seasonal, annual
- Measures to extend crop water availability period
- Water erosion: amount, rates
- Improved rainwater use efficiency
- Assessment of energy balance in different land-use systems and techniques to reduce evaporative demand and soil temperature

Nutrients

- Nutrient status monitoring
- Integrated nutrient management (nutrient budget) under different land-use systems
- On-farm diagnosis of nutrients
- Critical limits of nutrients
- Emphasis on building available P in the soil
- Efficient nitrogen management and utilization
- Community nutrient recycling
- Salinity/sodicity

Restoration of degraded ecosystems

This activity should also receive priority

Ecoregional focus

The group recommends that the specific priority stresses, technologies for adoption, new research initiatives and areas for intra- and international cooperation be developed for each of the 20 ecoregions in India and if possible at the subecoregional level. Future work should be increasingly focused in well defined ecosystems of the 20 ecoregions delineated by the ICAR, of which 6 are in the SAT. Each of these SAT ecoregions seems to have a distinct set of abiotic stresses adversely affecting sustainability and productivity. The examples of two SAT ecoregions, e.g., # 6 and # 8 were outlined as: (i) Moisture availability in black and red soils is contrastingly different; (ii) Quantity of harvestable water for rational use in optimizing productivity of different cropping systems is different in short and long duration crops; (iii) nutrient availability in black and red soils are different; (iv) soil crusting is a major constraint especially in red soils and cultivation of black soils poses other problems, which call for the need to develop appropriate tillage practices; and (v) Soil acidity is a constraint in red soils and amelioration is needed.

National Policies and Strategies for Mitigating Stresses in Semi-arid Tropics

The working group took note of the severe stresses suffered by the natural resources of the semi-arid tropics, mainly of sub-Saharan Africa and South Asia,

due to rapid population growth, agricultural stagnation and environmental degradation.

In sub-Saharan Africa, abundant land, scarce capital and limited technology had dictated shifting cultivation and grazing as the strategy for subsistence. With the dramatic expansion of population, these extensive systems evolved into more intensive systems, leading to the depletion of soils and forests. Availability of per capita arable land had come down by 40% in one generation. While there have been some success stories in Kenya, Rwanda and Burkina Faso, the general picture is one of an agricultural and environmental crisis. The agricultural sector is extremely important for the development of SAT Africa.

There was also a growing realization in South Asia, particularly in India, of the limitations of irrigation and "green revolution" based strategies. This led to a renewed emphasis by the Government of India on watershed management as a strategy for the holistic development of rainfed lands.

The working group recognized the importance of agrometeorology for developing strategies for sustainable agriculture. It also realized that there exists a considerable research and knowledge base on sustainable SAT agriculture. It called for structural reforms in the semi-arid tropics of Africa and Asia, on two fronts: (a) socioeconomic policy (b) agricultural policy. Only a handful of the 50 SAT countries had a deliberately articulated policy for the development of agriculture in this stressed environment and this lacuna needed to be overcome, at the earliest opportunity.

The following reforms in the socioeconomic policy framework are needed to create incentives for SAT farmers and to help generate demand for sound agricultural technology and services which would eventually lead to a robust growth in farm production and incomes:

- A farmer-friendly trade and price policy, both for farm produce and "inputs" so that agriculture would not be subject to "net taxation" in real terms.
- Greater security of land tenure to encourage investment in land conservation, in particular a review of communal land tenures and common property rights is needed.
- Provision of a better rural infrastructure, including roads to reduce the cost of input supply and marketing, processing and marketing facilities to help the farmer reap a larger part of consumer price, and improved financial services, to help farmers to save as well as to borrow for investment.
- Supporting programs for developing such sectors as women, health, nutrition, family planning and NGO's.

The Working Group recognized the priority placed by the Government of India on the development of rainfed agriculture in India through a 100% subsidized demonstration of selected watersheds, at a cost of Rupees 11 billion during the five years 1992–1997. The Group noted its various features, including participation by the beneficiary farmers, and the holistic approach to include all lands in the watershed for socioeconomically feasible activities including animal husbandry, horticulture, and agroforestry. In this context, the Working Group called for special attention to the following aspects for more effective policy formulation and implementation:

- Wise use of the subsidy mechanism to guarantee its use for genuine demonstration of technology and not for “selling” some thing in which farmers do not have any true interest;
- Scientific land-use planning, including farming systems approach, addressing the diversity of ground realities and avoiding straight-jacket formulae;
- Adequate investment in agrometeorology for gaining a sound database for scientific planning and advance drought alert to farmers;
- Emphasis on development, maintenance and efficient management of community assets like tanks, common lands, etc.;
- Decentralization in decision-making and empowerment of local community, through support to Non-Governmental Organizations; and
- Coordinated action by functionaries of different Government agencies, who should be trained to address themselves to their jobs in watershed development.

Symposium Conclusions

- High quality and reliable data are needed for assessment of stressed systems and for their evaluation and use through system models.
- Research and application of new concepts such as soil quality, soil resilience, agroecodomains must be actively pursued. Recent tools such as Geographic Information Systems, can be used effectively for the assessment and monitoring of stressed systems.
- Simulation models and expert systems are not only aids to research but can short-cut research.
- Crop residue management and conservation tillage and related technologies must be more actively pursued despite the current socioeconomic deterrents.
- Strategies for improving interdisciplinary research efforts to enhance the efficiency of rainwater for higher production and control of land degradation, must be developed.
- Genetic enhancement of plants must be in the context of resource stresses and not merely to increase yields.
- The stressed farmer must be considered as part of the stressed system. Farmers’ aspirations and perceptions must be an important component of research and development activities.
- Countries must strive to adopt and implement sustainability ethics and this requires visionary, scientific and political leadership.
- An integrated soil fertility management program needs to be conceptualized and researched for implementation.
- There must be paradigm shifts in research approaches and presentation of research information.
- At present an understanding of the nature and extent of interaction of weather parameters with soils, crops and organism causing disease and pest problem is extremely inadequate though crucial in managing ecosystems where climate related constraints are a major factor in achieving sustainable production. There is a need for a substantial investment of resources into research that

will lead to a better understanding of these interactors to enable development of strategies for crop and resources management for sustainable use and management of resources and for enhancement of environmental quality.

- Our past research and development efforts have emphasized technologies that relied heavily on expansion of four key inputs (irrigation, hybrids, fertilizers, and agrochemicals for pest control), seeds of new crop varieties, and fertilizers. There is need to undertake a systems (watershed) research that will capture resource qualities and potentials in planning options for sustainable systems.

II. Issues, Challenges, and Role of Institutions

Sustainable Agriculture: A Research Agenda

N.C. Brady

Abstract

Sustainable development has been widely accepted as a concept that must be central to all future human endeavors. This concept embodies two basic notions: economic development and ecological sustainability. Unfortunately, some environmentalists tend to focus on the ecological issues and ignore those related to economic development. Rapidly mounting food demands and poverty in developing countries indicate that the economic and ecological issues must be addressed simultaneously.

Public attention has been called to the conflicts between economic development and environmental enhancement. This is a problem worldwide but has particular sensitivity for low income countries whose economic development must be enhanced markedly in the years ahead. The major challenge to agriculture is not only to minimize these conflicts, but also to bring about synergism between development and environmental enhancement. Scientific research and technology transfer can play a pivotal role in bringing about the synergism. Changes can be made that will simultaneously increase food production and enhance environmental quality. In the next 30 years, developing countries must greatly increase their food production but they must do it differently from what has been the case in the past.

Curtailed financial support worldwide for agricultural science is forcing researchers to focus only on high priorities that are related to both economic development and environmental enhancement, and that have high potential for success. It is suggested that these high priorities will include three biophysical areas and two socioeconomic areas as follows:

- 1. Biophysical*
 - Genetic enhancement of selected crops and plants,*
 - Integrated pest management, and*
 - Efficiency of use of water and plant nutrients.*
- 2. Socioeconomic*
 - Policy change options at international, national and local levels, and*
 - Small holder aspirations, culture and potential.*

International agricultural research centers can be focal points for the linkages and networks involving public and private sector research institutes and nongovernment organizations (NGOs) in both the North and South to enhance attention on these priority research areas.

Introduction

Sustainable development has been widely accepted as a concept that must be central to all future human endeavors. This concept has evolved from the so-called Bruntland Commission report on "Our Common Future" (WCED 1988), which states, "Humanity has the ability to make development sustainable—to ensure that it meets the needs of the present without compromising the ability of the future to meet their own needs." Though this concept is widely debated it has been generally accepted among the leading development specialists around the world. It was the central theme of the recent UN Conference on Environment and Development (UNCED) in Brazil. While there was not a complete agreement as to how it could be achieved, the goal of universal sustainable development was generally accepted by countries from the North and the South, and by government and nongovernment officials.

This simple concept has been studied, evaluated, and restated in relation to all human systems and activities. But in very simple terms, the concept can be said to combine two basic notions: economic development and ecological sustainability (Braat 1991). If a system or an activity fails to include these two notions, it does not represent sustainable development.

As leaders have moved from the ideal concept to practical implementation, conflicts between economic development and environmental enhancement have arisen. Agriculture internationally faces such conflicts, as do most other development sectors.

Development versus Environment

The need to resolve the conflicts between emphasis on food production and on sustainability of natural resource quality is illustrated by a survey and subsequent conference of 135 US high-level natural resource scientists, professionals, and other leaders (RNRF 1992). These leaders, 56 of whom were from universities, 43 from government agencies, 24 from NGOs, foundations, and professional societies, and 8 from the private sector, were asked to rate the importance of some 121 issues related to six different natural resource management themes. In five out of the six themes, it is noted that sustainability was rated as most significant, but some conflicts exist. Issues such as "growth vs. environment," "ecology vs. economy," "environment vs. jobs," and "production vs. sustainability" were used to headline the conflicts.

It is encouraging to see this assessment of the need to protect our natural resources and to be concerned about the welfare of future generations. The world can no longer accommodate the steady destruction of our natural resources in the name of providing for human needs. At the same time, we must recognize that this quality assessment was not made by the millions of fathers and mothers in developing countries who as children were hungry, and who as parents witness the hunger and malnutrition of their children. It was not made by the African mother of six children, three of whom died of poverty-related diseases before they were five years old. It was not made by the landless laborers or by small-land owners whose incomes are too low to provide food for their families between

harvests, and who are victimized by moneylenders who charge outrageously high interest rates for loans to purchase food.

The contrasting assessments and attitudes I have illustrated provide developing societies with one of their greatest challenges during the next few decades. These countries cannot choose between production and environmental goals. They must achieve both. They must reduce poverty and improve the health and nutrition of especially their low income people. At the same time, they must reduce and eventually eliminate the degradation of their natural resources. This must be done in their own interest. They do not want to contaminate their soils and water with chemical, pesticides or heavy metals. They want to conserve their water and soil resources to enhance crop production today as well as for their future. They want to conserve their forests and not move them into degraded agricultural systems.

They also have global interests. They too will be adversely affected if, as predicted, global warming and probable changes in climate occur in the future. It is in their interest to help reduce atmospheric contamination with greenhouse gases. Their crops and animals will be damaged by ozone depletion and by increases in ultraviolet radiation. It is in their interest to cooperate to prevent these unwanted changes.

Mohamed El-Ashry, head of the World Bank's Environmental Department and Chairman of the Global Environmental Facility (GEF), provides a challenge for developing countries as he states, "Balancing economic development and environmental protection in developing countries requires a refocusing of economic activity—not towards producing less, but producing differently." Indeed, in the case of agriculture, the goal will be to produce more using different methods, as the following sections will illustrate.

The Green Revolution and Sustainable Development

Agriculture in the Third World can be justly proud of its accomplishments since the 1960s. In all major regions of the world, except sub-Saharan Africa, per capita food production has increased, and agriculture has contributed to overall economic development. Researchers developed high-yielding varieties of wheat, rice and maize. Their yields responded to inputs of irrigation and fertilizers, the uses of which were greatly expanded. Also, national policies were changed to make it profitable for the inputs to be used. This cereal-based green revolution opened the eyes of politicians and statesmen alike, and gave to science a new sense of responsibility. Researchers and policy makers joined forces to make the improved systems work.

But these successes were accompanied by two shortfalls. First, there was considerable unevenness in the food production progress in different commodities and ecologies. The production of rice, wheat, and corn fared well since most of the expanded research was on these crops, and they are produced in ecologies and management systems that provide good levels of water and plant nutrients. But the production of most other crops grown in regions less well endowed with crop producing potential was not as successful. Vast areas of Africa are deficient in rainfall and do not produce wheat and rice. Irrigation is not so

widespread as in Asia, and fertilizer use is a fraction of that for Asia and Latin America. Also, Africa's research institutions are not well established and supported (Eicher 1990).

A second shortfall some identify with the green revolution was its inadequate focus on environmental issues. Food production in the immediate future was the primary focus. Human populations were burgeoning and people had to be fed. Chemical pesticides were perceived in the 1960s as essential components of crop production systems. Little attention was given to their pollution potential. Also, new lands, some of which were marginal for agriculture, were cleared and cultivated. Increasing areas of sloping lands and even hillsides were cultivated, leading to deforestation, increased soil erosion and water runoff. Such natural resource deterioration is identified by environmentalists as a major global problem.

Three Major Challenges of the Future

Experience of the past plus an intelligent assessment of future needs to achieve sustainable agricultural development suggests three major challenges. Firstly, because of unparalleled increase in human populations in developing countries, future increases in food production must even exceed those of the remarkably successful past three decades. More than 90 million people are being added each year, a billion a decade. In terms of calories, the world must produce more calories in the next 35 years than has been produced since the dawn of agriculture 10,000 years ago. We cannot expect a repeat of the massive increases in irrigation and fertilizer use that characterized the last 30 years (Brown 1993). Except in Africa, the economics of increases in the use of these inputs began to decline in the mid-1980s and are not likely to increase in the decades ahead.

The expanded food needs must be met without great expansion in the area of land under cultivation. Most highly productive lands are already farmed and environmentalists will firmly resist further clearing of forests and grasslands for crop production. It is not likely that more than 25% of the expanded food needs will come from newly cleared lands (Crosson and Anderson 1992). The added production must come primarily from increases in yields per hectare.

The second challenge is to move the green revolution into ecologies, systems, and population segments that up to now have not benefited significantly from technological advances. This means improved technologies and systems, for areas less endowed with water and productive soils and gaining a better understanding of the hitherto by-passed poor, their cultures and community structures. It means policy changes that will permit low-income people to share in the benefits of these new technologies and systems (McLure 1988) and learning how their lives can be improved.

The third challenge is to couple food production efforts with those that enhance environmental quality. This coupling is essential first of all for the developing countries which depend upon their natural resources to underpin food production. It is also essential on a global scale as countries of the South join with their industrialized partners in reducing environmental contamination and natural resource destruction. It is essential to assure sustainable agriculture.

As El-Ashry suggests (El-Ashry 1993), every effort should be made to find ways to establish "win-win" systems that will provide both increased food production and environmental improvement. In agriculture there are some good examples of such systems that are on the horizon.

Role of Research

The green revolution of the past 30 years clearly illustrated what science can do to help the world feed itself (Baum 1986). Furthermore, the problems that are on the horizon for the coming decades suggest that research should be even more critical in meeting world food needs than it has been in the past. Research-created technologies to enhance yields per hectare will be the primary source of future food production increases.

Research is also critical in meeting the two other agricultural challenges discussed in the previous section. If the green revolution is to be extended into areas less endowed with rainfall, irrigation and productive soils, new and improved technologies and systems will be needed. Likewise, research will be needed to provide technologies tailored for the needs of the truly poor, and to ascertain policies and systems changes that will permit them to obtain these improved technologies.

The coupling of economic development and environmental improvement will require extensive research. The production-oriented scientist must incorporate environmental considerations into his or her decision-making process (NRC 1991). Every option for production improvement must take into consideration what it will do to environmental quality. Likewise, the environmental scientist must address the economic and social impacts of environmentally sound options that he or she may be pursuing. If the impacts are negative, they are not likely to be adopted by the country or by the cultivators.

Research Support and Priority Setting

There is a greater need to sharply focus research priorities today than 10 to 20 years ago. This is due in part to the declining financial support of developing countries and international and bilateral donors for agricultural research and projects. Worldwide economic stagnation has forced governments to reduce support for long-term development activities such as research and education. Agriculture-related loans for the World Bank have declined sharply in the past five years, as has bilateral support for agriculture. For example, the support of United States Agency for International Development (USAID) for technology development and transfer activities (research and extension) in Africa has declined from 34% of the agency's Development Fund for Africa in 1986 to 14% in 1991 (Oehmke and Crawford 1992). Comparable reductions have been made in technical staff to manage these activities. Anecdotal evidence suggests similar cutbacks in other regions of the world.

Agriculture's decline in priority is related to the subsidies-induced food surpluses in the United States, Europe and Japan. It is estimated that as much as \$300 billion annually of public resources (ECLAC 1992) are used for direct

or indirect subsidies that stimulate the production of food commodities in excess of the needs of these countries. This leads to national food surpluses and to the perception that the major world food problem is one of surplus and not deficiency. This perception discourages public support for international agriculture. The CGIAR-supported centers such as ICRISAT are suffering from these public perceptions as their financial support bases have declined in recent years. National research programs have suffered even more, especially in Africa (Eicher 1990).

While one might hope for a turnaround in support for agricultural research, it is likely that financial constraints will continue to be serious. This situation calls upon research institutions to reassess their priorities and to focus their research on only the highest priorities. In the present political framework worldwide, sustainable development with its economic and environmental components must receive high priority.

Areas of Agricultural Research Focus

The setting of research priorities is not a simple task. Some priorities will tend to be regional or location-specific since the nature of agriculture and the constraints on its performance will vary from one ecological and economic condition to another. Even so, there are some common constraints that tend to permeate different ecologies and economic systems, and that must receive universal consideration. Likewise, there are some research thrusts that are needed in almost every agricultural situation. I shall identify a few that I think should be on the high priority list, although their relative importance may well vary from one ecology or system to another. The list includes three major biological and natural resource priorities and two concerned with social sciences and economics. The priorities are:

Biological

- Genetic improvement
- Pest management
- Efficient use of water and plant nutrients

Socioeconomic

- Policy issues
- Small farmer/rural residents

Each of these priorities provides opportunities for advancement of both economic development and environmental improvement. They represent "win-win" potential.

Genetic Improvement

The incorporation into the genetic makeup of plants and animals of traits of importance to both economic production and environmental quality remains a very high priority. This involves continued concern with yields and production efficiency. It also means focus on host resistance to insect pests and diseases, tolerance of adverse soil and climatic conditions, and agronomic or nutritional traits that fit the economic and social needs of the producer and the consumer. It also addresses the requirements for vegetative cover of the soil to reduce water

runoff and soil erosion. Vegetative cover will be hard to come by if plants do not grow well on the soil that is to be protected.

Unfortunately, some have misjudged past efforts of crop improvement specialists in developing countries and have assumed that these efforts were focused solely on increasing production. Host resistance to insect pests and diseases and tolerance of adverse weather and soil conditions have been part of the research portfolio of international and national research centers for years. However, increased interest in environmental issues and the need to address the problems which have been bypassed by the green revolution should stimulate increased research efforts to develop effective pest management systems that reduce or even eliminate the need for chemical pesticides. This research area clearly illustrates how crop improvement benefits both the economy and the environment.

In time, the tools of modern biotechnology will be called upon to accelerate genetic improvement. Already, steps are being taken to use newly created methods of biotechnology to transfer desired genes into the genomes of crop plants, including those in the developing countries. While such research is in its infancy, almost every day one reads of progress being made to achieve that goal. Already in the United States transgenic plants have been studied in some 200 field experiments (NRC 1993).

In several international and national agricultural research centers, scientists are using recombinant DNA procedures to transfer genes carrying resistance to specific pests and diseases. While such traits may involve only one to two genes, characters such as drought tolerance and salt tolerance are thought to involve many genes. Even so, progress is being made in enhancing drought and salinity tolerances by both traditional and modern biotechnology methods. For example, in a recent study on transgenic tobacco (Tarczynski et al. 1993), salinity tolerance was enhanced by DNA transfer using modern biological tools. In time, similar progress can be envisaged for cereal crops and edible legumes.

The use of biotechnology in improving crops and animals will be enhanced by new links between international and national research institutes in developing countries and counterpart institutions in industrialized countries. It will also mean new partnerships between these Third World institutes and private sector research centers in both the developing and industrialized countries, since most of the progress on crop and animal improvement is being made in private companies.

Environmentally Sound Pest Management

Plant and animal pests and diseases have always been serious constraints in agricultural production, especially with small land holders whose management flexibilities are limited. These pests also have serious environmental implications since the chemical pesticides that have been used increasingly to try to manage them have serious environmental consequences. The residues of these chemicals can be harmful to humans and other creatures. They also damage natural enemies of the pests they are meant to control. Lastly, the continued use of pesticides stimulates genetic changes in the pests so that they become resistant to the

chemicals, and new pesticides must be sought. All in all, it is to the advantage of both the agriculturalists and the environmentalists to develop and use pest management systems that minimize or even eliminate the need for chemical pesticides.

Integrated pest management (IPM) systems that combine the positive effects of control mechanisms such as biological control, cultural management, and host-plant resistance and that use chemicals only when absolutely necessary are increasingly being sought after. Science can provide many of the basic tools needed for successful IPM programs, and the products of science can then be integrated into successful management systems. The remarkably successful rice pest management program in Indonesia is an example of a system that combines agricultural and environmental objectives (Kenmore 1991, Wardhani 1992).

Several kinds of research are needed to underpin and support IPM programs. First, the research to provide control tactics or technologies should receive high priority. Increased host resistance developed through the genetic improvement programs just described is central to viable IPM systems. Research will also be needed to seek out natural enemies of the pests, so that they can be used in biological control programs such as the highly successful cassava mealbug control program in Africa (Neuenschwander 1990). Research should also be conducted on cultural means of pest management and on economic thresholds.

Sharply focused IPM-related socioeconomic research must also receive attention. Research to identify and eliminate policy constraints to IPM conceptualization and implementation must be pursued, an example being the pesticide subsidies that are all too common. Operations research involving the active participation of farmers should be included as the IPM systems are developed and tested in the field.

Pest management researchers should be willing to participate as partners with farmers, NGOs, extension services and the private sector as and when IPM programs are conceived and implemented. They should also be willing to provide scientific backstopping as the programs progress.

The Sustainable Management of Water and Plant Nutrient Supplies

Crop production is largely dependent upon the availability and use of adequate water and plant nutrients. Likewise, natural resource conservation is markedly affected by how water and nutrients are managed. Water runoff and soil erosion are major components of natural resources degradation, accounting for more than half the soil degradation worldwide (Oldeman et al. 1991). Water deficiency (drought conditions) gives rise to wind erosion (28% of soil degradation) and to chemical degradation (12% soil degradation). The adequacy of vegetative cover to protect soils from erosion is determined to a considerable extent by the water and plant nutrient supply for plants.

Plant genetic research plays an important role in the management of water and plant nutrients. Enhancing the efficiency of water and plant nutrient utilization will be a challenge for genetic researchers. Tolerance to drought and toxic soil

conditions is essential for both the production of crops and the residues that will be needed to protect soils. If plants do not grow on acid soils, for example, little food will be produced and there will be sparse vegetative cover to prevent soil erosion. If crop plant varieties could be developed that are tolerant to aluminum and other toxic elements in the 170 million hectares of acid tropic soils (Grimshaw et al., In press), great opportunities for increased food production would be opened up. Plants that grow well on acid aluminum-toxic tropical soils have deeper root systems (Arija et al. 1992) and can utilize water from lower soil horizons.

Research to develop soil and water management systems that assure adequate vegetative cover of soils is imperative. Such cover will not only enhance the infiltration of water into the soil but also simultaneously decrease water runoff and soil erosion. This research must cover not only physical and biological issues but any socioeconomic constraints that limit the use of crop residues as soil cover.

The effect of soil erosion on crop productivity is generally greater in the tropics than in temperate zones. This is thought to be due to the greater concentration of soil organic matter in the surface horizons of tropical soils (Lal 1984). When erosion removes these upper layers, where much of the soil nutrients and water-holding capacities are found, soil productivity is negatively affected.

Research is needed to develop soil and crop management systems that maximize water use efficiency and minimize soil erosion. ICRISAT scientists have had some success in developing soil management systems for Vertisols that achieve these objectives. Recently in Mali, studies have demonstrated increased water use efficiency from ridge tillage and fertilizer application (Kouyate and Wendt 1992). The degree to which such results can be transferred to farmers' fields needs to be assessed.

One research area that should be more thoroughly explored is the possibility of using living grass barriers planted on the contour to diffuse the concentrated flow of water runoff from soils. Vetiver grass (*Vetiveria zizanioides* (L) Nash) barriers have been heralded for their potential to trap sediment and thereby help create de facto bench terraces, without the use of bulldozers or plows. A recent publication of the US National Academy of Sciences (NRC 1993) reviews the worldwide experiences in evaluating and using this hedging plant. The World Bank has aggressively encouraged its use where it can have a comparative advantage. Research is needed to assess not only this barrier plant, but also others that might conserve both soil and water.

Research also must be carried out to enhance the cycling of plant nutrients from the soil to plants and back to the soil. Such studies should increase the efficiency of use of native soil nutrients as well as those supplied by chemical fertilizers. The effectiveness of mycorrhizal associations in enhancing nutrient availability should be further evaluated.

A major challenge, especially in Africa, is to increase the supply of plant nutrients to crop plants. Assessments must be made of systems such as alley cropping to enhance nutrient cycling and residue coverage of soils. Likewise, assessments should be made of the complementarity between organic and

inorganic nutrient sources to maximize nutrient utilization efficiency. This will call for greater use of nitrogen-fixing crops.

The modelling of soil, crop, and atmospheric conditions should be further evaluated as means of better assessing options for management changes to increase productivity. Interdisciplinary approaches will be needed to carry out studies that can greatly increase the efficiency of technology dissemination from one ecoregion to another.

Policy Studies

Increases in agricultural productivity and equity in receiving the benefits from such increased productivity, along with the environmental consequences of these increases, are all markedly affected by public policies. For example, subsidies on agricultural inputs or on urban food consumers may have greater impacts than improved technologies on both increased food production and degradation of the environment. Similarly, these two issues may be affected positively or negatively by international or bilateral policies that discriminate against either the producer or environmental integrity. It has been said that wealth encourages environmental degradation in industrialized nations, while poverty is a major source of such degradation in most developing countries. National and international policies must be studied to ascertain changes needed to help move developing countries toward a "win-win" situation.

Smallholder Research

Small farmers and other rural people depend upon agriculture for their food as well as their livelihood. They are also responsible for at least part of the environmental degradation that has been accelerating in recent years. Research is needed to have a better understanding of the smallholder culture and needs, and to enhance the adoption of systems that emphasize both food production and environmental conservation (CIMMYT 1988). The farm family should be the focal point for these investigations and should, to the degree feasible, actually participate in the research (Jazairy et al. 1992). This bottoms-up approach would help the researchers gain a better perception of the problems that they are trying to solve and the steps needed to solve them. They would also change the agricultural research agenda to a demand-driven mode, and would involve the farm families in its planning and implementation.

Gender issues must be given far more attention by researchers than has been the case in the past. In sub-Saharan Africa, it is estimated that about 30% of the rural households are headed by women (Jazairy et al. 1992), and that 70% of the food staples are produced by low resource women farmers (Saito and Weidemann 1990). Unfortunately, most agricultural research seems to ignore this fact. Attempts should be made to better understand the effects of public policies, local customs, cultures, and educational systems on constraining the role of women in agricultural development. Blumbers (1992) recently reviewed this subject and suggested several courses of action that could be considered.

While most research relating to small-land holders and women may be performed by social scientists, research of the physical and biological are by scientists who should also take into consideration the needs of these disadvantaged groups. Such a course of action will have a positive influence on food production, poverty alleviation and environmental enhancement. Plant breeders and soil conservationists need to be aware of small-holder problems and perceptions as new varieties and systems are being produced.

Conclusions

The developing countries are faced with two dilemmas that are also opportunities. They must drastically increase their food production levels to accommodate the annual increase of 90 million in the human population. They must simultaneously arrest the degradation of their natural resources, much of which is associated with agricultural production. In modern terms, we say that sustainable agriculture is necessary to meet these two goals.

Sustainable agriculture demands simultaneous attention to economic development and ecological sustainability. Scientists and educators have the responsibility of creating and making available to food producers around the world environmentally sound and technologically efficient systems to provide adequate food for the anticipated massive increases in human populations in the decades ahead.

Regions with daunting environmental and economic constraints provide science with its greatest future challenges. Traditional crop improvement research backstopped by modern biotechnology must create crop varieties that will tolerate or overcome the adverse effects of pests and diseases, drought, soil toxicities and climatic extremes. These varieties must be fitted into farming systems that minimize natural resource degradation and enhance the economic well-being of not only the farmers who produce the food but also the low-income people who are the primary consumers of the food.

For scientists and educators to succeed, decision makers in both developing and industrialized countries need to recommit themselves to long-term support of agricultural research. At the same time, researchers must sharply focus their efforts on high priority areas that will provide the best for most of the people.

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Sustaining Agriculture in the Less Developed World: A World Bank Perspective

J.R. Anderson

• Abstract

The idea of sustaining the contribution of agriculture to the development process has often been paid lip service but is now receiving strong and committed attention in the Bank. There are several prongs to the recently articulated strategy, including investment in knowledge generation and transfer with respect to the technology of agriculture, to enhancing the institutional structures that service the sector, and these are briefly overviewed. In spite of some recent and probably transitory decline in agricultural loans, the agricultural sector continues to provide both challenge and opportunity for the Bank, in its role as the major international lending agency for the agricultural sectors of the less developed countries. All is not static, however, and this chapter charts some of the major contemporary developments, which include more explicit concern for the environment and greater attention to the role of the private sector in agricultural development.

Introduction

Over the past 30 years or so, the Bank has provided the means for many significant developments in the agriculture of the less developed world. Earlier, attention was focused primarily on infrastructural development, such as roads and irrigation schemes. As lending programs in such subsectors matured, the Bank's attention shifted to other forms of investment, many of which are characterized by a relatively long gestation period for the ensuing flow of benefits.

Perhaps foremost among the latter was support for the development of national agricultural research and extension schemes. In most cases, the role of the Bank was focused primarily on the infrastructural dimensions, including the provision of buildings and hardware, while other donors tended to take a relatively larger share of the activity on the human-capital front. Over the past three decades, such lending has accumulated to more than \$100 billion (Pritchard 1990).

Another major initiative for the Bank was, partly through the imaginative and institution-building ideas of visionaries such as Sir John Crawford, the underpinning of Bank grant funding for the establishment of, and subsequently

the continued support for, the Consultative Group on International Agricultural Research (CGIAR), with its growing network of International Agricultural Research Centers (IARCs) (Baum 1986). The Bank is a cosponsor of the system, which has demonstrably been of great significance in the agricultural development of many nations—notably the green revolution and related clichés, variously described and analyzed by many observers, including Anderson, Herdt and Scobie (1988). The IARCs include centers addressed primarily to plant breeding, now several with emphasis on natural resource management, and a variety of other organizations concerned more with institutional enhancement, related to such matters as food policy and national agricultural research organization. The Group has recently undertaken a major expansion of the system to include broadened mandates using a notion of food self-reliance (rather than self-sufficiency as earlier) in the less developed world and, accordingly, now includes new centers for international agricultural research on bananas and plantains, forestry, fisheries, agroforestry, irrigation management, and, perhaps one day, vegetables. It seems likely that other commodities will eventually be added to further expand the scope of international initiatives. These expansionary activities will make increasing demands for financial resources to be allocated to such long-term research activities but, since many of the same donors to the Group have already been supporting the existing related activities, this should not prove to be an impossible burden.

A New-look Bank

The Bank has gone through several major reorganizations in its history. These tend to happen soon after the appointment of a new President. For an institution dedicated to fostering developmental change, it is easy to rationalize the imperative nature of regular reorganization to respond to perceived changing needs of the client countries. So is it with the December 1992 reorganization that has taken effect as from 1 January 1993. There were several key elements in this change, including a radical restructuring of the technical support that was previously largely delegated to each of the Bank's regions, with now considerable centralization of such technical functions. It is planned that the strengthened central leadership and operational support will have a more explicit global perspective to facilitate wisdom-sharing across regions, a stronger function for channeling policy guidance, the achievement of some scale economies through larger aggregations of specialized skills, and, it is hoped, a strengthened external leadership within the development community. Other concurrent changes have seen a consolidation of research efforts and a stronger commitment to sector-operational activities.

In the new 1993 structure of the Bank (World Bank 1992), there are three new vice-presidencies:

Human Resources Development and Operations Policy, which concentrates on education, population, health and nutrition support services.

Finance and Private Sector Development, where many of the previous disparate divisions related to privatization, as well as the industry and energy units, are now aggregated.

Environmentally Sustainable Development, about which more will be said, if only for reasons of my bureaucratic location and the theme of this book.

The explicit attention to environmentally sustainable development is a natural and, some would say inevitable, outcome of many trends in the development dialogue in recent years, most especially the United Nations Conference on the Environment and Development (UNCED) event in Rio in 1992. The Bank is doing more than just making the "right noises" in this area and has made a major institutional commitment to pursuing this theme in all its work. Whilst poverty alleviation is the overarching ambition for defining the Bank's investment portfolio in general, in the new-look World Bank of the mid-1990s (and surely well into the new century and new millennium), there will be attentive heed to environmental sustainability in all the Bank's development endeavors.

The "teeth" for achieving such a newly articulated redefinition of Bank investment priorities are the more centralized and related "quality-control" functions of this new vice-presidency. It features three major departments, the Environment Department, the Agriculture and Natural Resources Department, and the Transportation and Urban Development Department, as well as housing the administration of the Global Environment Facility. The Environment Department and its regional divisions will play an everstronger role in planning and overseeing the environmental "correctness" of all Bank lending. This emphasis runs across all major sectors and is linked directly to agricultural work through the Rural Environment Division.

Overlapping to some extent with that division are the span of activities under the auspices of the Agriculture and Natural Resources Department (the successor to the previous Agriculture and Rural Development Department). This department is now the Bank's major unit providing advice on agricultural development within the bank and, within this department, the new Natural Resources Division will concentrate attention on the forest sector, water resources in general, and rural land management. Another division, the Agricultural Technology and Services Division, will continue to provide specialist advice on technical aspects of agriculture ranging from, say, crops and livestock to biotechnology. The third division in this unit, the Agricultural Policies Division, continues to foster social science perspectives, advice and research on policy issues in the agricultural and natural resource sectors.

The Technical Departments of the regions have gone through a major downsizing and fine-tuning. These now feature, divisions or units directed to environmentally sustainable development, as well as other counterparts to the new vice-presidencies. Presently there are only four such technical departments servicing, respectively, Africa, Asia, Latin America and the Caribbean, and Europe, the Middle East, and North Africa. In short, most staff working in the previous Technical Department Agricultural Divisions have been reassigned either to mainstream operations units or to the central vice-presidencies mentioned above.

These restructured units are yet to achieve smooth functioning and integration within the overall portfolio of the Bank's activities. Even within the new vice-presidencies, there are many cross-cutting issues that need to be resolved to engender an effective implementation of the work of various units.

Just what all this would mean for the way in which the Bank modifies its lending program and its working relationships with its borrowing member countries is, of course, yet to be seen. It could well be that the Bank has moved more quickly to recognize the important environmental dimensions of its work than have some of its borrowers. Development is, of course, a highly dynamic business with not just emerging fads and fashions, but also genuinely changed circumstances and needs. The structures now in place are at least set to facilitate a significant shift in the emphasis of lending to all sectors, including agriculture and natural resources. Already, many of the newest projects feature environmental aspects in project design.

Some Issues in Agricultural Technology and Related Policy

Regional Issues

The issues confronting those concerned with advancing agricultural technology vary considerably from region to region around the world. In the present brief discussion, a few topics of importance are identified to illustrate the global diversity of problems.

Sub-Saharan Africa. There has been a failure to bring to fruition in Africa, technologies analogous to either those of the green revolution of Asia and the rice-producing areas of Latin America or the modern technological developments that have characterized the sector in more developed countries. The notable lack of success comes in spite of significant investment in formal agricultural research systems in the public sectors of many countries, very notably Nigeria, as well as continued private efforts in the plantation sectors of African agriculture and, through input sales and promotion, also to some extent the small holder sectors. It should be noted, however, that the formal public sector agricultural research concerns for food crops in Africa came rather late, so there has not been the long tradition of research on food crops found in much of Asia (Pardey et al. 1991). An exception was early work by the Belgians in what is now Burundi, Rwanda, and Zaire.

The reasons for such generalized technological nonrealization are surely many. Part of the problem relates to a weak and sparse infrastructure in many African nations. Whether it be an absence of effective rail links, a deterioration of already inadequate rural road systems, corrupt and/or inefficient state-run marketing boards and parastatals, or any of the other infrastructural weaknesses, all such difficulties contribute to high transactions costs, which have the effect of reducing the returns on agricultural investment and innovation, and inflating to high (internationally speaking) levels the costs of purchased inputs. Overall, this tends to make adoption of "improved" techniques of agricultural production often unprofitable and frequently, given the variability of the natural environment as well as the economic environment, highly risky as well (Anderson 1992). Resource-poor producers are thus wise not to invest in such proselytized innovations in many cases. The technological problems of Africa thus cannot be addressed without a broad consideration of infrastructural investments at the

outset. This is not to deny, however, the continued need for an energetic and effective program of research in the field of agricultural technology for this vast and diverse continent (Lynam and Blackie 1993).

Central and Eastern Europe. Given the similarities of climate and soils across much of Europe, the technological challenges for agriculture to be faced immediately are primarily of a direct transfer nature. The profitability of such transfers will depend on the evolution of economic reforms and, of course, an opening up of Central and Eastern European markets to the private sector, both foreign and (when developed) domestic. Clearly, there are many gaps in information and commercial contacts to be filled but the prospects for agricultural advance in this "developing" part of Europe seem excellent once economic reform gains momentum.

Asia. South Asia has been at the center of the green revolution activity for the past two decades and the technology policy issues confronting much of it thus differ somewhat from those of the other parts of the less developed world. These have been referred to variously as "post-green revolution blues" or "second-generation" technological challenges. The nations of this region are still heavily dependent on the two major cereals—wheat and rice—and it is in the production of these staples that technological progress has recently slowed. It seems that further progress on the plant breeding front is not too promising (notwithstanding the longer-run optimism of Crosson and Anderson 1992) in the short run and that investors in agricultural research must look to other areas for the best prospects for advance. Generally, this will involve increased cropping intensification, given that the scope for expanded arable areas is in most cases, quite limited.

For the major staples, advances will probably mainly come through innovations in crop management involving more efficient use of purchased inputs, especially fertilizers through improved placement and timing, and more effective (especially from a biological point of view) use of crop-protection chemicals. Integrated pest management will surely play an important role here. The noncereal crops have thus far been somewhat lagging in the "new-technology stakes", but, as formal research and development work accumulates, good progress with hitherto neglected crops, such as the oilseeds, seems likely. Not all of South Asia is, of course, uniformly fortunate in its access to good irrigation and water management in general. There are many rather neglected and difficult "marginal" dryland farming areas, which have not been beneficiaries of large technological gains, and this situation seems likely to continue, notwithstanding the efforts of institutes such as ICRISAT.

Thematic Issues

Irrigation and drainage rehabilitation. There is much to be done in the way of restoring to earlier levels of efficiency the major irrigation schemes of the less developed world. Many of these schemes have fallen to a despairing level of technical efficiency and this is aggravated by an already questionable level of economic efficiency in the way water has been distributed and allocated.

The technological issues here span from structural engineering through to the agronomic, and have been largely ignored in formal research efforts addressed to the less developed world. These omissions are now being recognized and fresh research initiatives are being pursued. Such work is unlikely to yield early results in the short run because experimental work will be long in gestation and difficult to implement. To initiate the technical side of this work, an Executive Secretariat has been set up in the Bank.

Research. While the early major gains in research over recent decades have been centered on cultivars with wide adaptation, further progress in this direction presently seems highly constrained. Increasingly, it is recognized that cultivars, to be successful in the so far under-emphasized environments, need to be locally adapted to the particular growing conditions. This requirement calls for a somewhat different approach of selecting materials and practices that integrate more effectively into the nuances of niches. This work is necessarily more expensive than the typical previously used approaches, which could be handled from more remote centers and at low cost per unit of target area. Some of the work that has been grappling with tailoring innovations more conformably to the circumstances of resource-poor farmers has been conducted under the rubric of "farming systems research." This term is now less popular than earlier [for several reasons, some of which have been canvassed by Anderson (1991)], and these days is more likely to be called "research for environmentally sustainable farming systems" or some such term. The essence remains the same, however. The ambition is to accommodate not only the needs of the present generation of farmers and their resource scarcities but, through improved management of the underlying resources, including soil, water and forest, the better transition of resources to future generations of farmers, and therefore to consumers.

Extension. The Bank has been closely identified with an approach to extension often described as the Training and Visit (T&V) system. This system has been found to be technically superior in the transmission of extension messages and, at least in a couple of careful investigations, also more economical than traditional models of implementing extension work. There is much active interest in the Bank in distilling the lessons from several decades of extension efforts in order to refine more successfully, methods that can be used in future investment in agricultural advisory systems. A continuing problem has been the closer articulation of extension with research systems, particularly when sometimes these are handled not only in different departments but even through different ministries. The Bank has striven vigorously to bridge some of the yawning gaps in communication that have characterized some of the worst "systems." The present interpretation of recent history is that there is no "one" T&V system, for instance, but rather a broad approach that needs to be fine-tuned to the reality of particular nations' bureaucratic imperatives and agricultural needs.

There is an ongoing worry that any formal extension system is intrinsically too "top down," with insufficient true farmer participation and perhaps unnecessarily "public" in its funding. While there is some enthusiasm for more effective participatory methods of advancing technical innovation in agriculture, the means

of doing this through Bank-to-national-government lending are not too clear. This is an area where nongovernmental organizations (NGOs) have a generally better track record and the Bank is continuing to seek more effective links to NGO operations in the field and new mechanisms for supporting such "grassroots" activities generally.

Grants. The major grant activities in which the Bank is involved that are of relevance to agriculture are directed to the CGIAR, for which the Bank is a cosponsor and for which it also serves as a "donor of the last resort." This special donor role presently amounts to some \$40 million year⁻¹ in direct support for core activities of the IARCs. The Bank does not (at least yet) support Special Program activities, for which other donors (including UNDP) are much more important. Recent years have seen a major reevaluation of the direction of the evolution of the CGIAR system. The Bank is also involved in some of the non-CGIAR centers, including work on insect physiology (ICIPE in Kenya) and on fertilizers (IFDC with headquarters in Alabama and a major field station in Côte d'Ivoire). While this financial underpinning of the CGIAR and other international activities has been an important one, there is a growing concern within the Bank that such resources are not well expended and thus there is also growing scrutiny of improved ways of applying such grant funding.

Education. While the Bank has been supportive of educational enhancement in the less developed world in general, it has till date done very little of direct relevance to agriculture. There has been some lending for farmer training schemes, often as part of rural development programs but very little explicitly addressed to higher education for agriculture. In several parts of the world, most notably in sub-Saharan Africa, the universities servicing agricultural science education are in a parlous state and there is an urgent need of major resuscitation. The Bank has yet to address these issues squarely and to proceed in dialogue with member countries on such matters, since other more imperative matters seem to have stolen the lead agenda. Such work must surely soon be undertaken as a matter of priority, given the long lead times involved in reviving institutions that have reached low levels of academic performance and high student-staff ratios, with all the consequent compromising of educational attainment. Herein lies one significant gap in the World Bank operations of the mid-1990s.

General. Under this heading are many other initiatives in which the Bank is engaged that may eventually prove helpful to sustaining the agriculture of the less developed world. The most important, but unfortunately also the greatest failure thus far, is the general theme of trade liberalization. The unconsummated Uruguay Round of the GATT negotiations and the initiatives of the Cairns Group still stand (at the time of writing) as a profound disappointment for what should have been the considerable beneficiaries in less developed countries, not to mention those of outward-looking agricultural traders. The Bank will continue to use its good offices to foster progress but since some of the major "Part One" members of the Bank are those responsible for sabotaging the GATT round, prospects in this area do not appear promising.

Conclusion

In the World Bank's own policy-based lending activity in recent decades, however, much progress has been made in "getting prices right" in many borrowing countries plagued by distortions that have earlier been inimical to efficient economic growth, although not everyone concerned is necessarily pleased by some such changes. Many Bank agriculturalists, for instance, see the elimination of fertilizer subsidies as being counterproductive to their efforts in "getting agriculture moving" in areas that feature technological stagnation and exceedingly low levels of fertilizer use. Putting aside such concerns, however, the Bank's 1980s shift to policy lending, such as through structural adjustment loans, constituting a move away from project-based lending, has surely improved the economic environment within many nations. The problem for the future is that such gains are of a "one-off" nature in terms of the major effects, although the benefits are ongoing. In looking for new thrusts, it now seems that the Bank will have to get back into project-oriented lending activities, as the benefits to further arm-twisting and policy conditionality have diminished to such an extent that there are probably few major gains to be reaped in many countries—excluding, notably, India.

It is still premature to define all the attributes of the new thrust but one thing is certain—they will all feature extensive elaboration of environmentally sustainable development. Thus, it will typically be the case that any lending devoted towards productivity enhancement will, at the same time, simultaneously address matters of sustaining the resource base. This will feature greater attention to the improved management of common property resources, including forests and water resources, more explicit attention to better care of the land resource through greater investment in soil conservation activities (although probably seldom of the "heavy engineering" structural type), and, it is to be hoped, a more sympathetic understanding and engagement of the key resource managers themselves in all aspects of agricultural development—namely, the farmers, male and female, through novel forms of fostering effective participation in development projects. I don't pretend that all this will be easy and that the rhetoric will be readily matched by the complex lending activities that will doubtless be developed. A really honest go at it will, however, be made and I am confident that the world will be a better place for it. If it is to be successful it will need the continued commitment of the teams that bring in the potentially rich harvest from both national and international agricultural research investments.

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ICRISAT's Research on Sustainable Agriculture in the Semi-arid Tropical Stressed Environment

J.G. Ryan

Abstract

ICRISAT'S research strategy is focused on concerns for efficiency, equity, and sustainability. The goal of the Institute is to provide farmers in the semi-arid tropics with low-cost sustainable agricultural technologies based on an understanding of three broad sets of determinants: (1) physical; such as soil, water, and climate, (2) biological; such as diversified cropping systems and agroforestry, and (3) socioeconomic; such as equity, gender issues, and profitability. Based on these criteria the Institute has developed a Medium Term Plan. Priority themes of research for different agroecological zones have been identified.

Introduction

In the past, most gains in food production have come from irrigated agriculture and from areas with favorable growing conditions, such as assured rainfall and fertile soils. However, the limits of growth in food production from these high potential areas may well be in sight. The occurrence of biocide residues and nitrates in surface water and shallow groundwater poses a hazard to human health and the environment. This suggests that further increases in the use of agricultural chemicals could be at the expense of human health and environmental quality. At present, the land area under irrigation is growing significantly more slowly than in the past two to three decades, and in the future the rate of irrigated land going out of production may well exceed the rate of new land being brought under irrigation. These trends illustrate that the increases in food production that can be expected from high-input areas in the semi-arid tropics may stabilize in the near future.

Therefore, to meet increasing demands for both food and feed, pressure on rainfed agricultural land in the semi-arid tropics is likely to increase, and cultivation is likely to be extended to more marginal lands. The fragile ecosystems in the semi-arid tropics are already under great pressure, while soil and groundwater resources are in danger of severe degradation. The organic matter and nutrient content of these soils will be lowered through continuous cultivation, thus exhausting soil fertility, reducing biological activity and adversely affecting

soil structure and water-holding capacity. Already groundwater tables are being lowered, while water quality is deteriorating. Simultaneously, wind and water erosion are threatening large areas. If pressure on rainfed land increases, degradation of the resource base may proceed to a point where agricultural production becomes uneconomic in large areas.

The semi-arid tropics support a large rural population. In the absence of measures to stabilize the agricultural resource base, the sustainability of rural livelihoods is at risk. A major international effort is needed to reverse degradation of the resource base in the semi-arid tropics and to develop production systems that sustain farming communities and conserve the natural resource base.

Sustainability Research in the International Agricultural Research Centers (IARCs)

Sensitized by the Brundtland Commission report, the Technical Advisory Committee, of the Consultative Group on International Agricultural Research (CGIAR) began its deliberations on sustainability in the mid-1980s, and finally presented its report entitled "Sustainable Agricultural Production: Implications for International Agricultural Research" and made recommendations in 1988. A review of priorities within the group was then initiated. This resulted in the CGIAR redefining its goal and revising its priorities. The goal statement is given below:

"Through international research and related activities, and in partnership with national research systems the CGIAR aims to contribute to sustainable improvements in the productivity of agriculture, forestry and fisheries in developing countries, in ways that enhance nutrition and well-being, especially among low-income people."

CGIAR identified a number of priority research areas. Some of the important items of the research agenda are detailed here:

Priority Research Agenda

- Effective management and conservation of soil, water, forests, and germplasm for sustainable production.
- Improved productivity of important crops, livestock, trees and fish and their integration into sustainable production systems.
- Improved diets, family welfare and equity (including gender equity).
- Appropriate policies for improved agricultural productivity and sustainable use of natural resources.
- Strengthening of institutions and human resources in national research systems to accelerate the identification, generation, adaptation, and utilization of technological innovations.

ICRISAT's Research Agenda on Sustainability Research

The ICRISAT External Program Review (EPR) Team in 1990 reviewed our research and highlighted the following areas of sustainability research for further expansion.

These areas are:

- conservation of genetic resources for future improvements of crops;
- control of pests, diseases within minimum recourse to hazardous chemicals;
- maintenance and improvement of soil fertility; and
- maintenance of quantity and quality of water resources.

These research areas had received a high priority in ICRISAT from the beginning, but in the context of the need to increase food production. They indicated that, the group of soil related problems, especially those due to their insidious long-term development with serious consequences for future generations deserved greater attention, i.e., rates of soil loss (very long-term).

There was a need to initially define the nature and extent of unsustainable rates of soil degradation in the semi-arid tropics (SAT) and then to carry out research if the problem warranted it.

The effect of build up of complex soilborne pests and diseases both in the medium- and long-term time scale in cropping systems also deserved attention.

ICRISAT's Strategy for Research on Sustainable Agriculture in the SAT

Even though farming systems and resource management research has been conducted for some time at ICRISAT, as yet there is no comprehensive methodology for resource management research aimed at developing sustainable production systems for the ecologically fragile semi-arid tropics.

Resource management research at ICRISAT will be aimed at designing strategies for sustainable food production in rainfed areas of the semi-arid tropics, while improving the nutritional status and general economic well-being of low-income peoples. Concerns for efficiency, equity, and sustainability will be explicit hallmarks of this approach. Thus, resource management research will have a clearly discernible sustainability perspective and will concentrate on low-input agriculture, integrated management systems for controlling pests and diseases, and improved methods for dealing with edaphic and climatic stresses. Our overall goal will be to provide farmers in the semi-arid tropics with low cost sustainable technologies based on an understanding of three broad sets of factors: physical determinants such as soil, water and climate; biological determinants such as diversified cropping systems and agroforestry; and socioeconomic determinants.

ICRISAT's Strategic Plan

ICRISAT in its long-term Strategic Plan reiterated the importance of "Sustainability." The need for long-term comprehensive, well defined, and designed studies was emphasized. Let me quote a pertinent question that we asked ourselves in our Strategic Plan.

"Can agricultural production in the SAT be increased to meet the needs of expanding populations without threatening the resource base on which food supplies depend?" "ICRISAT's current research attempts to address this question in terms of soil and water conservation; maintenance of fertility; and diversification of cropping systems for food, fodder, and fuel. We believe farming systems

can be developed that increase production, protect environmental resources, use inputs efficiently, and, maintain genetic diversity. For example, the application of fertilizer to a nutrient-deficient soil stimulates the growth of leaves that protect the soil surface from impactation by raindrops, and plant material left after harvest contributes to soil organic matter.

"ICRISAT recognizes the need to quantify sustainability and to establish protocols for the long-term trials suggested by the TAC Sustainability Committee. Medium- to low-input systems will receive major emphasis. These include water-conservation measures in dryland agriculture, integrated nutrient management, and the use of low-cost tools and machinery."

ICRISAT's Research Portfolio

ICRISAT has been conducting research on soil management, water and nutrient resources, agronomy and cropping system, and socioeconomic issues for more than 20 years. New elements, however, become visible when research projects are formulated and integrated into research themes. Our extensive discipline knowledge of black soils (Vertisols) management must be consolidated so that interactions and temporal changes are better understood. At the same time, we need to intensify our understanding of the basic mechanisms regulating production in red soils (Alfisols). As with our Vertisol strategy, this work will be integrated with our crop improvement program efforts to better assess temporal changes. Our research emphasis will be on multidisciplinary basic and strategic research, strengthening cooperation among scientists within the Resource Management Program as well as in the commodity programs. There will also be a geographic shift in research emphasis: more resource management research resources will be spent in Africa, in particular southern and eastern Africa, and our activities in Asian countries other than India will be expanded. Cooperation with the national agricultural research systems (NARSs) will be strengthened in such fields as watershed managements, in particular on Alfisols, and the development of agricultural systems in which trees or other perennial crops are an important element. Geographic Information System (GIS) will be strengthened, as an important component of integrated modeling efforts to study soil/crop/economic systems across different agroecological environments. We will attempt to transform single physical, biological, and socioeconomic data into composite indices or parameters that are meaningful for designing strategies to increase and sustain food production in the semi-arid tropics.

ICRISAT's Medium Term Plan

ICRISAT's Medium Term Plan contains 92 research themes in its core priority portfolio for the next five years (1994–1998). The four criteria of efficiency (Net benefit/cost ratio), equity (Poverty/Female literacy), internationality (Simpson index), and Sustainability (Environment) were used in the analysis to rank the themes. All four criteria were given equal weights. Each theme was rated on a (1)–(5) quantitative scale with regard to its potential contribution to sustainability. That is, themes were evaluated for their likely impact in maintaining or upgrading

the resource base to ensure long-term productivity growth. The following index was used.

Sustainability: A Measure/Index

- 1 = makes no or only negligible contribution to sustainable agriculture.
- 2 = makes a slight contribution to sustainable agriculture.
- 3 = makes a moderate contribution to sustainable agriculture.
- 4 = makes a large and significant contribution to sustainable agriculture.
- 5 = upgrading the resource base is the primary focus of the research.

We are aware that the ratings index used is not perfect and will require refining and fine tuning. In the past all our projects contained a descriptive sustainability/environment assessment. All the themes from crop improvement programs, the Resource Management Program, and the Genetic Resources Unit were subjected to one sustainability index (Table 1).

Table 1. ICRISAT's Medium Term Plan (1994–1998)—Breakdown of themes by index¹

Sustainability Index	No. of themes	Percentage
5	8	9
4	25	27
3	36	38
2	13	15
1	10	11

1. Each theme includes factor for sustainability (quantified index 1–5).

Sixty-nine themes of the 92 in our research portfolio have an index of 3 and above, thus indicating the emphasis on sustainability (Table 2).

Table 2. Breakdown of themes by programs

Sustainability index	Number of themes				
	Total	RMP	Legumes	Cereals	GRU
5	8	4	3	0	1
4	25	7	15	2	1
3	36	7	16	12	1
2	13	4	1	8	0
1	10	3	5	2	0
Total	92	25	40	24	3

Seventy-five percent of all the themes in the research portfolio make a contribution [moderate (3), large (4), upgrades (5)] to sustainable agriculture. Seventy-two percent of the themes of the Resource Management Program; 85% of the Legumes themes; 58% of the Cereals themes and 100% of the themes of the Genetic Resources Unit have a sustainability index of 3 and above. Improvement of yield per se or maintenance of yield per se will not be the primary goal of our crop improvement efforts. Major effort will continue to be on developing resistant or tolerant cultivars to major biotic and abiotic constraints through multidisciplinary team effort. Management at ICRISAT has emphasized the need to blur the lines between disciplines, programs and locations in strengthening our "systems" approach. Both at ICRISAT Center here in India and at the ICRISAT Sahelian Center interdisciplinary systems approach has been followed, led by the Resource Management Program. During the coming Medium Term Plan (MTP) period resource management research will be strengthened at our other locations and in other parts of Asia.

Much progress has been made towards quantifying sustainability in the past few years but we have not yet identified a full set of protocols for the SAT. Robust and long-term large data sets are required for quantification of sustainability.

ICRISAT's Research on Quantifying Sustainability

Data from ICRISAT's long-term interdisciplinary trials on the Vertisol Watersheds (began in 1989) developed with the objective of evaluating "long-term effects of various production components on plant growth, soil fertility, insect and disease pests and crop yields," provide a foundation for research on sustainable resource management, along with simulation modeling for the purpose of extrapolating experimental findings to a wider range of environments. Economic sustainability of alternative production systems is quantified using indices to measure total factor productivity overtime. Changes in productivity can be related to other measurable changes in the systems, such as changes in soil nutrients or structure or the presence of pests and diseases. The information allows researchers to assess the relative productivity and sustainability of different systems, and probe the trade-offs between productivity gains now and in the future; to study the effects of different forms of environmental degradation on agricultural productivity and sustainability, thereby beginning to understand the costs of different types of environmental degradation in terms of productivity; and to evaluate the extent to which the productivity losses from different kinds of degradation are reversible. Similar long-term interdisciplinary work will be carried out on the Alfisol Watersheds during the MTP.

ICRISAT's Sustainability Research and UNCED Agenda 21

During the course of our preparation of the MTP last year, the "Earth Summit" meeting was held in Rio. The United Nations Conference on Environment and Development (UNCED) developed "Agenda 21" as a statement of goals, and a list of strategies and actions aimed at achieving those goals. There are clear

parallels between ICRISAT's objectives and those enumerated in Rio. Indeed, 80% of the 92 research themes in our portfolio directly address specific priorities for sustainable agriculture and rural development identified within "Agenda 21." Thirty-two percent involve improved soil, water and crop management and improvement to stabilize rainfed crop lands. Twenty-nine percent involve sustainable crop improvement techniques which aim to overcome major biotic constraints to enhanced crop performance, while reducing the use of chemicals.

The parallels between the priority portfolio of themes and some key "Agenda 21" priorities are presented here:

Agenda 21 priority	Percentage of ICRISAT portfolio
Improved soil, water, and crop management for sustained increases in yield	32
Biotechnology and crop improvement for sustained increases in yield	29
Developing sustainability indicators	5
Integrated conservation of water and land resources	4
Ecosystem interactions and characterization	3
Baseline surveys of biological resources	3
Policy research	2
Biodiversity conservation methods	1
Total	80

Conclusions

Assuring farmers and national agricultural research systems (NARS) participation is necessary; reducing poverty is imperative. Sustainability of agriculture underpins our research. It is the key to increased food production in the SAT. We believe both basic and strategic research in resource management are needed to provide knowledge on which to base the development of sustainable production systems. There is a need to recognize that natural resource management research requires long-term commitment. Robust indicators of sustainability are required that recognize the interdependence of economic and environmental sustainability and the potential trade-offs between them.

Sustaining Indian Agriculture— The Challenges

I.P. Abrol

Abstract

India's population continues to rise rapidly with a growth rate of over 2% per annum and will reach 1 billion by the end of this decade. The population is likely to be about 1.6 billion towards the middle of the next century. Our ability to meet the food, feed, fiber, fuelwood and other basic needs of the growing population is a key issue to be addressed when discussing the sustainability of our production systems.

In the past, our efforts to achieve self-sufficiency in foodgrain production resulted in the required gains, from both the expansion in area under cultivation and through increased productivity. Significant increases in productivity, however, were confined to relatively, well-endowed areas, i.e., regions which had very few soil or climate related constraints, and where, irrigation facilities were either available or could be created easily. With the availability in the mid-sixties, of high yielding dwarf, fertilizer responsive cultivars, particularly, of rice and wheat, the main strategy was to realize the cultivar potential through increased use of chemical fertilizers and plant protection chemicals. Progress has been particularly slow in rainfed agriculture which accounts for over 65% of the total crop hectarage and almost half of the total crop production in the country. Productivity gains were also negligible in areas where introduction of irrigation in relatively high rainfall regions led to an accentuation of problems of rain water management.

Mounting pressure on the natural resources due to increasing human and livestock population is responsible for a greatly accelerated degradation of soil resources. Deforestation, overgrazing by livestock on private, community and state owned lands, and excessive fuelwood extraction, the primary cause of degradation, have led to substantial areas of degraded lands in virtually every watershed throughout India. A continued neglect of these is a serious threat to the productivity of adjacent arable lands.

Even in areas, which in the past have contributed significantly to increase in productivity there are emerging second generation problems related to increasing input costs in production, secondary and micronutrient deficiencies, increased proneness to physical deterioration, problems resulting from changes in salt and water balances, ground water pollution, etc. The crop yields in these areas are also decreasing.

Our present predicament calls for a new paradigm in our future approaches to research. These approaches must consider the socioeconomic realities of the farming systems in different agroecological zones and the potentialities and limitations of the natural resources. The new approaches

must also ensure a more holistic system-based view of the problems ensuring integration of conservation and production strategies. Goals of sustainability will require that technologies are generated and promoted with the full involvement of the people.

As in the past agriculture sector shall continue to play a crucial role in the country's development. Though over the past four decades the contribution of agriculture to country's total economy has reduced from about 45% in 1960–61 to 30% in 1990–91 (Table 1), Indian economy currently sustains the livelihood of nearly 75% of our population, underscoring the need for high priority to this sector. The core challenge in achieving the goals of sustainable agriculture is to raise the productivity and income especially of the poor without degrading and depleting critical life support systems.

Table 1. Growth of Indian agriculture and overall economic growth

Year	Gross domestic production ¹		Contribution of agriculture (%)
	Total economy	Agriculture	
1950–51	42871	20860	48.65
1960–61	62168	28157	45.29
1970–71	89291	34785	38.95
1980–81	122184	41573	34.02
1990–91	199177	59633	29.93

1. GDP estimates are 3-year running averages.

Increasing Food Production—Our Past Experience

Any discussion on sustaining agriculture is intimately linked to the key question of meeting the food, feed, fiber, fuelwood and other basic needs of our growing human and livestock population. Our past experience should be of relevance. Over the past three decades India has successfully moved from a food-deficit state to one which is, by and large, self-sufficient in the production of foodgrains, though at a low level of availability (Table 2). Total foodgrain production increased from 78.61 million tons in 1960–61 to 100.64, 123.73 and 172.39 million tons respectively for the decades ending 1970–71, 1980–81 and 1990–91 respectively (Table 3).

Cropland expansion in the sixties and seventies were due to the conversion of traditional grazing lands of a low productivity to cropland. For this reason cropland expansion has played a relatively minor role in increased foodgrain production. On the other hand reduction of grazing land and resultant overstocking of the grazing land (Table 4) has been a cause of severe resource degradation. The expansion of area under foodgrains has decreased over the

Table 2. India's population and per capita availability of foodgrains

Year	Population (m)	Cereals (g day ⁻¹)	Pulses (g day ⁻¹)	Total (g day ⁻¹)
1961	439.2	399.7	69.0	468.7
1971	548.9	417.6	51.2	468.8
1981	685.2	416.2	37.5	453.7
1991	844.3	474.2	40.0	514.2

Table 3. Growth in foodgrain production

Year	Production (million t)	Increase over the past decade	
		Foodgrain (million t)	Area (million ha)
1950–51	52.87	—	—
1960–61	78.61	25.74	17.09
1970–71	100.64	22.03	7.38
1980–81	123.73	23.09	4.19
1990–91	172.39	48.66	0.36

Table 4. Grazing lands in western Rajasthan¹

	1951–52	1971–72	1977–78
Grazing land (million ha)	11.3	9.2	8.7
Share in total land area	0.61	0.48	0.45
Animal units/100 ha ⁻¹ of common grazing land	39	94	105

1. Source: Jodha (1990).

successive decades from 17.09 million ha in the fifties to practically none in the eighties (Table 3). Thus increased foodgrain production in the eighties was entirely due to increased yield and productivity. If these trends were any guide, future increases in production will have to come through increased productivity and a continuously shrinking resource base. The total cultivated area (net) has also stayed at about 140 million ha for the past two decades although the area sown more than once (multiple cropping) has increased by about 16 million ha over the same period. Increased cropping intensity will also be a key strategy for future gains in production.

Increased foodgrain production since the mid-sixties has come about largely through increased intensity of cropping and increased productivity in the relatively well endowed areas, i.e., areas where irrigation facilities already existed or could be developed relatively rapidly. These were the areas with very few soil and/or climate associated constraints limiting production. With the availability of dwarf, high yielding fertilizer responsive cultivars, of rice and wheat, in particular, the key effort in the experimental station research was to achieve the potential yields of new cultivars through appropriate inputs and management strategies. Similarly the main extension and development strategies aimed at higher area coverage with the new cultivars and promoting and achieving higher use of chemical fertilizers.

Irrigation, a key factor in achieving increased production, increased from net 24.7 million in 1960–61 to 45.2 million ha in 1989–90. During the same period, the gross irrigated area increased from 28.0 to 59.6 million ha, i.e., about 33% of the gross cropped area (Table 5). The use of chemical fertilizers, similarly increased from less than 0.3 million tons in 1960–61 to 12.54 million tons in 1990–91. In some states which have achieved high crop productivity, large areas are receiving chemical fertilizers equivalent of 300 to 400 kg nutrients per ha per annum although the average use for the country as a whole is still low, 70 kg nutrients ha⁻¹. The combination of expanding irrigation coverage, widespread adoption of high yielding crop cultivars and increased use of inputs have largely contributed to increased foodgrain production in the past three decades. Rice and wheat accounted for more than 85% of increase in foodgrains (Table 6). As a result of these, agricultural production and incomes have risen substantially in the states of Punjab, Haryana, western Uttar Pradesh and parts of Rajasthan, Tamil Nadu and Andhra Pradesh. In contrast, productivity and output growth have been very modest in eastern and central India and in the Deccan plateau. Progress has been particularly slow in the rainfed agriculture belt which accounts for over 65% of crop hectareage and almost half of total crop production in the country and will still account for more than 55% of the total cropped area by the turn of the century.

The Challenges

By the turn of the century, India's population will touch 1 billion. According to the Planning Commission, the aggregate requirement of cereals and pulses will be 235 million tons in addition to about 26 million tons of oilseeds. If self-sufficiency in foodgrains is to be maintained, this would imply raising annual foodgrain production from its 1990–91 level of 176.2 million tons by nearly 60 million tons over a 10 year period. From 1970–71 to 1980–81 and from 1980–81 to 1990–91, in comparison, foodgrain production increased by 23.1 and 48.6 million tons respectively (Table 6).

An important consequence of growing population is the declining trend in average farm size. In 1980–81 there were 88.88 million holdings operating 163.80 million ha of land. By 1985–86 there were 97.15 million holdings operating 164.56 million ha. The average farm size, 2 ha in 1976–77 was reduced to

Table 5. Expansion of net and gross irrigated area

Year	Irrigated area (million ha)		Cropped area	
	Net	Gross	Net	Gross
1950–51	20.9	22.6	118.7	131.9
1960–61	24.7	28.0	133.2	152.8
1970–71	31.1	38.2	140.3	165.8
1980–81	38.8	49.8	140.0	172.6
1989–90	45.2	59.6	139.5	181.1

Table 6. Increase in foodgrain production

Crop	Period		
	1980–81 to 1990–91 (million t)	1970–71 to 1980–81 (million t)	1960–61 to 1970–71 (million t)
Rice	22.97	9.11	8.43
Wheat	18.27	13.69	10.43
Coarse cereals	4.28	–1.14	4.41
Pulses	3.14	–0.84	–1.24
Total	48.65	23.09	22.03

1.84 and 1.69 ha respectively in 1980–81 and 1985–86 respectively. The process of marginalization is likely to continue with steady increase in the number of landless families and the number of farm families with very small and marginal holdings.

India's forest cover has been dwindling. According to the National Remote Sensing Agency the total area under forest in 1980–82 was 46 million ha compared to 55.5 million ha in 1972–75. It was further estimated that in 1982 only 36 million ha of forest area had a crown density of more than 40%. By any estimate the area under forest is greatly below the national policy goals. Absence of vegetal cover is leading to serious degradation of soils through erosion.

The growth of livestock population is an important source of competition for land resource. During the period 1951 to 1982 livestock population has increased from 292 to 416 million and is still increasing at the rate of 2% per annum mounting a tremendous pressure on the already degraded resources. There are vast areas of degraded common grazing lands, uncultivable wastelands and degraded forests that are a tremendous waste of potentially productive natural resources and a serious threat to the adjoining productive cropland. There are

substantial areas of such land in virtually every watershed throughout the country. Degradation continues unchecked due to overpopulation of livestock and of uncontrolled grazing and foraging far in excess of the sustainable carrying capacity of the land.

According to recent estimates (Abrol and Sehgal 1994) erosion of the top soil by water, the single most important factor leading to soil degradation is adversely affecting the productive capacity of nearly 155 million ha. Of these terrain deformation resulting from extremely high erosion rates account for some 12.8 million ha. Erosion by wind is the main factor leading to degradation of some 13.0 million ha largely in the arid regions. Degradation of soils through accumulation of soluble salts (soil salinization) is a major threat to sustainability in the irrigated, particularly, arid and semi-arid regions where the groundwaters are naturally loaded with salts. Use of these waters for irrigation or the redistribution of salts following introduction of canal irrigation is responsible for reduced productivity of some 11.0 million ha of otherwise productive soils.

The pressure on land and water resources is also threatening the native plant and animal populations. India has a uniquely rich and diverse genetic base the properties of which are far from being fully evaluated and understood. Factors that cause a reduction in the capacity of soils to absorb, retain and supply water to the plants will also lead to the dominance of vegetation that is compatible to the adverse moisture regimes.

Impact of Land Degradation

Widespread degradation of resources resulting in reduced productivity is the most serious threat to our efforts to achieve sustainability goals. Efforts to quantify the impact of degradation or direct experimental evidences of the effect of degradation on productivity are very limited. Amongst the earlier studies, a survey of soils of the Solapur district of Maharashtra in 1870 and again in 1945 showed that in a period of 75 years nearly 17% of the land under medium depth of soil (more than 450 mm) were converted into shallow soils of depth less than 450 mm (Basu et al. 1960). Continuing land degradation of top soil is a major factor for low and unstable crop yields in rainfed semi-arid tropics. Vittal et al. (1990) evaluated the effect of top soil depth on the yield of rainfed crops grown in an Alfisol over a period of 4–5 years. Based on rainfall data of 56 years, the expected yield loss as a result of erosion was calculated as 138,84 and 51 kg ha⁻¹ cm⁻¹ for sorghum, pearl millet and castorbean respectively.

Common property resources (CPR) have, in the past, contributed a significant, indeed a major fraction of such supplies as fuelwood, animal grazing and employment among the poor sections of the society. A study by Jodha (1990) spread over 82 villages in different parts of the country showed that in a span of 30 years there was a reduction in CPR by 31 to 55%. Physical degradation of the CPR has resulted from disappearance of a number of plant and animal species which the villagers used to gather from the common lands. Similarly CPR traditionally used for grazing more productive milch cattle, working bullocks etc., were now grazed by sheep and goat. The number of watering points had also declined significantly.

On a macroscopic level the impact of land degradation has been increasingly recognized over the past 3–4 decades. The initial concerns were largely related to higher than assumed siltation rates of large multipurpose water reservoirs.

The Shivaliks are amongst the most degraded due to excessive exploitation of surface vegetation. The area under *Chos* which carries a large amount of silt in the Hoshiarpur district has increased from 19,282 ha in 1852 to 200,000 ha in 1981 (Table 7). Similarly the area annually flooded, including the cropland, has sharply increased from an average of 6.86 million ha in the fifties to 16.57 million ha in the eighties (Table 8).

Table 7. Area under *chos*¹ in Hoshiarpur²

Year	Area (ha)
1852	19282
1884	32057
1897	37694
1936	60000
1981	200000

1. The *chos* are streams originating in the Shiwaliks which carry a large amount of silt. The river beds rapidly become wide and shallow. The widening of their beds has increased the area under *chos*.
2. Source: Center for Science and Environment 1991.

Table 8. Trend in flood affected and population¹

Decade	Average annual area affected (million ha)	Average annual flood affected population (million)	Average annual total flood damages (million Rs)
1950s	6.86	2.08	623
1960s	5.86	2.47	1041
1970s	11.19	5.55	6741
1980s	16.57	6.91	15904

1. Source: Center for Science and Environment 1991.

India has over the successive five year plan periods made massive investments in achieving a current net irrigation potential of 45.2 million ha. Of these, canal irrigation accounts for 16.36 million ha, tank irrigation 3.3 million ha and the remaining 25.5 million ha is irrigated by wells and other sources. Problems of soil degradation have been most serious in the canal irrigated areas. A study (Bowonder and Ravi 1984) made 30 years after the left bank canal of the Tungabhadra irrigation project was commissioned in 1953 showed that about

33,000 ha had been seriously affected by excess salts and water problems. It was further estimated that production from about 20,000 ha had already reached zero level forcing the cultivators to abandon their lands. In the initial years the cultivators tend to switch to more tolerant crops like rice but even the production of tolerant crops is substantially reduced apart from accelerating the degradation of additional area due to inefficient water use.

In a more recent study based on a survey of 110 farming households in Gauriganj block of Sultanpur District of U.P. under the command of Sharda Sahayak Irrigation Project, Joshi and Jha (1991) observed that between 12 and 13 years following the commissioning of the canal system, more than 87% of the farms were affected by salt-related problems. On the affected farms nearly 29% of farm area remained uncultivated. The yields of paddy and wheat were 41 to 56% lower in the affected soils and the net income on these lands was reduced by 87 to 92%. Growing paddy became the only option on waterlogged soils although the net income was reduced by 54 to 55% compared to paddy grown in normal soils. The unit cost rose by about 60% for paddy and by about 85% for wheat when the cultivation was extended to salt-affected soils. The authors concluded that the economic trade offs between creating additional irrigation capacity and improving drainage and other components of the existing irrigation systems could be highly competitive.

The issue of sustainability of production systems in the well endowed regions which in the past two decades have contributed a major fraction of the increases in foodgrain production needs serious consideration. There are signs of plateauing of the yields of the two most important crops, rice and wheat. Thus these areas are unlikely to provide the required increases as in the past. Even for sustaining the high production levels achieved in these areas would require a relook at our past strategies. Over the years, there has been a declining trend in the overall response to inputs, e.g., fertilizers. Thus for each unit of nutrients applied from external sources, the response in terms of additional foodgrains has been decreasing. In order to obtain the same yield, therefore, a farmer has to use increasing amounts of inputs. With continued depletion of the soils, crops are experiencing increasing deficiencies of secondary nutrients and micronutrients. Zinc, sulfur, boron, manganese, iron deficiencies are widespread and these nutrients need to be regularly repienished. Soils in the intensively cultivated areas are showing increased proneness to physical and chemical deterioration as evidenced by increased responses to and spread of such practices as deep cultivation, application of gypsum to promote infiltration, etc. In many intensively cultivated areas accession of applied chemicals to the ground water is causing pollution; changes in the water balance resulting in lowering of ground water in some and rise in others with attendant salt balance problems would need sound scientific approaches towards long-term resource management problems.

Meeting the Challenges

It is apparent that the challenges of food security are intimately related to those of environment and ecological security. Our present predicament would demand a continuing increase in productivity and total output ensuring that the quality

of the resource base is maintained and indeed enhanced. It is also clear that the development models concentrating largely on external inputs that we have pursued in the past will no longer be able to provide the desired results. This will call for a new paradigm in our future approaches to research. The new paradigm must enable us to develop strategies for improving production that takes into account the potentialities and limitations of the natural resources, climate, soils, water, and vegetation for their sustainable use. These strategies will, of necessity, have to be specific for each of the agroecological regions/subregions.

Our new approaches must also enable us to view the problems and the necessary solutions from a more holistic perspective. Only in recent years, we have become aware that the field problems we attempt to define and find solutions for, are in fact, an integral part of a larger and continuous environment and what we attempt to solve may indeed have a series of repercussions that we rarely take into account. It is indeed due to our piecemeal approach that we have encountered increasingly acute problems in managing and protecting our resources and the environment. Field problems to which we seek solutions are rarely amenable to solutions through a single discipline oriented research. Mechanisms to ensure that required scientific inputs are available to solve a problem in a mission mode are of urgent need.

So far, conservation and production strategies have been formulated and pursued independent of each other. It is quite frequent that while good seeds and fertilizers are promoted in one area, conservation measures are promoted in another. Similarly while conservation measures might be promoted in an arable land in a part of the watershed the other areas not belonging to individuals might remain untreated and may negate any measures taken in a part of the watershed. Integration of conservation and production strategies is crucial to ensure the complementarity.

A critical lacuna in our past approaches has been inadequate effort and lack of mechanisms to build up research programs that take into account the socioeconomic realities of the farming systems. Similarly we have taken little advantage of the experience and knowledge base that exists within the farming communities, in our effort to develop and improve upon existing technologies. Involvement of people in conceptualizing, generating and extension of technologies would appear very important.

India has a large scientific manpower and an infrastructure for research education and extension. Meeting the challenges of sustainability will require a quantum jump in reorienting our approaches to face the new realities. Making these changes happen will be crucial in achieving our goals.

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III. Sustainability and Resource Utilization

Indicators of Unsustainability

(Approaching Sustainability through Unsustainability)

N.S. Jodha

Abstract

Despite significant additions and refinements in the definitions of the term "sustainability," its operationalization continues to be a major gap, that reduces its practical utility. One pragmatic way to handle this problem could be "to approach sustainability through unsustainability or nonsustainability;" as this chapter illustrates with reference to the situation in fragile resource zones.

Accordingly, the absence or rapid erosion of conditions associated with sustainability (as per the definition or rather description of the term), would reflect the unsustainability or nonsustainability of a system. The restoration of the missing or rapidly disappearing sustainability conditions would mean making a system sustainable. Operationally, sustainability would mean a system's ability to maintain or enhance its performance, i.e., output, services, (even through linkages with other systems), without damaging its own long-term potential. The loss of this ability would mean unsustainability of the system. This implies loss of the prospects of intergenerational equity (due to a system's inability to maintain/enhance performance) or reduced range and quality of (production/welfare) options for a generation compared to the preceding one. In the case of fragile resource zones the deteriorations implied by the above description are currently manifested by various changes covering (a) decisions/actions of the communities facing the reduced range and quality of options, and (b) status of natural resource base and production processes characterizing the systems. The farmer would include: (1) The community's (or individual farmer's) acceptance of inferior (production/consumption) options; (2) high degree of "desperation" in resource use and production practices leading to over extraction and degradation of resource base; (3) acceptance of "dependency" as a normal basis of survival (e.g., normal production, consumption activities sustained by subsidy and charity).

The trends relating to the status of the production system, etc., are manifested through: (1) Loss of "systemic integrity" implying disappearance or weakening of resource regenerative, resource protective mechanisms; (2) ever increasing (chemical, economic) subsidization of the production system to maintain the same or lower levels of performance; (3) marginalization, decline and disappearance of the system or its components.

The above trends are manifested in more concrete forms if one looks at the persistent negative changes in different variables. These measurable negative changes (with varying degree of visibility), described as indicators of unsustainability relate to: (1) resource base (e.g., decline of ground water or reduced extent of biodiversity); (2) resource productivity (e.g., persistent

decline in crop yields as well as production of biomass); (3) resource management/production practices (e.g., disappearance of various forms of diversification, conservation promoting institutions, etc.). The chapter contains an inventory of such indicators.

By nature some indicators of unsustainability represent the process of negative change while others are negative consequences of the change. For instance, decline of diversification and resource regenerative farming practices represent a process; while depletion of organic matter in the soil, reduced biomass and crop yield are the consequences. To be effective, interventions against unsustainability should be focused on the process of change rather than the consequences.

The effective use of this approach, i.e., restoration of sustainability by understanding the reversing of unsustainability trends, calls for proper identification, inventorization and validation indicators of unsustainability. The chapter comments on some relevant methodological issues that relate to: (1) identification of a benchmark to compare the present with the past; (2) a mixed use of (a) focused interpretation of available records (b) oral history and (c) scientific methods to assess the past of a variable by looking at its present status; and (3) focus on "process" rather than "consequence" as indicators of unsustainability.

Reversal of the unsustainability trends is possible only if the above "process" part of unsustainability is understood and addressed. This means a need for greater attention to resource use practices, technologies, etc., which (as processes) contribute towards: (1) the loss of systematic integrity of a system; (2) over emphasis on (chemical, economic subsidization) production processes; and (3) dependency and marginalization of the system. Modern science and technology can play a crucial role in identifying and reversing such unsustainability promoting processes, provided the perspectives of R&D planners are reoriented.

The chapter illustrates the situation with reference to the fragile resource zones. The chapter comments on how resource regeneration processes in these areas were traditionally evolved; how they were marginalized under the changed demographic, institutional and technological circumstances; and how modern R&D can reorient and upgrade these processes. The role of modern science in strengthening the position of fragile resource zones in the context of intersystem linkages is emphasized. This calls for identification and harnessing of their niche, sharper focus on relevant secondary and tertiary sector activities besides the primary sector as being conventionally done, to help enhance the range and quality of options, which is the essence of sustainability.

Introduction

Despite significant growth and refinements in the definitions of the term "sustainability," its operationalization continues to be a major problem, that reduces its practical utility. One pragmatic way to handle this problem could be "to approach sustainability through unsustainability." This implies identification and analysis of indicators of unsustainability and their underlying processes and focused efforts to reverse them to restore sustainability to a system. The key

focus here is on the possible role of science and technology in arresting and reversing unsustainability trends. A broad methodological approach described as the unsustainability framework is presented. It is much easier to operationalize sustainability issues using this framework, as here one is dealing with actual situations, rather than projected or hypothesized future scenarios. We illustrate the situation with reference to fragile resource zones (e.g., dry tropical area or mountain/hill areas) where unsustainability already exists.

Unsustainability

The absence or rapid erosion of the conditions associated with sustainability would reflect the unsustainability of a system. The restoration of those sustainability conditions would make a system sustainable. What are these conditions? Based on the definitions of the term by ecologists, economists, environmentalists, development experts, etc., [Conway 1985, Tisdell 1987, Ruttan (In press), Markanday and Pearce 1988, Lynam and Herdt 1988, Graham-Tomasi 1991] sustainability would mean the ability of a system (e.g., dry land agriculture) to maintain or enhance its performance, i.e., output, services, (even through linkages with other systems), without damaging its own long-term production potential. Described in this way, sustainability is a dynamic (not static) phenomenon compatible with development; it focuses on the primacy of the natural resource base (a key integrative element of a production system) that cannot be stretched infinitely without degrading it; it recognizes the need for a system or system boundary, in the context of which the phenomenon becomes operative; and it focuses on the crucial importance of intersystem linkages (a product of prevailing socioeconomic arrangements) in the system's performance enhancement (Jodha 1991).

The loss of the above-mentioned ability of a system would mean emergence of unsustainability. Stated differently (and in keeping with the key elements of sustainability), unsustainability would imply the loss of prospects of intergenerational equity (due to a system's inability to maintain or enhance performance), or reduced range and quality of (production or welfare) options for a generation compared to the preceding ones.

Indicators of Unsustainability

The failures of a system to satisfy the sustainability conditions and consequent deteriorations in the situation are quite visible in several parts of fragile resource zones such as the dry tropical areas or mountain and hill areas (Jodha 1991). They are usually manifested in various changes in (1) the decisions or actions of the communities facing the reduced range and quality of options; and (2) the conditions of natural resources and production processes characterizing the systems (Jodha 1992a). The former would include: (1) the community (or the individual farmer) acceptance of inferior production or consumption options (e.g., consumption of conventionally disregarded low quality food, fodder, or fuel); (2) high degree of "desperation" in resource use and production practices leading to overextraction and degradation of the resource base (e.g., extending cropping

to submarginal locations, steep slopes); (3) acceptance of dependency as a normal basis of survival (e.g., closely linking the conduct of even normal production or consumption activities to availability of subsidy and charity); (4) loss of resilience or capacity to face shocks (e.g., inability to effectively face impacts of droughts without external relief).

The unsustainability trends relating to the resource base and production processes of a system are manifested in: (1) loss of "systemic integrity," implying disappearance or weakening of resource-regenerative, resource-protective mechanisms, intrasystem or intersystem linkages (e.g., decline in degree of diversification or flexibility); (2) ever increasing (biochemical, economic) subsidization of the production processes to maintain the same or even lower levels of performance (e.g., all forms of external subsidies to production, consumption activities); (3) marginalization, decline, and disappearance of the system or its components (due to loss of its identity; or its substitution by another system, e.g., land-extensive mixed farming systems losing their identity and efficacy in the changed context); and (4) loss of recoupment capacities (e.g., failure of postdrought recovery of rangelands).

In a more concrete form the above trends are manifested through persistent negative changes in different variables. These measurable negative changes (with varying degree of visibility), described as indicators of unsustainability, relate to: (1) resource base (e.g., decline of ground water table or reduced extent of agrobiodiversity); (2) resource productivity (e.g., persistent decline in crop yields as well as production of biomass); and (3) resource management or production practices (e.g., disappearance of various forms of diversification facilitating resource regeneration; disappearance of institutional arrangements to enforce resource conservation measures). This author has put together more than two dozen indicators for dry tropical areas and mountain areas to illustrate the situation (Jodha 1991). Some of them are summarized in Table 1.

If may be added that while some of the negative changes such as decline in yields and increased salinity of ground water and soil are clearly visible, others are concealed by human responses to negative changes (e.g., substitution of shallow rooted crops for deep rooted crops due to erosion of topsoil, or increased dependence on chemical fertilizers following the reduced regeneration of organic matter due to decline of farming-forestry-livestock linkages.) Furthermore, some of these changes are visible at the macrolevel while the others are visible only at the micro-level.

Finally, some indicators of unsustainability represent the process of negative change while others are negative consequences of the change. For instance, decline of diversification and resource-regenerative practices is a "process type" of indicator; the decline in productivity following these changes is a "consequence type" of indicator.

Application of Unsustainability Framework

The essence of "approaching sustainability through unsustainability" is to understand unsustainability indicators and their underlying processes, and to

Table 1. Negative changes as indicators of the unsustainability of agriculture (dry tropical areas)

Visibility of changes	Changes related to: ¹		
	Resource base	Production flows	Resource use/management practices
Directly visible changes	Various forms of resource degradation: Emergence of salinity coverage of fertile soil by shifting sands, vanishing top soils due to water/wind erosion; deepening of water tables; ground water salinization; emerging plant-lessness, reduced perennials, increase inferior annuals and thorny bushes; reduced per capita availability of productive resources.	Reduced total and per capita biomass availability; reduced average productivity of different crops, increased cropping on sub-marginal lands; reduced enterprise product recycling; higher dependence on inferior options, (e.g., harvesting/lopping premature trees), rising severity of successive drought-impacts; increased dependence on public relief, increased migration.	Changes in land-use pattern: cropping on sub-marginal lands; decline in common property resources; reduced diversity of agriculture (e.g., number of crops/enterprise and their inter-linkages); reduced feasibility and effectiveness of traditional adaptation strategies (e.g., rotations, intercropping biomass strategies).
Changes concealed by responses to negative changes	Substitution of cattle, camels, by small ruminants; increased emphasis on mechanization of cultivation and water lifting; reduced idling of land; large-scale reclamation (!) of wastelands; shift from local to external inputs (e.g., from manure to chemical fertilizers, wooden tyre to rubber tyres for bullock carts). ²	Higher coverage by public distribution system (food, inputs) and other anti-poverty programs; ² reduced reliance on self provisioning system and greater dependence on external market sources; changes in land-use pattern favoring grain production.	Discarding of minor crops, shift towards monocropping with standardization inputs/practices; increased land-use intensity; shift from two—oxen to one ox plough; tractorization ² ; practices; replacement of self-help systems by public support systems.
Development initiatives, etc.,—potentially negative changes ³	Research and development focus on: crop rather than resources; technique rather than user-perspective (e.g., method/species/inputs rather than group action for watershed/range development); resource upgrading ignoring its limitations (e.g., irrigation in impeded drainage areas); inducing high use intensity of erodible soils, and other resource extractive measures (e.g., tractorization).	Highly subsidized, narrowly focused production programs: focus on crops ignoring other land based activities; grain yield ignoring biomass; monocropping ignoring diversification; relief operations focused on people and livestock ignoring resource base, thus promoting high pressure on poor resource base.	Sectoral focus of research and development and other support systems ignoring flexibility and diversification needs; privatization of common property resources; extension of generalized external approaches to specific areas: disregard of folk knowledge in formal interventions; replacing local informal arrangements by rigid legal/administrative measures.

1. Most of the changes are interrelated and they could not fit into more than one block.
2. Since many changes could be for reasons other than unsustainability, a fuller understanding of the underlying circumstances of a change will be necessary.
3. Changes under this category differ from the ones under the above two categories, in the sense that they are yet to take place, and their potential emergence could be understood by examining the involved resource use practices in relation to specific area-resource characteristics.

reverse them. To attempt this there are certain essential steps to follow. They are: inventorize the unsustainability indicators; classify them; and assess them as real manifestations of emerging unsustainability. The next set of steps includes diagnosis of the factors and processes underlying the well-assessed indicators and designing strategies to manage the causes, factors, and process of unsustainability. This is elaborated below:

Operational Steps and Problems

Inventorizing the indicators. Identification and documentation (preferably with quantification) is a first step in using an unsustainability framework. For this a two-way approach may be used. A relatively easier method involves contrasting the situations in agroclimatically similar systems which differ in terms of the status of their resource base and production processes. The author had used this approach to examine the status of Common Property Resources (CPRs) in the dry tropical regions of India (Jodha 1986, 1992b). This involves identification of specific parameters for gathering details on their status in the contrasting situations. The other method involves a comparison of information on specific parameters in the same area at two reasonably separate points of time. The information in Table 1 is generated through such an approach. The key component of this approach is the determination of a benchmark with reference to which the present status of identified parameters could be assessed. Since the sustainability or unsustainability parameters have become a part of policy concern only recently, there are hardly any systematic records on these issues to offer a benchmark. Hence, the creation or recreation of a missing benchmark is the first methodological issue that needs the attention of researchers. In most cases "the bench mark" is determined by the availability of relevant (comparable) data. A few of the approaches to locate past data and benchmark period to identify unsustainability indicators may include the following:

- The periodical census records (though never collected with focus on sustainability issues) can help rebuild the past status of relevant parameters to examine the emergence of unsustainability.
- The descriptive account of some historical events (e.g., a major catastrophe such as an earthquake or a famine) can also provide data as they necessitated recording of information (even by nonstatistically oriented rules) on variables, which may also be the key parameters for judging unsustainability (Jodha 1975).
- Recording of oral history using recall methods is another important approach to assemble benchmark information. Identification of events of great socioeconomic significance (e.g., introduction of land reforms, that affect people directly) can facilitate easy recall (Jodha 1992b).
- The application of some scientific methods that can tell about the past status of a variable by looking at its present situation can be of a great help in generating benchmark information (e.g., methods applied for understanding vegetative succession, sediment deposition, hydrological shifts.)

- Yet another scientific method to identify emergence of unsustainability is comparison of old aerial photographic maps with the recent landsat imageries, as already attempted in some cases.

Classification of indicators. As a next step, classification of indicators of unsustainability is essential to facilitate their proper assessment and choice of interventions against unsustainability. At the first instance, the classification (Table 1) could be on the basis of: (1) context, i.e., negative trend relating to resource base, production performance, and resource use options; (2) visibility or invisibility of negative trends; (3) level of operation (or visibility) of the negative trend (e.g., at agroecosystem, watershed, village, or farm levels); (4) unsustainability indicators as a part of the process of change or as a consequence of a process.

Assessment of indicators. It is essential to separate the short-term decline from the negative trends that are manifestations of long-term unsustainability, and also to guide the choice of interventions against unsustainability.

The crucial problem in assessment of indicators is the choice of norms or yardsticks to separate a short-term decline from an unsustainability indicator. An important way to attempt this is to judge the indicators in terms of nonfulfillment of the conditions associated with sustainability. For instance, a system's inability to maintain or enhance the range and quality of options could be projected through an examination of the circumstances reflecting a community's choice of inferior options or degree of desperation or the status of the resource base and production processes reflecting loss of systemic integrity or levels of biochemical subsidization. In more concrete terms, besides the decline in production potential, the weakening of resource regenerative processes, and the loss of intersystem and intersectoral linkages could be the key criteria to differentiate the indicators from short-term changes.

Some unanswered questions. The understanding and documentation of the above changes is a huge task requiring multidisciplinary and multilocation efforts. Even after the availability of satisfactory information, the assessment of unsustainability indicators, leaves a number of critical questions unanswered. The first issue relates to the threshold levels or values of different variables showing decline, beyond which a situation could be treated as hopeless and therefore unsustainable. The second issue relates to a time frame, a duration for which a negative trend has to persist to be called an unsustainability indicator. The third issue relates to obsolescence or submersion of a system (i.e., a system or system component losing its viability or utility in its old form and through transformation or substitution becoming an integral but identityless part of a new sustainable system.)

Relatively definite and broadly acceptable answers to these questions need more conceptual and empirical work. Yet, on a tentative basis it may be argued that any change if it leads to decline in the range and quality of production, consumption, or welfare options for the community, should be considered an indicator of emerging unsustainability. Furthermore, it will be more objective and effective to judge any decline as an indicator of unsustainability if it has

its roots in the "process" type (rather than the consequence type) of negative change.

Operational Strategy

To be effective, any anti-unsustainability strategy should focus on the process type of unsustainability indicators. The latter is, reflected by changes in resource use and production practices that do not match the basic attributes of the resource base of a production system. One example is introduction of intensive annual cropping on submarginal lands in dry regions, suited to an extensive type of land-use (such as pasture or trees), which leads to below-average crop yields, frequent crop failures, and increased soil erosion. This sort of process begins with the disregard of the imperatives of resource characteristics by resource-use systems (Jodha 1990, 1991).

Assessment of this mismatch involves: (1) better understanding of the key attributes of the natural resource base and their imperatives in terms of appropriateness of its potential use system; (2) identification of the key attributes of current resource-use practices; and (3) juxtaposition of the two. This can help exhibit the degree of match or mismatch between the desirable and actual patterns of resource use. A mismatch causes loss of "systemic integrity" of a system, leading to its unsustainability (Lowrance et al. 1984).

Systemic Integrity

Considering the primacy of biophysical factors (Pezzey 1989) in the long-term sustainability of an agricultural system (especially in the fragile resource zones) and the leads offered by the ecological sciences (NRC 1986), the systemic integrity could be understood in terms of the patterns of energy and material flows and related interactions of biophysical and biochemical variables of a system; stability of these flows and interactions determining the system's stability and productivity (Jodha 1992b).

Stability is higher in the undisturbed natural state, but productivity (from the human point of view) is very low. Resource-use intensification involving disturbance and manipulation of biophysical resources raises the productivity but reduces the internal stability. However, in the long run the productivity improvements would also collapse unless a sufficient degree of the regenerative processes is maintained. Learning this through a process of trial and error, the traditional farm communities evolved several mechanisms to adapt their (relatively intensive) production systems to ecological requirements of their natural resource base (Jodha 1986, 1990, 1991), such as crop rotations, choice and combinations of cultivars, intercropping and mixed farming involving crops, livestock, and trees, ethno-engineering measures to conserve and regulate use of resource potential, and many institutional arrangements to support these measures. Through these measures they made fuller use of spatial and temporal diversity, harnessed the complementarities of annuals and perennials, captured synergic effects of crop centered and resource-centered measures, and raised productivity without resource degradation. These measures helped in stable production as well as

conservation and regeneration of resource potential (Reijntjes et al. 1992). Any productivity-driven intensification of resource use that obstructs the above regenerative processes would lead to loss of systemic integrity. This seems to have happened in the present-day agricultural production systems of fragile resource zones on both private and public accounts (Jodha 1986, 1991).

The fragile resource zones are characterized by relatively higher degrees of fragility and marginality of natural resource base which restrict the overall production opportunities and pay-offs, especially through land-intensive, input-intensive practices, and diversity of the resource base that restricts the scope for uniform pattern of land-use and closely links productivity and stability to the degree of diversification. These areas have their unique niches (a product of diversity) which remain underexploited because of their invisibility in the context of prime land production patterns (Foster 1992, Jodha 1991). The traditional farming practices in these regions showed greater sensitivity to these resource attributes. However, in the changed demographic, institutional, and technological contexts these practices have become less feasible. The modern agricultural research and development efforts have somehow by-passed the rationale of a traditional system while promoting inappropriate resource-use intensification without diversification.

This has led to the disuse of practices conducive to systemic integrity of dryland farming systems (production systems) as reflected through the decline of combinations of intensive-extensive types of land-uses, systems based on complementarities between annual and perennials, and between private and common property resource based enterprises, decline of local resource regeneration, recycling, and flexibility, and the institutional arrangements supporting these practices (Jodha 1991, 1992b).

Modern science, because of better knowledge and methods can help in diagnosis of processes necessary for organic integrity of the systems comprising resource regeneration, internal diversity and linkages, resilience and sustained performance of production without undue (chemical, biological) subsidization. Based on such diagnosis and application of new scientific knowledge, modern science can play an important role in reversing the unsustainability trends by promoting technologies that combine resource intensification (for high productivity) and resource extensification (for resource protection or conservation). This calls for appropriate emphasis on resource-centered and product-centered technologies tempered by the rationale of the traditional systems and guided by the systems perspectives (CGIAR 1992).

The above discussion on loss (and possible restoration) of systemic integrity of production systems in fragile resource zones mainly focuses on the proximate causes of unsustainability, such as reduced resource-use diversification causing loss of resource-regenerative mechanisms and inappropriate intensification discarding the crucial role of land extensive practices. However, reversal of these resource-degrading trends through new technologies may not last long unless the basic driving forces (as against the proximate causes) of unsustainability are taken care of. The following discussion elaborates on these issues.

Unsustainability: The Basic Driving Forces

The sustainability equation has both demand and supply dimensions which are well known but are rarely emphasized in equal terms. Most of the concerns in the global debate on sustainability are focused on the supply side of the problem. The emphasis on increased productivity, better resource management and/or conservation, and the technologies and institutional support to achieve them manifest the above focus (CGIAR 1992). Regarding the demand side, except some references to population factor, very little is mentioned, especially about the forces generated by market and state interventions that tend to disturb the demand-supply equation of sustainability. A proper understanding and management of factors operating on both demand and supply sides should be an integral part of the strategies for sustainable agriculture in fragile resource zones.

Supply Side

On the supply side of unsustainability of agriculture in fragile resource zones, the key factor is the inherent limitations of the natural resource base (which does not offer as many options as the prime land areas). Besides this constraint, there are important driving forces behind emerging unsustainability, rooted in the state policies and programs. This is reflected through technologies, support systems, and institutions, that are not designed in keeping with the limitations and potentialities of the fragile resources. Often they are impositions or extensions of interventions designed for prime land agriculture. Inappropriate intensification of resource use guided by short-term considerations and disregard of resource-regenerative processes and diversification measures as mentioned earlier are consequences of the policy and program interventions of the state (Jodha et al. 1992). Moreover, due to the application of resource allocation and performance assessment norms and yardsticks designed for prime lands to the fragile resource zones, the niches and areas of potential comparative advantage of fragile resource zones are bypassed. The insensitivity of R&D to the imperatives of fragile resources is also the product of the prevailing state policies and support mechanisms for agricultural research (Jodha et al. 1992).

Demand Side

The unsustainability indicators (both as a process and consequence) in the fragile resource zones emerge mainly because the pressure of demand on their resources far exceeds their productive capacities. This pressure also reduces the relevance and feasibility of slow and time consuming resource regenerative (productivity-protecting) traditional practices. There are three major driving forces responsible for the generation of this pressure on resources.

The most important source of increased pressure is the rapid population growth due to the "health revolution" that reduced the death rates without controlling birth rates even in the poorest of fragile resource zones [(Anderson and Jodha (In press)]. This was not accompanied by substantial resource upgradation. The consequent reduced production and consumption possibilities

on per capita basis initiated the process whereby an increasing number of people had to eke out their living from increasingly smaller and inferior (i.e., degraded or submarginal) land resources. This has led to a vicious circle of poverty resource degradation through inappropriate land-use intensification.

The market also played an important role in accentuating the demand pressure on fragile resources. The improved physical and market integration of historically, relatively isolated fragile resource zones led to a selective overextraction of resources in these zones. Timber, coarse grains, oilseeds, livestock and other products in demand in the prime land areas and urban centers led to the degree of resource use intensification that is quite incompatible with the carrying capacity of the fragile resource zones. Thus, the profitability driven resource extraction complemented the poverty driven resource degradation. More important, the interlinkages created by market integration did not sufficiently enhance the range of options for these areas due to generally unequal terms of exchange and focus on primary (extraction) activities rather than the secondary and tertiary sector activities within fragile resource areas (Jodha 1992a).

The State's role in demand accentuation took several direct or indirect forms. First, the lopsided welfare and relief strategies while contributing to increased population pressure did not address the problems of resource upgradation and carrying capacity. Second, concerned with the needs of the increasing population, local production programs (based on the experience of primelands) encouraged inappropriate resource-use intensification and input-intensive, external input-based technologies. They remained indifferent to diversification and resource stability needs. Third, despite power and authority, the state could not regulate the pressure of external demand on fragile resource zones or ensure equitable terms of exchange for these areas (Jodha 1991, Jodha et al. 1992).

An important joint product (impact) of the three factors, namely population, market, and state intervention is manifested by changes in the qualitative attributes of the population. This is reflected through rapid emergence of individualistic tendencies and growing indifference towards social sanctions and collective efforts designed for protection and conservation of the natural resource base (Jodha 1992a, 1992b).

Agricultural Research and Development and Basic Driving Forces

The management of the basic driving forces responsible for sustainability is the job of policy makers and planners. Science and technology on its own, may not help much. However, to the extent that several policy interventions are induced by the opportunities projected by technological breakthrough and the given institutional and management interventions acquire strength and effectiveness from appropriate technological support, there is a definite role for agricultural research and development to help reverse unsustainability trends by management of the basic driving forces mentioned above [(CGIAR 1992, Anderson (In press))].

To facilitate the management of the supply-side forces causing unsustainability, the agricultural research and development will have to reorient itself. Firstly, greater focus on fragile resource upgrading is essential. Secondly, high priority will have to be accorded to resource-regenerative production technologies

directed to the simultaneous satisfaction of productivity and resource conservation needs. Thirdly, it will have to concentrate on identification, development and harnessing of niche (products or activities with comparative advantage) of the fragile resource zones. The former two are focused primarily on biomass and productivity of the system. The last one is directed towards the sustainability requirements of the fragile resource zones in a dynamic and open system, where, to be sustainable, agriculture will have to acquire an agrobusiness orientation (Jodha 1992a).

To facilitate management of demand side forces, agricultural technologies can play a crucial role in reducing the pressure on land and cutting the vicious circle of poverty and resource degradation. This implies an approach of option enhancement in rural areas without raising (or rather, by reducing) pressure on land (CGIAR 1992). The key to this approach lies in the identification and harnessing of niche or comparative advantage of fragile resource zones. Harnessing of niche too should not be confined to "primary sector" (i.e., agricultural production). It needs to be extended to secondary (e.g., processing) and tertiary (e.g., marketing and other services) activities. Such value-adding activities and off-farm employment opportunities inherent in this process would not only reduce the resource-degrading pressure on land but also (1) enhance the quality and range of options, (2) strengthen the level of diversification involving market responsive activities with high pay offs, and (3) facilitate inter-system linkage—the important precondition associated with sustainability [Jodha 1986, 1992a, Anderson and Jodha (In press)].

However, this would call for extending the scope of agricultural research and development to product processing and related activities, which can enhance competitiveness of a fragile resource products vis-a-vis prime land products. Given the equitable terms of trade and necessary infrastructural support, the expanded scope for agricultural research and development can go a long way in restoring sustainability to agriculture in the fragile resource zone.

The public policies in the past have bypassed these possibilities with high sustainability potential, mainly because of their skewed perspectives on agricultural development in fragile resource zones, as shaped by the experiences of primeland agriculture. The lack of alternative perspectives helped in the persistence of rather blind approaches to problem solving and prospects of fragile resource agriculture. Reoriented research and development can redress the situation.

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Soil Resource Information for Evaluating Sustainability

S.W. Buol

Abstract

Soil resource is evaluated according to its ability, with feasible management, to provide for the production of human digestible food. The four roles of the soil that must be sustained are: (1) a capability of holding higher forms of plant life in a position to intercept and utilize the radiation from the sun; (2) temperature dynamics at the site sufficient to provide time for the food plant to produce biomass and/or grain; (3) moisture to sustain growth for sufficient time for the food plants to produce biomass and/or grain; and (4) a supply of those elements that are necessary components of human food. Each of these soil functions can be augmented by proper management. Unaided by proper management, the soil resource is not able to provide for present human needs. Therefore, an evaluation of sustainability must consider not only soil properties but also the sustainability of management inputs into the soil resource. Managements augmentation of physical support, temperature and moisture, is vital in specific instances but the replenishment of those elements derived only from earth minerals becomes necessary in all soils. Techniques to increase the availability of certain elements are only temporary measures in all soils but perhaps desirable in some situations. Chemical augmentation of the soil resource to achieve sustainable production needs to achieve improved efficiency by better orchestrating the form of the amendment, the specific requirements of the various crops and the specific properties and dynamics of individual soils in situ. Complete conversion of added fertility into digestible food with minimum land-use is a desirable objective for research and agricultural sustainability.

The soil resource can be evaluated with respect to its ability to sustain human food needs only if the ability of people to provide necessary management input is also evaluated. Some 15 years ago Buringh and van Heemst (1977) concluded that a labor-oriented (without modern agricultural technology) agriculture could only feed 85% of the then present world population. Several optimistic assumptions of good crop rotations, manure use from animal grazing land unfit for cultivation and animal traction were included in this estimate which also anticipated deforestation of all forested land of suitable temperature.

Evaluation of Soils

To evaluate the sustainability of food production on soil based agriculture, the role of soil can be divided into four functions.

The soil resource must physically support plants thus enabling them to intercept radiation and photosynthesize. This is seldom a limitation. Exceptions do occur if friable soil is thin in upland areas or if soils subject to flooding have crop plants leveled by floodwaters. Mechanical intervention by brace wires or water control structures are the management techniques required.

The soil resource must provide a suitable continuous length of time when the temperature is adequate for growing the desirable food crop. This is lacking in many areas of the world. This limitation is rather accurately known from long-term weather data from which crop requirements can be geographically plotted and measured. It is feasible to heat or cool small areas to provide for production of high value crops and perhaps more often high value ornamentals rather than food crops.

The soil resource must supply adequate amounts of water for a certain number of consecutive days while the temperature is adequate for crop growth. Also, there must not be too much water so as to produce anaerobic conditions for certain types of crops. In this respect, trial and error has taught farmers rather sophisticated methods of irrigation and drainage. More recently, modern agricultural science and massive engineering infrastructure has aided the natural soil resource in its water supply function. Therefore, evaluation of water must not only plot climatic data to evaluate the soil resource but also groundwater reserves, runoff and reservoir reserves as coupled with the energy supply for pumping and distribution. Similar calculations are required for soil resources that can be improved by drainage and flood protection.

As water is often in short supply, evaluating its sustainability must often consider not only the physical supply but also its economic value for uses other than irrigated agriculture. Most often the alternative uses are to service relatively affluent urban life styles. Perhaps minor on a world scale, but environmental concerns for wetlands threaten sustainability of some poorly drained soils for agricultural production.

Soil as a Resource for Nutrients

The soil resource must supply certain chemical elements for the synthesis of human food. While the roles of physical support, temperature and moisture are relatively easily seen by the layman and the scientist, the vital role of soil as a source of chemical input into the food chain appears to be poorly understood. Many misconceptions exist regarding the role of soil in providing the different elements needed in human food. If a soil is classified as being chemically infertile, then the management augmentation takes many forms around the world. Often the practice is to "rest" the soil. This is a viable technique if the fertility limitation is nitrogen. Nitrogen comes from the air and by waiting for more nitrogen containing rainfall or the action of nitrogen fixing microbes, the supply of plant available nitrogen in the soil is almost certain to increase. Legumes, as a green-manure crop, can greatly enhance the rate of nitrogen buildup in the soil between food crops.

Infertility of the soil resource is unfortunately not limited to a low content of nitrogen. The mineral containing nutrients such as phosphorus, potassium,

calcium, magnesium, and other minor elements almost entirely originate from minerals in the lithosphere. Traces of these elements do exist in the air but the quantities in the air are so low as to be almost insignificant, the exception being sulfur. Thus, this role of the soil resource in supplying those chemical elements that originate in the geologic crust of the earth is vital in an evaluation of food production sustainability.

To evaluate the magnitude of the mineral nutrient requirement, a few crop requirements have been assembled in Table 1. Yield levels presented represent relatively high production. However, they reasonably represent the amount of each element removed by the harvest of each crop. Table 2 is a very incomplete representation of the total content of mineral nutrient elements in some major soils in tropical areas. The elemental contents have been calculated on an 18 cm thickness of soil per hectare using reasonable but not measured bulk density values. A quick comparison of the four elements presented points out that if only total amounts are considered, phosphorus will clearly be the most limiting. A crude estimation of 20 kg P per crop removal could be expected to remove all of the P in the top 18 cm of the soils in Table 2 in 10 to 35 crops. If one considers that root depth may extend up to 180 cm, 10 times the surface plow layer thickness, the number of crops would not be 10 times greater because subsoil contents in every case are lower than surface values. Lower subsurface contents of nutrients are commonly observed in soils of humid areas and attributed to surface enrichment by biocycling under natural or no-harvest conditions.

Certainly, total elemental analysis has been discarded by Soil Science some 50 years ago as a method of evaluating crop production. However, this brief look at total analysis should point out that technology developed for the sole purpose of making more of the total P in the soil available has limited value and is not a solution to sustainable crop productivity on much of the soil resource.

Table 1. Representative elemental removal in various food crops¹

Crop	Yield ² (t ha ⁻¹)	Element (kg ha ⁻¹)			
		P	K	Ca	Mg
Corn (grain)	7.0	20	37	14	11
Rice (grain)	8.0	32	20	4	1
Wheat (grain)	5.0	22	20	2.5	8.0
Sorghum (grain)	8.0	10	27	16.0	9.6
Cassava (roots)	16.0	21	100	41	21
Potatoes (roots)	22.0	20	166	40	26
Bananas (bunches)	10.0	2	54	23	30

1. Source: Sanchez (1976).

2. Yields of grain on dry weight; roots and bananas at 15–20% moisture.

Table 2. Example of total and available amounts of mineral supplied nutrient elements per 18 cm layer of various kinds of soil¹

Soil	Depth (cm)	P	K	Ca	Mg
(kg ha ⁻¹ 18 cm)					
Paleustalf ²	0-18	700 (16.8) ⁴	1700 (473) ⁴	-(3 720) ⁴	1700 (927) ⁴
	42-60	320 (3.6)	1800 (237)	-(1 400)	1400 (195)
Ustipsamment ²	0-18	200 (27.8)	700 (321)	-(360)	300 (98)
	42-60	120 (3.4)	500 (78)	-(80)	200 (24)
Haplustoll ²	0-18	540 (10.4)	8100 (156)	-(31 200)	1600 (366)
	42-60	200 (2.8)	2700 (78)	-(11 700)	700 (73)
Haplustox ³	0-18	246 (4)	-(78)	-(160)	-(98)
	42-60	212 (2)	-(23)	-(40)	-(24)

1. Assumed bulk density of 1 gm cm⁻³ (2 M kg ha⁻¹ 18 cm).

2. Ibadan, Nigeria – in Moorman et al. (1981).

3. Brazil — SCS-SMSS 1986. Tour Guide 8th International Soil Classification Workshop (1986).

4. Values in parentheses are available or exchangeable amounts.

Certainly, total elemental analysis has been discarded by Soil Science some 50 years ago as a method of evaluating crop production. However, this brief look at total analysis should point out that technology developed for the sole purpose of making more of the total P in the soil available has limited value and is not a solution to sustainable crop productivity on much of the soil resource.

Nutrient Management in Soils

Agricultural practices of adding mineral nutrients to a soil at a crop site have taken many forms. Perhaps the most common is the long rotation method best described as slash and burn cultivation. In the many variations of this practice slow growing vegetation is allowed to grow, unharvested, for several years and then the nutrients are converted into a plant available form by fire. This practice essentially “mines” the total elemental reservoirs in that particular soil and although I have seen no data, it seems reasonable to conclude that the number of slash and burn cycles cannot include more harvests than that dictated by the total elemental content of the root zone.

Use of animal manures to augment mineral nutrition at a selected crop site is also a common practice. However, such practices rely on the animal ingesting nutrients via vegetation harvest at another site and concentrating those nutrients on the selected site. Clearly, this practice can only succeed in a global sense if all the refuse from the cities of the world are recycled to crop sites. At present the high cost of transporting these very diluted nutrient sources and the extreme concentration of food consumption in cities limit adoption.

Perhaps the most common practice in replacing soil mineral derived nutrients at a crop growing site is the importation of concentrated, highly soluble forms of the elements in the form of mineral fertilizers. Adoption of soluble mineral fertilizers depends upon many factors not the least of which is the natural fertility of individual kinds of soil. Table 3 points out that in the US, mineral fertilizer application started much earlier on infertile Ultisols than on Mollisols. However, under present conditions the amount of fertilizer applied essentially matches the amount of the harvest, regardless of initial native soil fertility.

Table 3. Historical comparison of average farmer fertilizer application rates on an Ultisol and a Mollisol in the USA¹

Year		Kandiudult (N.C.)		Argiudoll (Iowa)	
		1925	1983	1919	1979
Yield corn (kg ha ⁻¹)		2 038	6 899	2 634	8 153
Fertilizer (kg ha ⁻¹)					
Rate	N	36–53	134–177	0	168–202
	P ₂ O ₅	7–13	45	0	78–123
	K ₂ O	7–13	90	0	90–134

1. Source: Buol et al. (1990).

Clearly the soil resource, in toto, has to have help in supplying those nutrients of mineral origin, especially P and ultimately K, Ca, and Mg if food is going to be harvested and consumed at another site. Whereas temperature, water, and nitrogen contents in the soil are restored by atmospheric sources, no such nonmineral source is available for the mineral derived elements. Technologies that only allow crop plants to obtain larger portions, so called available forms, of these elements are at best delaying actions. Deep rooting to enlarge the volume of soil from which these elements can be extracted only offers a similar scenario.

Natural Nutrient Endowments and Sustainability

There are wide differences in the natural endowment of individual kinds of soil within the soil resource. Although for true infinite sustainability, augmentation of the chemical supply in soils is needed for all cropped sites, practices that enhance the availability of the most limiting nutrients can help for a period of time in some kinds of soils only. These soils need to be identified, quantified and this information provided to those making decisions about implementation of agricultural systems. Total elemental composition data, especially for the elements necessary for human food, of soils is scarce. Present data sets seldom contain such total elemental values. Further, solubility rates or other transformation rates, that are responsible for converting unavailable forms into plant available forms of essential elements, are not known except perhaps under

controlled laboratory conditions. We should attempt to quantify these rates in situ under various ambient climatic conditions and with various mineral mixtures.

Accepting the requirement of replacing the elements exported from the soil in food crop harvest is necessary for sustainable food production, two questions need to be addressed. Firstly, what is the total mineral reserve of such needed elements as P and K? I cannot cite a source, but present proven reserves of P, subject to present technology are estimated at 150 years. Although this probably is an underestimate of actual reserves, there is the ultimate goal of complete recycling and improved technology is needed toward reaching such a goal.

The second most often asked question regarding chemical augmentation of the soil is how to avoid contamination. Most contamination events occur when rates, forms, or timing of application are inappropriate for a given site. The ideal situation would be 100% conversion of added food essential elements into an eatable product. At present, we have not achieved this and further research in the field is needed. Such research should orchestrate not only soil specific variations in mineralogy, texture, landscape position, water and temperature dynamics but also the physiological requirement of individual cultivars. New high yielding germplasm in use today and certain to be developed in the future usually requires higher concentrations of nutrients in available forms during growth than lower yielding cultivars. Augmenting the soil resource with those elements needed by food crop plants in such a way that the crop plant can fully utilize the energy and water available, taking full advantage of its genetic potential, leads to higher yields per unit area. Policies that encourage more intensive, sustainable food production on land not subject to degradation would reduce further exploitation of fragile soils for crop production.

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Modeling Climate for Evaluating Sustainability

E.T. Kanemasu and G.F. Arkin

Abstract

Climate models derived from climatological data have demonstrated their utility for strategic planning and tactical, site specific management decisions and mitigation practices. Not only are sustainable agroecosystems affected by climate, but they in turn affect climate. Sustainable agroecosystems must be in harmony with nature, implying sustainability at all temporal and spatial hierarchical levels.

Global climate models (GCMs) prophesy change. Although there is no agreement on the magnitude, rate, and in some quarters, direction of the change, there is a general consensus that change is imminent. Adapting to the prophesied change is dependant upon the credibility of the prognostication and the vulnerability or sensitivity of the agroecosystem concerned.

Managing or adapting agroecosystems to global change is complex, requiring a diversified portfolio of research and educational technological tools. Climate probabilities and weather generators enable more efficient site specific, tactical planning and mitigation decision making. The need for climate modeling to help manage sustainable agroecosystems is heightened in a changing climate.

Global climate models require considerable improvement before they can be considered reliable. Climate probability and weather generator models suffer from data inadequacy problems. Regardless of this, agricultural researchers, recognizing the importance of climate and sustainable agroecosystems, especially in stressed environments, must be earnest in their attention to advancing climate modeling technology. Agricultural researchers have a comparative advantage for doing this work because of their infrastructure, and history of developing technologies for adapting to changing environments.

What is now needed are ways to link terrestrial biophysical models with GCMs. The new generation phytotrons, called Envirotrons, are needed to improve our biophysical models and speed their development. Also, coordination of global automated agricultural and environmental monitoring networks and associated databases is needed. And although probabilities help, farmers need and want forecasts and, therefore, work in this direction is needed. The teaching and demonstration of climate model use has been inadequate and so farmers, educators and policy makers must be taught to use climate models to sustain agroecosystems.

Climate modeling implies the ability to predict future climate. Climate is the long-term pattern of weather events versus that of weather, which is the description of short-term (e.g., 2 weeks) meteorological events. The most used tool for predicting future climates is the general circulation model (GCM). The GCMs are physically based and out of necessity simplified with numerous parameterizations of small scale processes. They, however, play a key role in evaluating, developing and managing sustainable agroecosystems.

Direct atmospheric measurements of CO₂ and other radiative-absorbing gases (CO₂, CH₄, N₂O, O₃, CFC, water vapor) indicate that these atmospheric constituents are increasing due to human induced activities (Figures 1 and 2). The most cited anthropogenic examples are the burning of fossil fuels and deforestation of the tropical forests which have caused a 26% increase in CO₂ since the industrial revolution, according to the Intergovernmental Panel on Climate Change (IPCC). The greenhouse effect is a physically-based phenomenon. If the earth did not have its atmosphere, the earth's surface would be about 33°C cooler.

The earth system is a very complex and interactive system of biosphere, hydrosphere, cryosphere, and atmosphere. Modeling one of the components cannot be done without considering the others. To predict future climates with higher concentrations of greenhouse gases, the GCMs must be tested on the observed climate. The validation studies indicate that GCMs illustrate good capability in producing the large-scale global distribution of pressure, temperature, wind and precipitation. However, large discrepancies appear at the regional scale.

There are many GCMs available. While they are similar in many respects, each of them have their strengths and weaknesses (e.g., parameterization of clouds, effect of aerosols and ocean coupling). In general, when the GCMs were run with double the atmospheric CO₂ concentrations, the following equilibrium changes in climate were observed.

- The lower atmosphere and surface becomes warm;
- The stratosphere cools;
- The temperature of the earth's surface increases between 1.5 to 4.5°C;
- Surface warming for high latitudes is greater than the global average in winter;
- The global average precipitation increases and is greater at high latitudes;
- The area of sea-ice and seasonal snow-cover diminishes.

To date, the interest in climate change has been primarily as a research program and a policy issue. In agriculture, we are concerned with food and fiber production. How will a higher percentage of CO₂ in the world hurt or help agricultural production? There are very few, if any, simulation models which can be used to accurately predict crop growth and yield in future climates. Currently available crop models need to respond better to CO₂ (i.e., include CO₂ and temperature interactions, insects and weeds effects, etc.). Because plants respond quickly to weather and photoperiod, future weather events must be accurately predicted, especially in marginal production regions of the world. Further research is required on both fronts—(1) crop models that respond

appropriately to future climates, and (2) GCM to provide accurate regional climate projections.

Issues, including evaluating sustainable agroecosystems that are related to climate change and global warming are clouded by (1) predictions challenged by some members of the scientific community; (2) multidecadal predictions which are perceived with low priority; (3) media hype and sensationalism, e.g., sea level changes; and (4) the view that agriculture has survived larger changes in climates than predicted by GCMs.

While agricultural researchers have little or no comparative advantage in climate modeling, they are well-prepared to study land surface and atmosphere interactions. Improved understanding of the feedbacks between the terrestrial surface and the atmosphere will enhance GCM predictions. The state and condition of the surface are important to the energetics of the atmosphere. Biophysical issues related to climate change include:

- indirect and direct effects of CO₂ on plant processes such as photosynthesis, respiration, phenology, and transpiration and their interaction with temperature;
- changes in plant species composition (e.g., C₃ vs. C₄);
- changes in pests;
- changes in albedo, hydrology and land-use;
- changes in carbon allocation (e.g., root to shoot ratio); and
- changes in residue quality.

It is clear that these issues are spatially and temporally dependent. Therefore, it will be important to understand the scaling problem associated with these issues.

Agriculture will play an important role in mitigation and adaptation to climate change. Management decisions and planning strategies will require historical climate data from representative and important ecosystems. The value of extrapolating these data temporally and spatially is questioned because of the quality of the data, density and representativeness of the network, and standardization of measurements and instruments used. The development of sustainable agroecosystems will be determined to a large degree by modeling both biological and physical systems on many spatial and temporal scales. Shortcomings acknowledged, climate modeling should have the following roles in sustainable resource utilization:

- GCMs generate coarse grid outcomes for global change strategic planning.
- GCMs generate longer outlook outcomes.
- Climate models generate site-specific probabilities that can be aggregated from the field to the watershed, the region and larger areas.
- Climate models generate more representative (finer grid) shorter outlook outcomes.

What is needed:

- Earnest reckoning with the state-of-technology and pace of scientific discovery as well as technology development and implementation.
- Commitment to adequate automated agricultural and environmental monitoring networks.

- Develop, then demonstrate, the credibility (accuracy and precision) of climate models to garner public trust in model generated outcomes.
- An intuitive belief that all sustainable agroecosystems are weather and climate driven.

Cropping Systems Management

I.C. Mahapatra

Abstract

The existing and promising cropping systems, their sustainability indicators, new and improved technology, management of resources to ensure sustainability and research and development needs of emerging cropping/farming systems in arid, semi-arid humid, subhumid and coastal ecosystems are discussed in this chapter.

The sustainable cropping systems in different ecosystems, both for rainfed and irrigated conditions, have been identified as under:

In the arid ecosystems, the dominant cropping systems in rainfed conditions are pearl millet-fallow, pulse-fallow, fallow-wheat and fallow-chickpea and in irrigated conditions are pearl millet-mustard, pearl millet-chickpea and pearl millet-wheat. The emerging cropping systems are cowpea-wheat and pearl millet-wheat-green gram. The research issues in this region are mainly on tillage and crop establishment.

In the semi-arid ecosystem, the promising cropping systems are rice-wheat, rice-mustard, rice-gram in the lowlands, while in the uplands sorghum-mustard, pearl millet-wheat and groundnut-wheat are the important cropping systems. The most sustainable cropping systems have been rice-wheat production system in the irrigated areas of the ecosystem. The research issues are on salinization of many areas due to intensive use of irrigation water. The deficiency of micronutrients is another domain in which work needs to be undertaken.

The subhumid ecosystem is predominated with the cropping systems of rice-wheat, rice-wheat-sugarcane, rice-gram, rice-lentil and rice-mustard in the lowlands, while in the uplands, maize-wheat pulse-wheat and sorghum-potato-fodder are the promising ones. Rice-wheat is a dominant production system in the Indo-Gangetic plain, but then, the research issues are on sustaining its productivity at high level which would require balanced nutrient application and improved crop and water management practices. To maximize the output of the system, more intensive on-farm analysis in production constraints and development of suitable farm technology is necessary.

In the humid-ecosystem, jute-rice-rice is a dominant system. Amongst the emerging cropping systems, green manure-rice-wheat has been quite promising. In addition to this, several cropping systems like rice-rice, jute-rice and rice-rice-oats (fodder) have come up in the lowlands. In the uplands, maize-green gram/black gram-rapeseed and mung bean-rapeseed have been the established systems. Though rice-rice system is an important production system, the productivity is low. Hence, the research issues should be on water and nutrient management and good physical condition of the soil to enhance the productivity.

Under the coastal ecosystem, two continuous rice crops are common in most of the areas. But then, the new emerging cropping systems have been rice-rice-rice, rice-finger millet-rice, rice-green legume-rice.

Inclusion of short duration legumes such as groundnut or green manure increases the cropping intensity. Application of only N-P-K is not adequate to sustain the high productivity of a rice-rice system. Deficiency of secondary and micronutrient is the primary cause of yield decline. Balanced application of secondary nutrients and micronutrients is essential for sustaining high productivity of a rice-rice system.

Rice cultivation is also moving into areas of problematic soils with salinity, alkali, strong acidity, severe nutrient deficiencies or unknown toxicities. With the increase in the intensity of cropping in the rice based cropping system and continuous removal of plant nutrients, soil fertility management is of paramount importance. In areas where rice-rice system is predominant, the use of urea super granules has been quite effective.

It has been observed that in an integrated nutrient management system, 75% of recommended N-P-K through fertilizer plus 25% N through organic manure (as Azolla) during rainy season supplemented by 75% N-P-K through fertilizer during post-rainy season performed the best in rice-rice system under the conditions prevailing in Orissa State, India.

On-farm studies with respect to production constraints like fertilizer have revealed that 25%, cut over the normal recommendation resulted in 14% to 27% of sacrifice in yields in rice under the coastal ecosystem. The reduction in plant population from 100% to 75% of recommended level showed a decline of only 5% yields. Again arhar + groundnut has been a promising intercrop in the tribal pockets of Orissa State (Mayurbhanj district), India.

Energetic approach in cropping systems is comparatively new and research efforts in this field gathered momentum due to global fossil fuel crisis and rapidly increasing demand for food. Such studies solely focus on acceleration of the pace of crop production on one hand and efficient energy utilization particularly in intensive cropping system on the other. Plants use solar energy to synthesize food through photosynthesis. Primary photosynthetic activity of earth stands at 15.2×10^{11} t year⁻¹. Current energy consumption of 1130×10^{17} kcal year⁻¹ could be met up to 77% by the potential energy from the biomass.

Energy relationships in cropping systems vary and constitute a dependent function of the total energy content of the crops knitted in a sequence, yield level, nature of power used, soil type, energy input and agroclimate. Efforts should be made to include legumes, oilseeds and root crops in the systems for favorable monitoring of energy relationships, as far as possible. Further, the share of nonrenewable energy dominates, even at present low level of total energy inputs, in crop production systems in developing countries. It calls for the identification and exploration of renewable sources of energy and methods to augment energy use efficiency of various inputs including animate energy.

Hence, the thrust areas of research should be on efficient resource management for small and marginal farmers and bridging the gap between the current and potential farm yields with conventional technology. Added to this, the integration of farm enterprises such as crop, livestock, fishery,

agroforestry, apiary, mushroom and aquaculture to optimize farm resource use is necessary.

It is evident that there is no option but to see that each unit of available natural as well as man made production resources are put to the best possible use. Intensive research efforts are needed to raise the use efficiency of all the major crop production inputs.

Introduction

As we march into the 21st Century, international attention will have to be focused on issues relating to agricultural development. There will be an increased interest in all aspects of converting the concept of sustainability into an operational reality. In agriculture, the concept of sustainability has so far been considered predominant at the level of economics. Through a sustainable agricultural production system, we can promote and protect national and global food security. It must be clearly understood that no single indicator is likely to ensure fully the sustainability of agriculture. It calls for attention on issues like soil degradation, salinity, acidity, rise in water table or biomass yields per hectare for long-term measures.

The productivity of Indian agriculture increased dramatically during the late sixties and early seventies. The magnificent progress in cereal production came through the use of semi-dwarf rice and wheat cultivars responsive to fertilizer under irrigated condition. Oilseed production increased significantly during the recent years. But then, this increase in crop production is not commensurate with the demands of population explosion. India's population in the last half century grew almost in geometric progression. The food production grew over 300% from 51 million tons in 1951 to 178.5 million tons in 1990.

Constraints in sustainable growth in agriculture production in India into the 21st century will be posed primarily by a degraded resource base, need for high inputs, high energy use and environmental degradation. If these constraints are ameliorated in future, the pace of food production may continue to match the population growth.

The goal of any cropping system research is to develop an efficient cropping system that maximizes the resource use, i.e., soil, water, solar radiation, vegetation and human beings and animals. This can be done through identification of crop adaptation zones for maximum productivity, based on soil, climate and management strategy. India's geographical area has been mainly divided into ecosystems like arid, semi-arid, subhumid, humid and coastal.

Hence, attempts have been made in this chapter to identify suitable and efficient cropping systems for various agroecological zones and strategies for their sustainability. In the process, the understanding of a farmer's traditional wisdom and analysis of past and present farming systems under normal and exceptional stress is also essential for a decision making process.

Added to this, the research thrust and strategy for the remaining years of this decade and early part of the next century are discussed in this chapter.

Rationale

The experiments that were conducted under different ecosystems pertaining to cropping systems management under the All India Coordinated Agronomic Research Projects and Cropping Systems Research Project were collated together for appropriate assessment of their sustainability and performance. All the experiments conducted were statistically analyzed. The results are discussed below:

Results and Discussion

Sustainability in Arid-ecosystem

In the arid regions, due to the constraints of water, normally a single crop is grown. It could be a single crop of either a pearl millet or a pulse or even a single crop of mustard or chickpea. But, there are also situations, where pearl millet-wheat cropping system is possible. Amongst the new emerging cropping systems of the region cowpea-wheat, pearl millet-wheat-green gram are made possible (Table 1). But the research issues are mainly on tillage and crop establishment.

The productivity of rainfed crops is limited by a shortage of water and poor inherent fertility. Efficient crop production calls for in situ moisture conservation and its effective utilization through suitable crops and cropping systems based on rainfall and soil water retentivity along with optimum fertilizer use, its time and method of application. The recent results of the Dryland Research Project suggest a revision of the current recommendation. In high moisture storage soils, higher quantities of N would be more meaningfully utilized than the low moisture storage soils. With wheat crop, drilling the whole of nitrogen at sowing was better than broadcasting.

Semi-arid Ecosystem

In the lowland situations of this region, rice-wheat, rice-mustard, rice-gram are the cropping systems followed. In the uplands, sorghum-mustard, pearl millet-wheat and groundnut-wheat are the important cropping systems. But the coverage has been mostly on rice-wheat system which has been found to be quite sustainable and productive (Table 1). The yields can be stabilized even better, if the problems of salinity are sorted out. Of late the problem of micronutrient deficiency is creeping up and therefore, needs detailed studies.

Sub-humid Ecosystem

The prevalent cropping systems in lowland situations are rice-wheat, rice-wheat-sugarcane, rice-gram, rice-lentil and rice-mustard (Table 2). The uplands are predominated by maize-wheat, pulse-wheat and sorghum-potato-fodder. While examining the sustainability, it may be mentioned that rice-wheat is the most dominant production system in the Indo-Gangetic plain. Apart from sustainability, the productivity with higher inputs may give still more added dividends. In this

Table 1. Promising cropping systems of arid and semi-arid ecosystem

Center	Crop sequence			Grain yield (kg ha ⁻¹)		
	Rainy	Postrainy	Summer	Rainy	Postrainy	Summer
<i>Arid ecosystem</i>						
<i>S.K. Nagar</i>						
Rainfed	Pearl millet	Fallow	—	2390	—	—
Rainfed	Greengram	Fallow	—	792	—	—
Rainfed	Fallow	Chickpea	—	—	1584	—
Irrigated	Pearl millet	Wheat	—	1825	1894	—
<i>Hissar</i>						
Irrigated	Pearl millet	Mustard	—	1129	1521	—
Rainfed	Fallow	Wheat	—	—	3715	—
Irrigated	Pearl millet	Chickpea	—	2090	1700	—
Emerging cropping system	Cowpea	Wheat	—	842	1342	—
<i>Hanumangarh</i>						
Emerging cropping system	Pearl millet	Wheat	Greengram	895	2386	49
<i>Semi-arid ecosystem</i>						
<i>Rudrur</i>						
Lowland	Rice	Mustard	—	3183	437	—
Lowland	Rice	Gram	—	3126	1030	—
<i>Kanpur</i>						
Lowland	Rice	Wheat	—	3575	3494	—
<i>Bichpuri</i>						
Upland	Pearl millet	Wheat	—	2118	3116	—
Upland	Groundnut	Wheat	—	1581	3742	—
<i>Akola</i>						
Upland	Sorghum	Mustard	—	5298	437	—

context, judicious use of balanced nutrients, needs detailed investigation. With the hike in water rates, economic use of water is of paramount importance. These studies need to be done under on-farm situations for the appropriate generation of new technology.

Humid Ecosystem

The dominant cropping systems are jute-rice-rice and green manure-rice-wheat. The other double cropping systems are rice-rice and jute-rice (Table 2). Of late

Table 2. Promising cropping systems of subhumid, humid and coastal ecosystem

Center-3	Crop sequence			Grain yield (kg ha ⁻¹)		
	Rainy	Postrainy	Summer	Rainy	Postrainy	Summer
<i>Subhumid ecosystem</i>						
<i>Varanasi</i>						
Lowland	Rice	Wheat	—	4.0	5.3	—
Lowland	Rice	Gram	—	4.3	0.6	—
Lowland	Rice	Mustard	—	4.5	1.0	—
<i>Pantnagar</i>						
Lowland	Rice	Lentil	—	4.6	1.3	—
<i>Faizabad</i>						
Upland	Maize	Wheat	—	2.3	2.7	—
Upland	Blackgram	Wheat	—	0.7	2.7	—
<i>Sehore</i>						
Upland	Sorghum	Potato	Fodder (Berseem)	2.0	8.7	29.1
Lowland (2 year sequence)	Rice	Wheat	Sugarcane (contd.)	1.5	1.4	96.1
<i>Humid ecosystem</i>						
<i>Kharagpur</i>						
Lowland	Rice	Rice	—	4.2	4.3	—
Lowland	Rice	Rice	Fodder (maize)	4.2	5.1	5.8
Upland	Mung	Bean	Rapeseed	0.5	0.1	0.8
<i>Kalyani</i>						
Lowland	Jute	Rice	—	1.8	4.6	—
Lowland	Jute	Rice	Rice	2.1	3.8	2.0
Upland	Maize	Gram	Rapeseed	6.5	1.5	1.0
<i>Coastal ecosystem</i>						
<i>Karamana</i>						
	Rice	Rice	Rice	4.5	2.7	2.4
	Rice	Finger- millet	Rice	4.7	4.4	2.7
<i>Thanjavur</i>						
	Rice	Greengram	Rice	5.9	0.5	4.2

rice-rice-oats (fodder) is also popular in the lowlands. In the upland situation, maize-green gram/blackgram-rapeseed and mung bean-rapeseed have been the established systems. The research issues to be focused, are mostly on nutrient management, water regimes and on the physical condition of the soil for enhancing production.

Coastal Ecosystem

Rice is the major crop under the coastal ecosystem (Table 2). Wherever irrigation facilities exist, growing of two crops of rice one during the rainy season and other in the summer season, is a common practice. But then with the advent of short duration high yielding varieties, even three crops of rice in a rice-rice-rice system has been feasible. This system has the weakness of more pest and disease load. In order to waive out this disadvantage, either a crop of green legume or a finger millet is taken in between the two crops of rice grown in a system. It may further be mentioned that rice-groundnut is becoming a popular system in Orissa both under rainfed and irrigated conditions. The cropping system of rice-groundnut-rice is followed when cultivation is by irrigation.

Problems of Nutritional Disorders

Application of only N-P-K is not adequate to sustain the high productivity of a rice-rice system. The problems of nutritional disorders and toxicities are coming up gradually, wherever rice-rice system is being followed. Introduction of high yielding crop varieties, increased use of high analysis fertilizer, additional irrigation facilities, reclamation of marginal and problematic soils though have increased the food production in the country but in the process, it has caused soil degradation especially by depleting the nutrient reserve of soil due to the heavy withdrawal of essential plant nutrients by the bumper harvests. Simultaneously, inadvertent addition of micronutrients as contamination through low analysis N-P-K fertilizers has ceased because they were replaced by high analysis fertilizers. The combined effect of these changes in agricultural production system has aggravated the deficiency of micronutrients. The data on Zn responses obtained in Cuttack, Sambalpur and Puri districts are presented in Table 3. The salinity problems are also being tackled with the introduction of new high yielding varieties like "Lunisree" released by Central Rice Research Institute, Cuttack. Due to heavy floods and water stagnation in the delta areas, fertilizer efficiency is increased by the use of urea super granules.

Integrated Nutrient Management

Instead of fertilizing a single crop of rice, the concept of integrated nutrient management for rice-rice system needs detailed consideration. In this context, the results obtained in Orissa situation is very relevant and the data is given under Table 4. The performance of 75% recommended N-P-K through fertilizer plus 25% N-P-K through organic manure (as Azolla) during rainy season, supplemented with 75% recommended N-P-K through fertilizer, during postrainy season performed the best in rice-rice system.

Table 3. Responses of rice (kg ha^{-1}) to zinc¹ in Orissa State (1985–86), rainy season

Rice variety	District	Subzone	Block	Soil group	No. of trials conducted	Yield $\text{N}_{90}+\text{P}_{60}+\text{K}_{60}$	Yield with $\text{N}_{90}+\text{P}_{60}+\text{K}_{60}+\text{Zn}$	Response due to Zn application	SE response	CD (5%)
Sathi	Cuttack	I	1. Haripur 2. Sujanpur	Laterite	6	3807	4140	333	87	173
			1. Banki-II 2. Kanpur	Red and Laterite	2	4461	4605	144	177	190
	Sambalpur	District mean			8	3970	4256	286	78	156
				Mixed red and yellow	7	4514	4567	53	93	196
CR-1018	Puri	III	1. Laikera-I 2. Lakhanpur	Red soil Gaisilet	7	4366	4450	84	70	141
			1. Padampur 2.		14	4440	4508	68	60	119
	Puri	IV	1. Ranpur 2. Bhubaneswar	Laterite	7	4469	5227	758	107	217
			1. Nayagarh 2. Odagaon	Red and Laterite	6	7079	7673	594	213	426
		District mean			13	5674	6356	682	113	223

1. Zn was used @ 25 kg $\text{ZnSO}_4 \text{ ha}^{-1}$

Table 4. Rice yield (t ha⁻¹) (1985–86) with integrated nutrient management¹ in rice-rice system at Chiplima, India

Treatment	Rainy Rice (Lalata)	Postrainy Rice (Lalata)	Total (Rainy + Postrainy)
T ₁	2.3	2.2	4.5
T ₂	2.9	3.0	5.9
T ₃	2.9	3.0	5.9
T ₄	3.4	3.4	6.9
T ₅	3.8	3.7	7.5
T ₆	3.2	3.3	6.5
T ₇	3.7	4.0	7.7
T ₈	3.3	3.2	6.6
T ₉	3.7	3.7	7.4
T ₁₀	3.5	3.6	7.1
T ₁₁	4.7	4.6	9.4
T ₁₂	3.5	3.5	7.0
CD (5%)	6.3	4.2	3.6
CV (%)	6.0	7.0	6.0

1. Recommended fertilizer level N₈₀ P₄₀ K₄₀

Treatment details:

Legend	Rainy	Postrainy
T ₁	No fertilizer, no organic matter (control)	No fertilizer, no organic matter (control)
T ₂	50% of recommended NPK dose through fertilizer	50% of recommended NPK dose through fertilizer
T ₃	50% of recommended NPK dose through fertilizer	100% of recommended NPK dose through fertilizer
T ₄	75% of recommended NPK dose through fertilizer	75% of recommended NPK dose through fertilizer
T ₅	100% of recommended NPK dose through fertilizer	100% of recommended NPK dose through fertilizer
T ₆	50% of recommended NPK dose through fertilizer + 50% N through FYM	100% of recommended NPK dose through fertilizer

(contd.)

T ₇	75% of recommended NPK dose through fertilizer + 25% N through FYM	75% of recommended NPK dose through fertilizer
T ₈	50% of recommended NPK dose through fertilizer + 50% N through crop residues/rural farm waste	100% of recommended NPK dose through fertilizer
T ₉	75% of recommended NPK dose through fertilizer + 25% N through crop residues/rural farm waste	75% of recommended NPK dose through fertilizer
T ₁₀	50% of recommended NPK dose through fertilizer + 50% N through green organic manure or through Azolla	100% of recommended NPK dose through fertilizer
T ₁₁	75% of recommended NPK dose through fertilizer + 25% N through green organic manure or through Azolla	75% of recommended NPK dose through fertilizer
T ₁₂	Farmers' practices, i.e., 2 tons FYM/ha + 20 kg N/ha in 2 splits	Farmers' practice (Conventional) (Dummy plot)

Rationalization of Inputs

The performance of observing economy in the inputs is very relevant now with the hike in costs of fertilizers, herbicides and quality seeds. This is more relevant in the rice-rice system of the coastal region. The studies revealed that 25% cut over the normal recommended fertilizer use, resulted in a yield sacrifice of 14%. Again the plant population reduction by 25% over the normal, showed only a decline of 5% yields in rice. Though the yield levels were comparatively reduced, the sacrifice was not heavy as the input cost of fertilizers and seeds were even more (Table 5).

Double cropping is practiced in many rainfed areas having adequate precipitation. A rainy season crop is followed by a post-rainy season crop. Organic mulches are known to increase soil moisture storage, maintain a higher water content in the upper few centimeters of the soil and add to the fertility of soil on decomposition. Crop responses to mulch application have been found to vary. However to rationalize the use of mulches, situations under which these are effective need to be identified. Dryland wheat yield depends on rainfall, applied N and mulching in preceding maize, where maize-wheat sequences are followed. Mulching increases yields of maize by 9%–12% and that of the following wheat by 25%–28%.

Energetics of Cropping Systems

Energetic approach, though new, is expected to assume added dimensions in the cropping system management studies. More emphasis should not be placed on determination of realistic relationship between energy inputs and crop

Table 5. Rationalization of input management in rice ($t\ ha^{-1}$) (1983-85) at Cuttack, Orissa, India

T ₁	P ₁ F ₁ W ₁	5.3	T ₇	P ₂ F ₁ W ₁	4.9
T ₂	P ₁ F ₁ W ₂	4.9	T ₈	P ₂ F ₁ W ₂	4.8
T ₃	P ₁ F ₂ W ₁	4.4	T ₉	P ₂ F ₂ W ₁	4.2
T ₄	P ₁ F ₂ W ₂	4.3	T ₁₀	P ₂ F ₂ W ₂	4.1
T ₅	P ₁ F ₃ W ₁	3.7	T ₁₁	P ₂ F ₃ W ₁	3.5
T ₆	P ₁ F ₃ W ₂	3.6	T ₁₂	P ₂ F ₃ W ₂	3.5
CD (5%)			1.47		
	F ₁	F ₂	F ₃	Mean	
P ₁	5.1	4.4	3.7	4.4	
P ₂	4.8	4.2	3.5	4.2	
W ₁	5.1	4.3	3.6	4.3	
W ₂	4.9	4.2	3.6	4.2	
Mean	5.0	4.3	3.6	—	

Treatment levels:

Plant population

- P₁ – 100% of the recommended level of plant population (15 cm × 10 cm spacing)
P₂ – 75% of the recommended level of plant population

Fertilizer

- F₁ – 100% fertilizer level (Recommended level N₈₀P₄₀K₄₀ kg ha⁻¹)
F₂ – 75% of the recommended level of fertilizer
F₃ – 50% of the recommended level of fertilizer

Weed control

- W₁ – Weed control with herbicide
W₂ – Weed control by 2 hand weeding

productivity. Total energy consumption has been steadily increasing with the increasing demand of the agricultural products over recent years. Table 6 presented in respect of energy use for rice-rice system and rice-wheat is self-explanatory.

It may, however, be mentioned that the energy relationships in a cropping system vary and constitute a dependent function of the total energy content of the crops knitted in a sequence. The yield levels, nature of power used, soil type, energy input and agroclimate have a vital role to play. There is a need

Table 6. Energy relationship in rice-rice and rice-wheat sequence

Cropping	Yield	Energy input			Energy output		TMP/ THB	Energy ratio (ER)		Energy produc- tivity (g MJ ⁻¹)	Remarks
		Opera- tional	Non- opera- tional	Total	TMP ¹	THB ²		TMP	THB		
Rice-rice (Small farm)	62.06	47 509	16 632	64 141	91 232	169 110	0.54	1.4	2.7	97	Midnapur (W.B.)
Rice-wheat (Small farm)	50.82	12 281	20 883	33 164	74 706	134 470	0.56	2.3	4.2	153	Anantapur (A.P.)

1. TMP: Total main product.

2. THB: Total harvested biomass.

for inclusion of legumes, oilseeds and root crops in the system approach for favorable monitoring of the energy relationship.

Future Strategy

The future strategy of cropping systems research should be on efficient resource management for small and marginal farmers. We should also aim at integration of various farm enterprises like crop, livestock, fishery, dairy, poultry, agroforestry, apiary, mushroom and aquaculture to optimize farm resource use. Efforts should be made on efficient use of available natural and man-made production resources for putting into the best use possible. Last though not the least, efforts should be made to raise the use efficiency of all the major crop production inputs. This would enable us to bring new packages for efficient cropping-systems and farming-systems management.

Integrated Pest Management

S. Jayaraj and R.J. Rabindra

Abstract

Despite several disastrous experiences consequent on the increased dependence and indiscriminate use of chemical pesticides, intensive agriculture in most parts of the world still depends on ecodestabilizing chemical pesticides. Even though it may be impossible to avoid chemical pesticides altogether, dependence on harmful pesticides can be reduced by integrating nonchemical methods in pest management. Keeping this in mind, entomologists and pest management specialists have developed several strategies such as mechanical, cultural, physical, physiological, behavioral, botanical, and biological control apart from host-plant resistance. Pest surveillance and monitoring is a basic prerequisite in integrated pest management (IPM) programs. The role of IPM practices in sustainable agriculture, new technologies, resources utilization, and specific areas of future research are discussed.

To feed the future generations without degrading the resource base that supports crop productivity, agriculture must become economically viable and ecologically sustainable. Increased chemicalization in agriculture erodes the economic and ecological sustainability. The various facets of management in agriculture should therefore be suitably engineered to maintain the productivity in a sustainable manner. Integrated pest management based on biorational approaches and local resources contribute substantially in this regard.

Pest—A Constraint in Sustainable Agriculture

Worldwide, an estimated 67000 pest species attack agricultural crops (USDA 1960). Despite the use of an estimated 2.5×10^9 kg of pesticides, plus the use of biological control and other nonchemical controls, we still suffer a loss up to 35% of agricultural production to pests (Pimental et al. 1991).

The introduction of the green revolution methods of crop production, have brought about a marked change in the status of pest and disease complexes that affect crops. The problem of crop pests has become a major constraint in sustainable agriculture. According to Atwal (1986), the estimated value of annual crop losses caused by pests in India was Rs.51812 million (USD = Rs.30) (Table 1). Agriculture in the dryland stressed environments is also affected. Rainfed areas which constitute nearly 69% of the total cultivated land suffer significant loss in crop production due to pests and diseases. In the United States the loss due to the boll weevil *Anthonomus grandis* alone was estimated at US\$ 40 million.

Table 1. Estimated value of annual crop losses caused by pests¹

Crop	Production (x 10 ⁹ kg)	Loss (average) (%)	Value of loss (in million rupees)
<i>Field</i>			
Wheat	41.5	10	5191
Rice	53.6	20	13078
Maize, sorghum, millets	30.0	25	9150
Cotton	8.0 m bales	50	3400
Brassicas	2.1	35–73	613
Groundnut	7.3	10	2380
Cotton seed	2.6	7	500
Pulses	11.35	10	5000
Losses during storage	54.2	7	12500
Total			51812

1. Source: Atwal (1986).

Current Trends in Chemical Pesticides

More than US\$ 3 billion are spent worldwide each year to control insect pests (Wilcox et al. 1986). In India, the consumption of technical-grade pesticides has risen from 7341×10^3 kg in 1960 to 79482×10^3 kg in 1989–90. The demand in 1994–95 is predicted to be 107864×10^3 kg (David 1992) (Table 2). Since 1960, there has been a 12-fold increase in the consumption of insecticides alone, though the area under cultivation has not registered any significant increase.

Of the pesticides consumed in India, insecticides constitute about 80% (Atwal 1986). Cotton occupies only 5% of the cropped area but accounts for 52–55% of the pesticides used. Rice, cotton, fruits, vegetables, and plantation crops together account for 89% of the consumption of pesticides, though they are grown on only 34% of cultivable area. In the United States also in 1990, 30% insecticides were applied on cotton (ERS 1990), half of which were synthetic pyrethroids. Problems associated with pesticides are more frequent in these crop, resulting in less sustainable production.

Consequences of Increased Chemical Use

The use of synthetic organic pesticides has undoubtedly played a key role in increasing agricultural production. But indiscriminate use of these compounds has led to accumulation of toxic hazards through pesticide residues in the food

Table 2. Consumption of technical-grade pesticides in India¹ (x 10³ kg)

Year	Insecti- cides	Fungi- cides	Herbi- cides	Rodenti- cides	Others	Total
1960	6729 (92) ²	598 (7)		104 (1)		7341
1965	10428 (86)	1480 (12)		268 (2)		12176
1970	21741 (92)	1774 (7)	15 (0.06)	80 (0.3)		23610
1974-75	46515 (81)	9600 (17)	715 (1)	250 (0.4)	150 (0.3)	57230
1977-78	46755 (80)	9685 (16)	1425 (2)	270 (0.5)	845 (1.5)	58980
1985-86						67218
1989-90	60450 (76)	11387 (14)	5710 (7)	1790 (2)	145 (0.2)	79482
1994-95 ³	81390 (75)	15564 (14)	8125 (8)	2615 (2)	170 (0.2)	107864

1. Source: David (1992).

2. Figures in parentheses indicate percentage share.

3. Estimated.

chain (Mehrotra 1986). It has been reported that the number of insects which exhibited resistance to pesticides was seven in 1935; and this number swelled to 462 in 1986 worldwide. Several insecticides are known to induce the resurgence of pests on crops (Jayaraj 1987).

Role of Chemical Pesticides in IPM

Sensible use of chemical pesticides is essential for pest management. Optimum use of physiologically and ecologically selective insecticides which are IPM-compatible can maximize their effectiveness against target pests and reduce environmental hazards and the destruction of beneficial insects. Insecticide resistance management with the aim of preserving the susceptibility of pest species to chemical pesticides can prolong the use of chemical pesticides. Increased emphasis on IPM coupled with environmental, economic, and social pressures has resulted in dynamic changes in the development of new chemicals such as avermectins and insect growth regulators, which are IPM-compatible. However, in stressed environments, cost-effectiveness would be a key factor since some of these newer compounds could be very expensive. Ideally, IPM in a stressed agroecosystem should not be solely dependent on chemical pesticides to ensure economic sustainability.

Biorational Pest Management and Sustainable Agriculture

While sensible use of chemical pesticides can prolong their usefulness in agriculture, it has become essential to look for alternatives to chemical pesticides. Dependence on ecodestabilizing chemicals can be reduced by integrating nonchemical biorational methods in pest management.

Host-plant Resistance

Host-plant resistance (HPR) to pests will play a key role in IPM in stressed agroecosystems. The resource-poor farmers particularly of drylands cannot invest in expensive pest control inputs. Host-plant resistance along with cultural strategies, natural enemy sampling, and economic thresholds should form the basis of IPM. Reduction in pest numbers by HPR is constant, cumulative, and practically without being costly to the grower.

The green revolution has led to widespread reliance on monocultures. The genetic base has become narrowed. This has resulted in environmental degradation. Many of the wild rice varieties at present show resistance to pests like the brown plant hopper (Tsung et al. 1986). The possibility of transfer of insect resistant genes from *Oryza officinalis* to cultivated rice (*Oryza sativa*) across crossability and recombinant barriers has been demonstrated by Khush and Jena (1987). Wide hybridization can pave the way for the development of pest-resistant varieties. The western ghats and adjoining regions have contributed to some 20 major genes for disease and pest resistance in the case of rice.

Agronomic Strategies

Agronomic strategies provide a strong base for an ecologically oriented pest management system. The farmers are well aware that by adopting or modifying certain agronomic practices, the pest population and ensuing damage can be reduced. Increasing seed quantity to compensate for shoot fly damage, adjusting the time of sowing of cotton to reduce pest attack, and application of *Azospirillum* biofertilizer to control the sorghum shoot fly *Atherigona varia soccata* (Mohan et al. 1987) are some popular agronomic methods which help reduce pest damage.

Intercropping, a traditional and popular farming practice, increases biodiversity, helps reduce pesticide use, improves weed control, and controls soil erosion. When suitable legumes are used, efficient utilization of soil nutrients takes place. The African Regional Pest Management Research and Development Network in eastern Kenya has shown that intercropping of early-maturing maize with cowpea under marginal rainfall increases the yield by 4.5 times (Hokkanen 1991). Mung bean intercropping in cotton has been found to reduce the incidence of leaf hopper in cotton (Rabindra 1985). Similarly, the intercropping of lab-lab in sorghum reduces damage by the stem borer, *Chilo partellus* (Mahadevan and Chelliah 1986). Pearl millet intercropping in groundnut reduces damage by the leaf miner, *Aproaerema modicella*. Castor when grown as a trap crop in cotton, tobacco, and chilies reduces *Spodoptera litura* damage (Jayaraj and Santharam 1985). The above may be listed as some of the examples of agronomic strategies.

Mechanical Method and Physical Methods

One of the oldest methods of pest management is mechanical control. Hand collection of insects such as *H. armigera* and *S. litura* on cotton, grain legumes, tobacco, etc., hooking out *Oryctes rhinoceros* beetles from coconut crowns and destruction of their grubs in manure pits, setting bow traps in rice fields, and providing tin sheets around coconut trunks for rat management are still practiced by farmers. Activated clay at 1% was found to control effectively the storage pests of grain legumes and sorghum. Similarly, vegetable oils at 1% effectively reduced the damage by the pulse beetle, *Callasobruchus chinensis*. These practices can be easily followed by small and marginal farmers without incurring heavy financial expenses.

Farmers have been taught to use pheromone traps for monitoring pests such as the pink bollworm, *Pectinophora gossypiella*, *H. armigera* and *S. litura* (Jayaraj et al. 1986). The use of these traps, as well as light traps in rice, in pest management is common among Indian farmers. Similarly fishmeal traps for *A. varia soccata* (Rangarajan et al. 1985) and yellow pan traps or yellow sticky traps often used to monitor whiteflies (*Bemisia tabaci*) (Jayaraj et al. 1985) are useful techniques in pest management. Such behavioral methods are less expensive and do not disrupt the ecosystem.

Control of pink bollworms by disruption of their mating using the pheromone has already been demonstrated in India (Sundaramoorthy and Basu 1990), and in Egypt, commercial control of the pest by using a slow release formulation of gossypure was achieved (Critchley et al. 1989). These findings indicate that semichemical technology may have an economic future in IPM programs.

Use of Plant Products

Indian farmers have used pesticides of plant origin long before synthetic chemical pesticides were discovered. The plant kingdom is a vast storehouse of chemicals that can check the insect population. Grainage et al. (1985) compiled a database of plant species that possess pest-controlling properties. These included 1005 species with insecticidal properties and 384 species with antifeedant properties; 297 were repellent, 27 were attractant, and 31 species had growth-inhibiting properties. The use of neem products for pest management, both in the field and in storage, is quite popular (Schmutterer 1990). The plants provide a renewable source of pesticidal materials and can therefore play an important role in sustainable agriculture.

Biological Control

Biological control together with plant resistance is the core around which pest control in crops and forests should be built (Wilson and Huffaker 1976). Many benefits result from a successful control of a pest species with biocontrol agents. Natural enemies according to Pimental (1991), are self-powered, self-sufficient, and self-regulating; once established, further investments in control are not necessary. Some failures in the use of classical biological control methods are

probably due to the genetics of natural balance that initially evolved between the natural enemy and its host in the native environment of the two interacting species (Pimental 1986). The objective of "new association biocontrol technology" should therefore be to prevent failures by taking advantage of lack of evolved balance common to the natural parasite-host system and to use the diversity of natural enemies. This approach leads to identification of more virulent parasites and predators. It also results in a more frequent success in biological control than with the old association of classical biological control (Pimental 1991).

The other dynamic approach followed in biological control is the inundative release of parasites, predators, and pathogens. Insecticides like endosulfan and phosalone have been found to be less toxic to beneficial insects and hence the use of biocontrol agents can be successfully integrated with these chemical insecticides (Singh 1986). Jayaraj (1986) reviewed the role of insect pathogens in microbial control of pests in India. He observed that the most widely used microbial insecticide is *Bacillus thuringiensis* (Flexner et al. 1986; Wilcox et al. 1986). Unfortunately, Tabashnik et al. (1990) have reported field development of resistance to *B. thuringiensis* in diamond back moth *Plutella xylostella*. In India, *B. thuringiensis* has been introduced recently and a careful watch has to be kept for development of resistance. Recent advances in genetic engineering have increased the scope for the development of novel microbial insecticides with multiple modes of action (Wilcox et al. 1986).

The Tamil Nadu Agricultural University (TNAU) has recently created large-scale facilities for mass production of biocontrol agents under a program supported by the Department of Biotechnology and the Biotech Consortium India Limited. The value of biological control can be enhanced tremendously if the biocontrol technology is suitably integrated in IPM. Combining host-plant resistance with natural enemies and integrating these two with other nonchemical control methods appropriate to various agricultural ecosystems would further enhance the success of all biocontrol programs and lessen the need for pesticides (Pimental 1991).

Pest Surveillance in Sustainable Agriculture

Pest surveillance and monitoring are essential to avoid unnecessary application of chemical insecticides. The TNAU in cooperation with the Tamil Nadu State Department of Agriculture launched in 1984 a pest and disease monitoring program: nearly 7250 points in the state were adopted as fixed-plot and roving surveys (Jayaraj and Chandramohan 1987). The farmers were advised to initiate pest management measures only when the pest population level exceeded the economic threshold. Estimates made by the Tamil Nadu State Directorate of Agriculture indicate an annual saving of nearly rupees 20 million (USD = Rs.30) worth of pesticides since the introduction of this program.

Integrated Pest Management for Sustainable Agriculture

Integrated pest management has a key role to play in sustainable agriculture. Many ecologically based IPM practices have been developed to reduce the loss

caused by pests (Jayaraj et al. 1988). Through collaborative efforts with the departments of Agriculture, Horticulture and Plantation Crops, and Seed Certification, TNAU has implemented IPM programs in rice, sorghum, cotton, groundnut, and coconut in about 100 Technology Development and Demonstration Centers. This program has without doubt increased the sustainability in agriculture in the areas of its operation.

The practice of IPM in cotton was demonstrated (Figure 1) through an operational research project of the Indian Council of Agricultural Research (ICAR) by the entomologists of the Central Institute for Cotton Research, Regional Station,

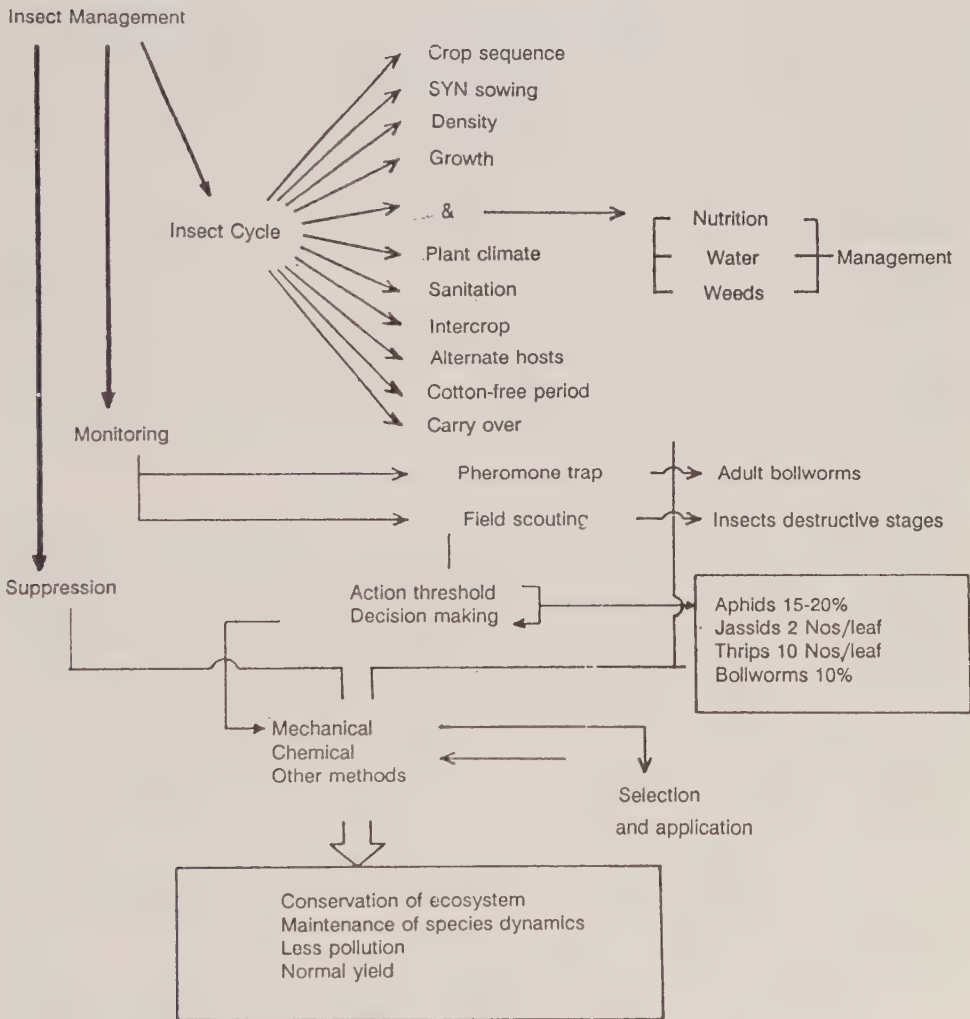


Figure 1: IPM system for cotton pests
(Source: Sundaramoorthy and Chitra, 1992)

Coimbatore (Sundaramoorthy and Chitra 1992). The results of this project showed that IPM enabled the reduction of insecticide pollution by reducing the pesticidal sprays, conserved natural enemies, and gave economic control of cotton bollworms.

The concept of IPM for sustainable agriculture must be given greater emphasis in the developing countries; research efforts on developing ecologically stable and economically viable pest management strategies particularly in stressed agroecosystems need emphasis.

Economics of IPM

The active participation of agricultural economists in the IPM projects is essential both for evaluation of projects and to assist in setting research priorities. Many times IPM does not significantly increase yields but significantly reduces the cost of production. Hence, the bottom line for IPM should be increased farmer profit by reducing costs. An effective IPM program should have social, cultural, economic, political, technical, and organizational fitness.

To enhance the viability of IPM programs, strict quarantine laws to prevent the introduction and spread of pests, legislation to implement IPM in important crops, insecticides registration and use, as well as suitable policies on funding of research and education on IPM are necessary. Subsidies on pesticides should be scaled down. Sustainable agriculture policies require promotion of domestic supply of crops in agriculture instead of export-oriented cash crops which consume a lot of chemical pesticides, shift from monoculture to crop diversity, and encouragement of small farmers instead of commercial land holders.

Marginal Farmers' Farming System and IPM

Farming system research on marginal farmers has demonstrated that indigenous systems have much to contribute in farming and human health including innovations derived from indigenous pest management practices (Gabriel 1989). Modifications of small farmer practices can lead to better pest management (Mattesan et al. 1984). According to Haskell et al. (1981), traditional peasant systems of agriculture are not primitive but are, on the contrary, finely tuned and adapted both biologically and socially to the needs of what is often a harsh and inimical environment. It is akin to throwing the baby out with the bathwater to suggest that these methods be scrapped and replaced with some totally different alternative system.

Future Research Needs in IPM in Stressed Environments:

A Suggested Agenda

- Generation of information pest ecology
- Development of simple monitoring tools and methods
- Development of IPM-compatible low cost biorational pesticides
- Fixing economic threshold levels for key pests with reference to the use of biorational pesticides

- Development of information support system
- Involvement of women in IPM
- Proper economic analysis of the IPM system

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Disease Management and the Quest for Sustainable Systems

P. Trutmann and H.D. Thurston

Abstract

Information collected over the last two decades shows that "Modern" agriculture has lost many of the building blocks of sustainable systems that were the hallmarks of "traditional" agriculture including those pertaining to disease management. To develop more sustainable disease management practices, basic principles from traditional systems must be reincorporated into agricultural systems without reducing crop productivity. Efforts should be concentrated on the understanding and reestablishment of genetic variability in crops, the use of organic based soil amendments to quantitatively and qualitatively increase soil microflora and fauna, to evaluate the multitude of cultural disease management practices in traditional systems, to develop strategies which provides a high degree of flexibility to the user, and to encourage education and training programs for farmers, extensionists, and scientists. To improve traditional systems efforts should be concentrated on thoroughly understanding the systems and farmers from a crop protection perspective, maintaining existing sustainable components, while building productivity components and new disease management strategies into the system. An extended philosophy of Integrated Pest Management is advocated with an ecological and systems perspective to problem solving and the use of tools such as biotechnology, agroecological databases, epidemiology, microbial ecology and anthropology. Biotechnology is regarded not as a major component of new sustainable systems, but as a valuable tool which, if used prudently, should provide understanding of mechanisms and technologies for systems which have been the basic building blocks of sustainable systems. Selected chemicals are likely to have a role in disease management in sustainable systems if used prudently and in small quantities. New generations of chemicals based on natural products with very specific and known characteristics compatible with the environment should not be excluded a priori as inappropriate.

Most scientists and farmers have abandoned traditional farming practices and systems to increase food production and income and to improve the efficiency of land and labor use. The "modern" agricultural systems mostly ignore many of the sustainable practices, including crop protection practices, that have evolved over the years, among farmers, to cope with the multitude of environmental stresses under which crops are grown. Slowly, we have come to realize that

many of the modern systems are not sustainable, and if we do not devise better agricultural systems we will impair our ability to produce adequate food in the future.

This is a time of questioning and building the framework for new approaches to agriculture. New strategies are still in a formative stage and solutions for the many fundamentally complex problems in agriculture, especially those relevant to stressed environments, are difficult, if not perhaps impossible, to arrive at. Bird et al. (1990) and Thurston (1992) have discussed approaches needed for plant protection in sustainable systems. We will use some of the previous recommendations, and discuss the problems and fundamental directions needed to attain disease management, compatible with sustainable systems.

Practices must maintain and raise productivity, they must not harm the environment, and should encourage social equity. This is the basic dimension of the challenge ahead. Today, it is essential to integrate into the components of strategy, designs for conservation of nonrenewable resources, consideration for environment, the increasing demand for food by more people, and the need for equity. This combination of factors precludes sustaining agriculture at low productivity levels, or emphasis on maximizing productivity as done in the past. In formulating our strategies we must recognize that food production per se often is not the problem, but rather its availability to the poor. Sufficient food may exist, but the poor often do not have the money to buy it. Or it may not be available because it is channeled away for export. The manner in which these inequities are resolved at the policy level will strongly influence future strategies for crop disease management.

The basic components of sustainable systems are characterized by their ecological compatibility which provides production stability. Ecological compatibility should be the primary concept designed into crop protection research in the systems affected by the green revolution technology and characterized by some as unstable. On the other hand, in systems with many stability factors already in place, the productivity issue must be tackled without eroding the sustainability components in the system. Often such traditional systems are regarded as efficient but are unable to meet food demands beyond a subsistence level (FAO 1989). Traditional systems however, are not intrinsically unproductive (Table 1). Stable and often surprisingly productive systems are found in natural ecosystems and in many long established traditional and indigenous systems. Examples of such systems are found in the intensive and highly productive systems of mainland China (Wittwer et al. 1987), the highly sophisticated systems in South and Southeast Asia (Marten 1986), and the crop production systems in Latin America derived from ancient Indian civilizations (Wilken 1987). Genetic diversity, through the use of species and varietal mixtures or highly diverse landraces, are characteristic of these systems. Unfortunately, few of these systems have been systematically studied, particularly from a crop protection perspective. Hence, we still know little of the mechanisms which have kept these systems stable, sustainable, and productive.

Table 1. Productivity, sustainability, stability, and equity of selected traditional and modern agricultural systems of the tropics¹

	Productivity	Sustainability	Stability	Equity
<i>Traditional tropical systems</i>				
Home gardens (Indonesia)	High	High	High	High
Cassava/Intercropped	High	Intermediate	High	High
Chinampas (Mexico)	High	High	High	High
Maize/Squash/Beans	Intermediate	High	High	High
Paddy rice	Intermediate	High	High	High
Plantains (Uganda)	High	High	High	High
Slash and burn ²	Low	High ²	High	High
Tapado, beans (Costa Rica)	Low	High	High	High
Upland rice	Intermediate	High	Low	High
<i>Modern tropical systems</i>				
Banana for fruit	High	Intermediate	Intermediate	Low
Beef Cattle	Low	Intermediate	Intermediate	Low
Cacao	Intermediate	High	Intermediate	Low
Coconut	Intermediate	High	High	Intermediate
Coffee	High	High	High	Intermediate
Oil palm	High	High	High	Low
Rubber (Hevea in Asia)	High	High	High	Intermediate
Sugar Cane	High	Intermediate	Intermediate	Low

1. Source: Thurston (1992).

2. Under high population pressure the slash and burn system is not stable or sustainable.

Let us examine some of the principles of crop protection practiced in such systems. Traditional farming systems, especially in the tropics, often resemble natural ecosystems and, in addition, rely more on a variety of cultural practices, the pest resistance of landraces, and natural biological control rather than heavy dependence on inorganic chemicals for both soil fertility and pest control. This approach appears to give traditional farming systems a high degree of stability, resilience, and efficiency. Traditional farmers are not always interested in the highest yields, but rather are more concerned with attaining stable, reliable yields. The common principles underlying crop protection in such systems are high degrees of both intra- and interspecific genetic diversity (Clawson 1985; Thurston 1992), a high degree of flexibility in farmer decision making options [Trutmann et al. (In press)], diverse cultural and biological control practices (Thurston 1992), little use of external inputs, and practices which often have multiple uses [Trutmann et al. (In press)]. Most of these practices are sustainable, use few external inputs, and vary in their labor requirements (Table 2).

Table 2. Sustainability, external inputs needed, and labor requirements of selected plant disease management practices of traditional farmers¹

Practice	Sustainable	External inputs	Labor
Adjusting crop density	Yes	Low	Low
Adjusting depth of planting	Yes	Low	Low
Adjusting time of planting	Yes	Low	Low
Altering of plant and crop architecture	Yes	Low	High
Biological control (soilborne pathogens)	Yes	High	High
Burning	Yes ²	Low	High
Fallowing	Yes	Low	Low
Flooding	Yes	Low	High
Manipulating shade	Yes	Low	Low
Mulching	Yes	High	High
Multistorey cropping	Yes	Low	Low
Multiple cropping	Yes	Low	High
Planting diverse crops	Yes	Low	Low
Planting in raised beds	Yes	High	High
Rotation	Yes	Low	Low
Site selection	Yes	Low	Low
Tillage	No	Low	High
Using organic amendments	Yes	High	High
Weed control	No	Low	High

1. Source: Thurston (1992).

2. Under high population pressure the slash and burn system is neither stable nor sustainable.

Components of Sustainable Disease Management

Genetic Diversity

Long established or traditional systems are generally genetically very diverse. Müller (1916) found over 90 different colors and grain types in local beans and great diversity in intercropping in Burundi. Over 2000 named potato cultivars were grown in Peru. In one isolated valley with about 1000 inhabitants over 50 cultivars were found (Brush 1977). Many types of multiple cropping arrangements are discernible in traditional agriculture, and different researchers have given the terms listed below, specific meanings (Francis 1986; Harwood 1979; Kass 1978). There may be an increased efficiency in the use of light, water, or nutrients, especially nitrogen. There also may be better management of weeds, insects, or plant pathogens. Clawson (1985) has discussed in detail intraspecific diversity among tropical crops. Many traditional farmers have

maintained high levels of diversity within cultivars of a single crop species. Clawson called this "intraspecific polyculture" and gave examples of its occurrence with maize, cassava, yams, taro, beans, millet, rice, potatoes, and sweet potatoes.

Genetic diversity is especially important from the disease perspective when it provides diversity of resistance to plant pathogens. Genetic diversity also influences disease incidence by increasing the distance between susceptible individuals, by changes in the microclimatic conditions which may be unfavorable to diseases, by encouraging induced resistance, and by creating barriers between susceptible plants (Wolfe 1985). Buddenhagen (1983), Harlan (1976), and Leppik (1970) noted that the greatest number of genes for disease resistance are usually found in landraces, where the host and pathogen have coexisted for long periods of time. Trutmann et al. (In press) showed that in the Eastern African highlands a rather large percentage of the varieties in the traditional mixtures had resistance to *Colletotricum lindemuthianum*. In addition, they found that the percentage of the traditional mixture that consisted of resistant varieties increased with altitude where conditions were more conducive to anthracnose. Plant breeders found resistance in Ethiopian barley lines to powdery mildew (*Erysiphe graminis*), loose smut (*Ustilago segetum* var. *tritici*), leaf rust (*Puccinia hordei*), net blotch (*Drechslera teres*), Septoria (*Septoria nodorum*), scald (*Rhynchosporium secalis*), barley yellow dwarf virus, and barley stripe mosaic virus (Harlan 1976). When many barley cultivars were tested for resistance to barley yellow dwarf virus, 113 of those found to have resistance were from Ethiopia. Thus, farmers over the centuries selected landraces with resistance to many major diseases.

Modern or nontraditional systems are often genetically uniform. There are three main reasons for this. Firstly, when new crops were introduced away from their center of diversity, (Vavilov 1951), often only a few were selected and distributed. Secondly, modern breeding techniques, such as the pureline selection technique and the rapid spread and use of high-yielding varieties (HYVs) of wheat and rice, have seriously eroded genetic diversity in what has come to be known as the "Green Revolution". For example, over 75% of the rice area in the Philippines is planted with HYVs developed since 1965 (Herdt and Capule 1983). From 49000 ha in the 1965/1966 crop year, the area planted to the HYVs of wheat and rice in Asia and the Near East had by 1976/77 increased to almost 55 million ha (Dalrymple 1978). In 1980, almost 40% of the rice produced in South and Southeast Asia consisted of HYVs, and they were estimated to contribute 4.5 billion dollars annually to the value of rice produced in Asia (Herdt and Capule 1983). Thirdly, in many cases genetic uniformity has been implemented by pressure to conform to commercial standards. Farmers had little choice, but to conform or risk having no buyer of their crop.

Increased uniformity has increased the vulnerability of crops to diseases both in the centers of diversity, which are also centers for pathogen diversity, and introduced epidemics through pathogen introduction by increased movement of genetic material. Examples of epidemics arising from genetic uniformity are many. Genetic uniformity can produce devastating effects. Classic examples include the Irish potato famine in which over a million people died, the southern corn blight

epidemic in USA, and the devastating coffee rust epidemic in Sri Lanka. Genetic uniformity, unstable resistance, and quests for maximum productivity are also major reasons for the excessive use of chemicals, both pesticides and inorganic fertilizers, on many crops. Pesticides are affecting human health, destroying natural microbiological control mechanisms, are encouraging development of resistance by target organisms, and are contaminating the environment.

Uniform systems are maintained by what is termed as "maintenance research", a now common place breeding strategy to introduce new resistance varieties to replace those affected by apparent disease and arthropod pest resistance breakdown. Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) an institute instrumental in the green revolution, now estimates that it spends two thirds of its total effort in wheat improvement on maintenance research (FAO 1989). It is essential that highly genetically diverse germplasm with highly variable mechanisms of resistance to diverse diseases and arthropod pests becomes a corner stone of disease management strategies in sustainable agricultural systems.

Microbial Diversity

In many traditional agricultural systems farmers have added substantial amounts of organic matter to the soil over centuries in sustainable systems. Youtai (1987) wrote that the value of manures to agriculture was established in China before the fifth century B.C. According to Spurr (1986), at some times in ancient Rome the quantities of manure used in agriculture were higher than those used in Italy today. Denevan (1987) noted that the soils of Peruvian terraces were "now maintained by the application of manure and compost and by periodic fallowing, and both were likely true prehistorically." In China's intensive traditional agricultural systems the use of copious quantities of organic matter has been suggested as one of the reasons why root diseases appear unimportant (Baker and Cook 1974), whereas in modern systems dependent on inorganic fertilizer, root diseases are increasingly greater production constraints.

Although the use of pesticides has been identified as the principal cause for reduced levels of natural enemies of arthropod pests, the same cannot necessarily be said of their use in disease control. The move away from wide spectrum agents, which affect both bacteria and fungi, to fungicides with more specific action has been a positive trend from the biological control perspective. In general, fungi are the most important pathogens of crops, and bacteria appear to be the most important biological control agents. Hence the bacterial component is not the target of most pesticides.

On the other hand, dependence on inorganic fertilizers and agricultural practices which encourage extensive removal of organic material from soil and encourage depletion of organic matter in soil have probably had a significant impact on the quality and quantity of populations of microbiological control agents of soilborne plant pathogens. Soil microorganisms are mostly associated with organic matter in soil. Soils fertilized with organic fertilizers have a higher microflora biomass than those treated with inorganic fertilizers (Fraser et al. 1988;

Goyal et al. 1992) and the population structure is different (Rempe et al. 1989). Adding inorganic fertilizers causes a flush of high microbial activity through the release of high doses of N, P, and K which may deplete available sources of these, carbon and other essential soil nutrients in later periods in comparison to the more balanced nutrition and microbial communities in organically amended soils. We now realize that organic amendments contain diverse microbial populations including many competitors and antagonists of soilborne plant pathogens (Hoitink and Fahy 1985). These communities also contain populations of growth promoting bacteria, bacteria capable of inducing resistance in plants and greater numbers of soil fauna feeding extensively on the microflora including resting structures of plant pathogen. In addition, improvements in the soil structure and porosity aid plant health. The mechanisms by which organic amendments such as composts, control disease have been little studied or understood. In most cases the suppressive effects are known to come from the biological components. The use of organic amendments in soils to promote residence and survival of a large and diverse microflora as well as to enhance fertility and soil structure is a critical component of disease management in sustainable systems.

Flexibility and Cultural Control Methods

In traditional systems numerous cultural practices are used to protect crops (Thurston 1992). Such practices may have multiple purposes, only one of which may be the management of certain pathogens. Cultural practices have high sustainability ratings (Table 2).

Our knowledge of integrated crop protection strategies in traditional systems is very limited. However, a study conducted in Africa shows that farmers in these systems use their agricultural and environmental knowledge to regulate these systems and protect crops principally through cultural management of microclimate and plant vigor [Trutmann et al. (In press)]. Flexibility of decision making options is critical to them. As farmers have moved away from traditional agriculture, cultural disease control practices have been used less frequently, and farmer flexibility to manipulate the microclimate and plant vigor has lessened. For example, there are often stipulations, or pressure, to conform to sowing times, row spacing, fallows, reduced rotations, genetic uniformity etc. These pressures reduce the farmer's ability to vary cultural practices to protect the crop. To compensate there is more reliance on pesticides and more instability in disease management systems. The importance of flexibility in disease management strategies recognizes the need for approaches that hold both globally, such as genetic diversity in crops, abundant soil fauna and microflora, and also locally allowing for diverse strategies with farmer decision making power needed to manage diverse pathogens in the highly variable environments.

Integrated Pest Management

Stability components in highly stressed systems may need supplementation with other technologies to maintain crop productivity. Crop losses due to disease in these environments can still be chronic [Trutmann and Graf (In press)] and can

mask the benefits of productivity improvements such as increased soil fertility. Although the concept of economic thresholds is not widely applicable for plant disease management, an effort should be made to better quantify and simplify information needed to evaluate the worthiness of investments in disease management with regard to returns to farmers. We must also develop our capacity as individuals and scientists which allow us to look at problems holistically. We must also understand better the interactions between organisms, populations, communities, and entities on the microbial and macro level using traditional and powerful new techniques and approaches using a systems approach, new tools to study microbial communities in situ, such as laser scanning confocal microscopy, genetic markers and other molecular techniques, and translate derived knowledge into practical components of integrated pest management (IPM).

IPM has many definitions, but basically it is defined as "a systems approach to reduce pest damage to tolerable levels through a variety of techniques, including predators and parasites, genetically resistant hosts, natural environmental modifications and, when necessary and appropriate, chemical pesticides" (Bird et al. 1990). The concept recognizes the importance of the management, not eradication, of pests and the often site-specific nature of disease management strategies.

The acronym IPM was invented by entomologists and today the field is still dominated by entomologists. Most reviews on the subject have been written by entomologists and issues are generally explored from their perspective. This has obscured the perspectives of plant pathology relative to IPM. There are some fundamentally different problems confronting the two disciplines. Firstly, pesticide abuse and overuse is probably the major issue for arthropod control. In plant disease management it is of less importance, although it still requires serious consideration. Secondly, disease management strategies have historically relied more on disease resistance than arthropod management strategies, and the factors which cause the breakdown of resistance have become the greater issue in disease control. Thirdly, the manipulation of biological control agents has so far been far more successful in entomology than in plant pathology.

It is therefore not surprising that IPM has been used principally as a means of reducing pesticide use, and to some this has come to mean Integrated Pesticide Management. To other groups IPM has come to mean breeding more resistance into crops, or the use of biological control. However, as a holistic and ecologically based philosophy for crop management, the emphasis of IPM must be on all three words: integrated, pest, and management. We must design a management system using diverse and complementary methods for multiple diseases and arthropod pests compatible with cropping and social systems in stressed environments. Better understanding of the relationship of macroclimate with microclimatic conditions in crops would be one valuable tool when used with real time weather data and accurate models to facilitate the integrated management of diseases. A truly holistic approach to plant protection is not an easy concept to grasp for discipline oriented beings like ourselves. Neither is the investigation of crop protection principles and methods in traditional systems,

when there are more prestigious and financially rewarding avenues to follow. Furthermore, we should realize that interdisciplinarity and holistic approaches to such problems require fundamental changes in reward systems.

Recombinant DNA Technology

The international scientific community has extensively promoted recombinant DNA technology, especially genetic engineering, as the panacea for crop protection in sustainable agricultural systems. Some go so far as to predict that recombinant DNA technology by enhancing disease resistance of crops and through biological control will eventually eliminate the need for chemical pesticides. Hundreds of millions of public and private dollars have already been invested in the facilities and research, and a spectacular but unrealized impact was predicted by some for the year 1992 (Katafia and Puriton 1988). At this stage, it is not clear to us how valuable recombinant DNA technology is going to be in the facilitation of sustainable crop disease management systems. Our belief is that biotechnology may provide important additional tools, but will not be the principle factor in disease and pest management in sustainable systems. Recombinant DNA technology is providing invaluable tools to study the ecology of plant pathogens and microbiological control agents and communities [Nelson and Maloney (In press)]. In addition, it has become a valuable tool for understanding the mechanisms of plant defence systems and recognition factors for pathogenesis. Clearly, better understanding and manipulation of plant and pathogen genetics could provide powerful defenses against diseases. However, Bird et al. (1990) warned in their review on the design of pest management systems for sustainable agriculture, that it is certainly plausible that these technologies are going to be used in an attempt to strengthen humankind's mastery over nature. To do so would be an attempt to further disregard ecological principles in the management of crop diseases. Pathogens and arthropod pests are dynamic, diverse, and complex for each crop. The movement of genes with recombinant DNA technology to other organisms will change interactions between plants and their environment, but we cannot predict how or whether the changes will add to the sustainability of the system, especially not without a thorough understanding of the ecology of such changes. On another level, the impact of intellectual property rights on research for developing countries is likely to be negative as private companies based in industrialized countries will require financial compensation for the use of DNA sequences which might be vital to a genetic enhancement program. The complexity of avoiding the inadvertent use of already patented gene sequences or purchasing all the components for use in small farm systems in the developing world is unlikely to be conducive to rapid progress producing adapted crops with the features promised to multiple specific sites with often specific multiple problems. Further, there is the added complexity of producing, testing and extending transformed materials in incompatible cultural and religious environments. Finally, genetically engineered crops face a similar adoption problem as other technologies produced for ecoclimatically and culturally variable environments do. Optimistically, we

foresee the impact of molecular biotechnology products in stressed environments to be slow and their sustainability uncertain.

Research Requirements

Genetic Diversity in Crops and Systems

We must devise and support approaches and policies which encourage, not discourage, genetic diversity of crops. There are numerous approaches which increase genetic diversity of crops. They include the use of multilines, varietal mixtures, and mosaic patterns of cultivation (Wolfe 1985). However, we still know little about host pathogen interactions and the durability of resistance in mixed systems, or how to best integrate stability components for multidisease and pest management. There is a need to use more diverse sources of resistance to pathogens, especially "durable" and rate-reducing resistance. Some are pessimistic about the efficacy of genetic engineering for transferring durable or rate-resistance genes. A knowledge of the mechanisms of durable resistance is important for the effective application of recombinant DNA technology in crop protection and to determine whether genetic engineering can be effectively used for this purpose. In addition, one must first identify durable resistance. However, if we use more genetically diverse crops, we should also reexamine the stability and effectiveness of using diverse sources of monogenic resistance in varietal mixtures. For example, it may be applied in a manner similar to that found in natural communities, monogenic resistance may provide durable resistance to crops from diseases.

In programs aimed at improving disease management of traditional systems much thought needs to be given to genetic erosion. The strategy of complete genetic displacement of local mixtures with a single HYVs is rarely justified, and every effort should be made to discourage the practice. However, we must also analyze the potential of strategies which selectively displace 25–50% of local mixtures by a resistant variety to effectively protect susceptible components to a single disease (Pyndji and Trutmann 1992). Are such strategies allowing for conservation of sufficient relevant genetic variability in the long-term? Certainly they are better than strategies which cause total displacement of local genetic variability. Is there a role for some use of fungicides, both synthetic and biological, to increase productivity in traditional systems? We believe that in some situations, strategies which target small quantities of chemicals to control multiple diseases should be compatible with the quest for sustainable systems. Could productivity be increased by introducing better on-farm phytosanitation and local seed quality? It is difficult to address these questions without a better knowledge of currently practiced crop protection practices in traditional systems.

Microbial Diversity and Disease Suppressiveness

Soil. There is an urgent need to support significant efforts in research to reestablish disease suppressive environments in agricultural soils. We must obtain a better understanding of the effects on the microflora of using inorganic fertilizers and

practices which deplete organic matter in soil. There must be a better understanding of the ecology of the microflora and soil fauna of agricultural soils amended with composts, manure, and inorganic fertilizer, especially now that promising new study tools are becoming available. We must explore the ecology and maintenance of disease suppressive microbial population and communities in the soil and the mechanisms by which soils develop disease suppressiveness with organic amendments. We should explore further the role and ecology of bacteria which induce resistance in plants, those components of the microflora which eliminate germination stimulants of pathogens, the role of organisms genetically capable of producing inhibitors and chelating agents such as siderophores, of mycoparasitism, and of the role of the soil fauna on pathogen suppression. In addition, there is a need to reexamine the reasons for the lack of success in the past in manipulating microbiological control agents. Were ecologically sound principles used? What improvements are needed to economically mass produce and deliver biocontrol agents?

Aerial crop parts. A better understanding is needed, of the dynamics and interactions which control the microflora and plant pathogens on the phylloplane and surfaces of post harvest products. There is also a need to further explore the potential of increasing the suppressiveness of the phylloplane microflora by qualitatively and quantitatively changing it through manipulation of the microclimate, the nutrient status of leaf surfaces, direct application of components, or through the use of compost extracts whose use and mode of action we are just beginning to understand.

Flexibility in Integrated Control Practices

Disease management practices which are effective when used flexibly and in combination deserve more study. Cultural disease management systems should be components of such a strategy. They are principle components to protect crops used in traditional agricultural systems. Traditional agricultural systems require study to document sustainable components and devise ways of adapting them to modern systems of agriculture. Conversely, we require ways to better adapt and devise modern technologies for traditional systems. To adequately understand crop protection practices in a holistic manner, we must recognize that there are social components to research in plant pathology which cannot be left solely to anthropologists and social scientists. To date, closely interactive research between the hard and soft sciences has been discouraged by training, work descriptions, and expectations of scientific journals. It is also evident from past failures that we must encourage greater farmer participation in the development of relevant site-specific disease management technology, through participatory research and education strategies. Indeed, the education of farmers, extensionists, and scientists relative to the knowledge of each group is probably the most powerful tool to impact and improve, crop protection practices. Such education would be helpful in improving the consideration of site specificity, cultural, religious, and economic differences among farmer groups, which are not adequately incorporated into system designs at present.

Sustainability Indicators

Finally, what should we use as indicators of whether agricultural practices are sustainable or not? Many disciplines have indicators of which are often poorly understood or even regarded as inadequate, inaccurate, or misleading by other disciplines. Much more needs to be done to develop reliable indicators of sustainability which all disciplines can accept. We also believe that diagnostic research to provide base line information on plant disease severity, indicators of human health, environmental contamination, and destruction and economic impact of crop protection is needed, as well as simple and cost effective ways of doing this.

Conclusion

In conclusion, we realize that disease management is but one component of the efforts to introduce sustainable agricultural systems, and that sustainable agriculture transcends the agricultural sector. For this reason we must stress a systems approach and recognize that crop protection is but a small subsystem. In other words we must think and approach problems with an understanding of the whole. To do so we must set in place reward systems that do not bias research into narrow fields as we have seen in the past and present, but which reward those that investigate problems holistically and thoughtfully. Bertrand Russell once said, "Most people would agree that although our age far surpasses all previous ages in knowledge, there has been no correlative increase in wisdom". In crop protection and in research in general, today we need to augment our wisdom more than ever before, if we are to be successful in our quest to find and implement disease management and technologies which will sustain and enhance agricultural production for generations to come.

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IV. Resource Base and Stresses

Land Related Stresses in Agroecosystems

F.H. Beinroth, H. Eswaran, P.F. Reich and E. Van den Berg

Abstract

This chapter focuses on the agrobiophysical parameters of land as these parameters affect the potential of the land for rainfed agriculture in the tropics. Rainfed agriculture in the tropics is constrained by a multiplicity of land related stresses. There are, in fact, no land resources in the tropics which have no limitations. The land factors constraining agriculture are considered as intrinsic stresses, such as nutrient retention capacity, or externally induced stresses, such as moisture availability. The Food and Agriculture Organization of the United Nations (FAO) has evolved a comprehensive list of land characteristics that may be employed as diagnostic factors in the synthesis of the land qualities which is the basis for the assessment of land potential, including stress conditions. Land characteristics, in turn, can be derived from land resource inventories, particularly soil surveys and characterization data.

This chapter advances the concept of agrodomains. These are defined as areas with the inherent capacity for a specific land-use. They are divided into subdomains on the basis of production levels which are controlled by biophysical and socioeconomic factors. Subdomain analysis is conducted to identify production constraints and to develop prescriptions for performance improvement. The domain approach differs from the traditional approach to land evaluation, in that, it is economics driven and seeks tactical solutions for performance enhancement, whereas land evaluation is resource driven and more strategic in nature.

It is concluded that the judicious husbandry of land resources requires:

- *the generation, mobilization and integration of knowledge for scientific land-use planning that utilizes digital information technology;*
- *a shift in research imperatives to future-oriented issues, such as identification of indices of sustainable land management, and the long-term on-site and off-site consequences of agricultural practices; and*
- *visionary scientific and political leadership that precipitates public policy and action programs that ensure a healthy future for the land.*

A major challenge in the coming decades will be to manage the interaction between land-use and the environment to increase the prospects for environmentally, economically and socially sustainable improvements in the quality of life.

Introduction

The United Nations Conference on Environment and Development (UNCED), the "Earth Summit"—held in Rio de Janeiro, Brazil, in June 1992 focused the world's

attention on the harmful impact of development on the Earth's life-sustaining capacity. The UNCED generated eloquent and passionate rhetoric but so far has not precipitated the massive and concerted action programs it called for. If nothing else, however, it created wide awareness of the environmental state of affairs and moved the issues into the political arena. The UNCED may thus be considered a culmination of the work of the Brundtland Commission (WCED 1987) which emphasized the finite limits and fragility of global resources.

The UNCED also produced Agenda 21, a global blueprint for environmental action organized around seven themes, one of which is "Efficiently using natural resources: land, water, energy, forests, biological resources". This is unquestionably a theme of central importance. Not only have the Earth's land resources already been extensively altered by human activity, but such human impacts will inevitably intensify as the world population doubles in the next 50 years. The Food and Agriculture Organization (FAO 1989) reported that in the tropics the cultivated land per person declined from 0.28 ha in 1971 to 0.22 ha in 1986. Considering the current population projections, this negative trend is certain to continue. In addition, disruptive changes in sociocultural patterns are expected to affect land-use and productivity. Near the end of this decade, mankind will pass a demographic milestone: for the first time in history, more people will live in and around cities than in rural areas. With a 50-year horizon during which land related problems might approach critical dimensions, there is a degree of urgency to seek solutions to these problems now.

Eswaran (In press) identified the major issues that need to be addressed in this regard:

- **Limits of land resources.** With much of the arable land already under the plow, increased food and fiber production must result primarily from increased production per unit area rather than an increase in the area of cultivated land.
- **Land degradation.** Degradation and, to a lesser degree, urbanization of arable land reduces the area of productive land at accelerated rates. This causes increased use of marginal and fragile lands which are difficult to maintain under sustainable production.
- **Rural poverty and unequal equity distribution.** Continued migration of people from rural to urban areas results, at least partially, from inadequate opportunities and poor support for agrobased industries in rural areas.
- **Weak institutional research and development framework in the National Agricultural Research System (NARS).** There is a continuous lack of infrastructure, capital, and human resources in the NARSs to respond to changing needs.
- **Research emphasis on past concerns rather than future problems.** Greater emphasis must be placed on systems-based information technology and resource-focused rather than commodity-oriented research.
- **Global climate change.** Alternative strategies must be developed to reduce the risks of an uncertain future.
- **Public policy.** Scientists must develop the databases and decision tools to allow decision makers to formulate environment-conscious public policy.

It is obviously beyond the scope of this chapter to comprehensively address these issues. However, it is in the general context of this perspective that this chapter attempts to assess the nature and extent of the biophysical constraints to agriculture. This should enable the targeting of research, specific to the dominant stresses of agrobiophysical constraints and also facilitate land evaluation and agrotechnology transfer.

The following discussions are confined to the land resources of the tropics and to rainfed agriculture. Also, sociocultural aspects, micro- and macro-economics, infrastructure, and demographic trends, though important features of land, are not considered.

Land and Stressed Land

Ever since the first schemes of land evaluation were developed, the concept of land has been the subject of much discussion. The pioneer efforts initiated by the Food and Agriculture Organization in 1972 ultimately produced this definition (FAO 1976).

Land: An area of the earth's surface, the characteristics of which embrace all reasonably stable, or predictably cyclic, attributes of the biosphere vertically above and below this area including those of the atmosphere, the soil and underlying geology, the hydrology, the plant and animal populations, and the results of past and present human activity, to the extent that these attributes exert a significant influence on present and future uses of the land by man.

In essence this land is viewed as areas composed of biophysical environmental characteristics which are or may be of importance to human use (Davidson 1992). The FAO definition excluded purely economic and social characteristics from the concept of land on the rationale that these form part of the economic and social context (FAO 1976). Nonetheless, these characteristics become decisive criteria in the process of land evaluation. They are time-specific, however, whereas the biophysical conditions are of a more permanent nature.

Stressed ecosystems [Eswaran (In press)] are those which have degraded or have reached such a stage of degradation that they cannot support their original biotic communities or cannot support agriculture in the absence of relatively high inputs. In the context of this chapter, which is focused on land constraints relative to agriculture, we consider stressed agroecosystems as those where the land-use requirements are not matched by land qualities.

Land Conditions Constraining Rainfed Agriculture

Rainfed agriculture in the tropics is constrained by a multitude of adverse land conditions. There are virtually no land resources in the tropics which have no constraints and are equally well suited for all potential agricultural uses. A general analysis of the stress conditions is further complicated by the fact that most lands have more than one kind of stress and frequently have numerous ones. Moreover, stress is not a neutral but use-specific condition and consequently what may be beneficial property for one land-use can be adverse for another one. Tea, e.g., tolerates subsoil acidity well whereas sorghum does not. Further complication

is caused by the time dependence of some constraints. A seasonally high water table, for instance, may result in oxygen deficiency for some months but pose no problem for the rest of the year.

Eswaran (1977) evaluated 615 taxa of Oxisols, Vertisols, Alfisols, Inceptisols, and Entisols with respect to 15 limiting conditions. He found only about 25 subgroups of Alfisols, Inceptisols and Entisols to have no major limitations as far as they can be inferred at the subgroup level. More recently, Dent (1990) examined the land resources of Asia relative to 12 broad stress categories as shown in Table 1. For India he reports the following:

Stress category	Percentage of land
Cold land	5.6
Semi-arid land	16.0
Dryland	10.2
Steep land	10.0
Shallow soils	5.7
Wet lands	2.5
Sandy soils	1.2
Heavy clays	20.4
Fertility limitations	2.4
Saline/sodic soils	4.1
Acid sulfate soils	0.1
Peat lands	0.1

Table 1. Major kinds of soil related stresses in the Indian subcontinent¹

Country	Stressed lands ² (%)											
	A	B	C	D	E	F	G	H	I	J	K	L
Afghanistan	12	92	9	68	49	1	7	Tr	1	4	0	0
Bangladesh	0	0	0	11	Tr	48	0	0	2	5	Tr	4
Bhutan	49	11	8	21	Tr	0	5	0	16	0	0	8
India	6	16	10	10	6	2	1	20	2	4	Tr	Tr
Nepal	33	1	14	18	4	6	8	0	5	0	0	1
Pakistan	22	31	63	3	0	0	0	Tr	0	Tr	0	0
Sri Lanka	0	Tr	0	13	5	6	4	Tr	13	7	Tr	Tr
Total	17	14	14	21	9	9	3	3	6	3	Tr	2

1. Source: Dent (1990) except for Afghanistan. The area of semi-arid lands is from USDA-SCS/WSR estimates.

2. A = Cold land; B = Semi-arid land; C = Dryland; D = Steep land; E = Shallow soils; F = Wet lands; G = Sandy soils; H = Heavy clays; I = Fertility limitations; J = Saline/sodic soils; K = Acid sulfate soils; L = Peat lands; Tr = Trace.

According to this analysis, about a fifth of India's land resources have no limitations for crop production. The data may be questioned, however, as an estimated land area of only 2.4% having fertility constraints appears rather unrealistic.

Land related stresses can be grouped in two basic categories: intrinsic and induced factors. Intrinsic factors are chemical, physical, biological, and holistic conditions that are inherent properties of the land. Examples are nutrient deficiencies, shallow sola, and low organic carbon content. Induced factors, on the other hand, are caused by external phenomena, mainly climate and human activity, and include moisture stress, soil compaction, soil erosion, pests and plant diseases. Table 2 lists intrinsic and induced stresses and provides examples. For a more complete discussion of stress factors reference is made to a book titled "Soil-Related Constraints to Food Production in the Tropics" published by the International Rice Research Institute (IRRI 1980).

Table 2. Biophysical stress factors constraining rainfed agriculture

Category	Examples of stress factors
Intrinsic stresses	
Chemical conditions	Nutrient deficiencies Excesses of soluble salts Low base saturation
Physical conditions	High susceptibility to erosion Steep slopes, shallow soils Surface crusting
Biological conditions	Low organic matter content High termite population
Holistic conditions	Low soil resilience Natural soil degradation
Induced stresses	
Chemical conditions	Oxygen deficiency Acidification Contamination with toxicants
Physical conditions	Accelerated soil erosion Soil compaction
Climate-controlled conditions	Soil moisture deficiency Unsuitable temperature regime Insufficient length of growing season
Biological conditions	High incidence of pests and diseases Allelopathy Elimination of predators
Catastrophic events	Floods and droughts Earthquake-induced landslides Volcanic activity
Holistic conditions	Poor soil health Lack of aesthetic value of agricultural landscapes

Assessment of Land Related Constraints

The FAO extensively evaluated lands using modern techniques and published books such as the "Framework for Land Evaluation" (FAO 1976) and "Guidelines: Land Evaluation for Rainfed Agriculture" (FAO 1984). FAO developed the concept of land quality which is defined as "a complex attribute of land which acts in a manner distinct from the actions of other land qualities in its influence on the suitability of land for a specific kind of use." Land qualities are properties of land units that affect a specific land-use in a particular manner.

Land qualities can be determined on the basis of land characteristics which are attributes of land that can be measured or estimated. These land attributes are also employed in establishing diagnostic factors. As defined by FAO (1984), a diagnostic factor may be a particular land characteristic or a function of several land characteristics, that has an understood influence on the output from, or input to, a specified kind of land-use.

For land evaluation for rainfed agriculture, FAO (1984) established 25 land qualities that are related primarily to crop requirements, management exigencies, and conservation needs. Examples are moisture availability, nutrient availability, and erosion hazard. The FAO guidelines (FAO 1984) also provide a list of about 100 land characteristics which may be employed to assess land qualities. Examples are rainfall, cation exchange capacity, and slope angle.

For each of the 25 land qualities, the guidelines elaborate on the nature and effects, application to evaluations, and means for assessment. Nutrient availability, for example, can be assessed by chemical analyses or, more qualitatively, with the fertility capability classification (FCC) of Buol et al. (1975) as modified by Sanchez et al. (1982).

In the process of land evaluation, the land qualities are compared with the requirements of the specific land-use under consideration. If there is a mismatch and the land qualities are not matching with the requirements, the system is stressed.

For a comprehensive discussion of the principles of land evaluation the reader is referred to the classic "Framework" (FAO 1976), the subsequent "Guidelines" (FAO 1984), and a recent book by Davidson (1992) that is noteworthy for its breadth and depth.

Information and Knowledge Needs and Sources

The quality and accuracy of land evaluation and stress assessment depends on the availability of processed knowledge on crop growth and development, and environmental characterization data. For most of the important crops of the tropics, the global aggregate of basic knowledge about crop physiology and growth requirements is adequate, although in many cases still widely dispersed. There thus exists a reasonable amount of qualitative knowledge of the environmental requirements of the crops to permit measurements needed to correct constraints to optimal production. Detailed assessments that must take cultivar-specific genetic characteristics into account, however, are still hampered by the lack of knowledge about these genetic coefficients.

Inadequate or incomplete environmental information, notably soil and weather characterization data, on the other hand, often constitutes the limiting factor in land appraisal, particularly when specific assessments at large scales are involved (Eswaran et al. 1992).

Reliable area- or site-specific primary data obviously provide the best database, but in their absence default procedures may produce satisfactory surrogate data. Where soil surveys employing soil taxonomy (USDA 1975) classes are available, reasonable inferences about soil properties can be made from the name of the taxon that identifies a map unit.

For example, one of the soils at the ICRISAT farm is classified as a Lithic Rhodustalf; coarse-loamy, mixed, isohyperthermic. The following analysis indicates the properties and, by implication, constraints that can be derived from the various elements that compose this name.

Category	Formative element	Defined or inferred accessory property
Order	Alf	Subsoil with high base saturation; no Al toxicity
Suborder	Ust	Ustic soil moisture regime: subsoil is dry for more than 90 cumulative days during the growing season
Great group	Rhod	Red soil colors, high iron content may cause P fixation
Subgroup	Lithic	Lithic contact within 50 cm of the surface, limited rooting volume and moisture storing capacity
Family	Coarse-loamy	Less than 18% clay, low cation exchange capacity; susceptible to moisture stress
	Mixed	Less than 40% of any single kind of mineral other than quartz or feldspars; intermediate clay-related properties
	Isohyper-thermic	Mean annual soil temperature is 22°C or more and difference between mean summer and mean winter temperatures is less than 5°C; year-round growing season

Many properties important to plant growth can thus be inferred from the name of the soil. Moreover, the name of a taxon, by virtue of its position in the key to orders, suborders, great groups and subgroups, it also indicates what properties it cannot have. Thus, Alfisols cannot have the properties that are, at the order level, diagnostic for Histosols, Spodosols, Andisols, Oxisols, Vertisols, Aridisols, Ultisols, and Mollisols. Similarly, the parameters that differentiate

Aqualfs and Boralfs from Ustalfs cannot be properties of Ustalfs. And, at the great group level, the differentiating factors for Durustalfs, Plinthustalfs, Natrustalfs, Kandiestalfs, Kanhaplustalfs, or Paleustalfs cannot be attributes of Rhodustalfs.

Land Degradation in the Tropics

The Journal of Land Degradation and Rehabilitation defines land degradation "as the loss of utility or potential utility through reduction of or damage to physical, social or economic features and/or reduction of ecosystem diversity." Land degradation is a major threat to development and the Brundtland Commission (WCED 1987) noted that "there is a growing realization in national and multinational institutions that not only many forms of economic development erode the environmental resources upon which they are based, but at the same time environmental degradation can undermine economic development."

In an effort to establish baseline data about the state of land degradation, the United Nations Environment Program (UNEP) commissioned the International Soil Reference and Information Center (ISRIC) to initiate a project entitled Global Assessment of Soil Degradation (GLASOD). The project recently published a world map of the status of human-induced soil degradation. According to the explanatory note that accompanies the maps (Oldeman et al. 1991), the percentage of land affected by soil degradation is as follows:

Africa	17%
Asia	18%
South America	14%
Central America	21%
Australasia	12%
World	15%

The GLASOD project arrived at these estimates by evaluating land resources and degradation resulting from water erosion, wind erosion, chemical deterioration, and physical deterioration. It differentiates four degrees (light, moderate, strong, and extreme) and also indicates the causative factors (deforestation, overgrazing, agricultural mismanagement, overexploitation, and bioindustrial activities). At the scale of 1:10 M, the assessments are necessarily broad but, nonetheless constitute a first step towards a global evaluation of the nature and geographic extent of land degradation that indicate the magnitude of the problem.

The island of Puerto Rico, for example, carries the map symbol wt 2.3 f/g. This indicates loss of topsoil through water erosion (Wt), of a moderate degree and affecting 10 to 25% of the island (2.3). The causes are deforestation (f) and overgrazing (g). At the chosen scale, these estimates are a fair representation of the actual situation.

It should be mentioned that not all land degradation results from human activity. In many instances loss or reduction of land performance is induced by natural phenomena, notably catastrophic events such as volcanic activity and pedogenic processes leading to acidification, salt accumulation, and nutrient leaching. It must further be noted that not all human intervention is negative. In many cases soil management and erosion control have, in fact, improved land

conditions, stabilized landscapes, and reversed degradation trends. But it must also be emphasized that although identifying the causes, nature and degree of severity of stressed ecosystems and developing techniques for control and rehabilitation is crucial, it may be an exercise in futility if political and socioeconomic conditions prevent their implementation.

Soil Resilience and Sustainable Land Management

In view of the preceding discussion, it should be obvious that sustaining or enhancing the production levels of agroecosystems is a major challenge. The realization that stable food production levels is a *conditio sine qua non* for achieving food security for future generations has brought the concept of "sustainable agriculture" to the forefront. But although it is a prominent and fashionable topic among agriculturalists and environmentalists, a generally accepted definition has yet to emerge. However, employing ideas advanced by Conway (1987) and Conway and Barbier (1988), one can describe "a sustainable agricultural system as one that maintains productivity, stability, and resilience over time."

Central to this paradigm are the concepts of sustainable land management (Dumanski et al. 1992a) and soil resilience (Brinkman 1990). In a paper that addresses these two concepts in the context of Agenda 21, Eswaran (1992) defined sustainable land management as: "a system of technologies that aims to integrate ecological and socioeconomic principles in the management of land for agricultural and other uses to achieve intergenerational equity."

In the same paper he defines soil resilience as: "the ability of a system to revert to its original or near original performance or state that existed before the impressed forces altered it."

Both concepts are still new to the scientific community and efforts to formulate action programs continue to be rather tentative. Nevertheless, an international workshop on "Evaluation for Sustainable Land Management in the Developing World" held in Chiang Rai, Thailand, in 1991 (Dumanski et al. 1992b), and an international symposium on "Soil Resilience and Sustainable Land Use" held in Budapest, Hungary, in 1992 helped to bring the topics into sharper focus. The awareness created will hopefully precipitate the concerted research programs that are needed to effectively address these critical issues.

Agrobiophysical Domains: An Alternative Approach to Land

Evaluation

The Framework for Land Evaluation (FAO 1976) constitutes a scale-independent methodology for evaluating land performance for a given agricultural use. The key process of the framework is "matching", i.e., the comparison of land-use and land. Although it is emphasized that evaluations have to be made in terms that are relevant to the economic and social context of the area, the methodology is largely based on environmental characteristics of the land and crop requirements. One of the underlying principles is that "evaluation involves comparison

of more than a single kind of use" (FAO 1976). The Framework may thus be characterized as a resource-driven methodology that evaluates land-use alternatives for strategic planning.

Land evaluation, however, can also be approached from another perspective. One can begin with a specific land-use and analyze performance constraints in a given area or at a site. This reasoning led to the concept of "agrobiophysical domains which are defined as areas with the inherent suitability for a specific land-use." The domains can be subdivided into subdomains on the basis of actual production levels which are controlled by biophysical, sociocultural and economic factors. These factors are analyzed to identify the constraints and develop prescriptions for performance improvements. Actual and potential performance values are a function of environmental characteristics, management inputs, and output returns. The specificity of such assessments is obviously scale-dependent and increases with decreasing domain areas.

Table 3 indicates a hierarchy of domains that should facilitate the assessment of the biophysical suitability of agricultural systems, actual and potential production levels, and the environmental effect of the managed system on the land resource from global to local levels. Also shown in the table is the approximate scale of the domains, the categoric level of the soil units in the domains, and the increasing specificity of land factors related to moisture availability.

Table 3. Hierarchy of agro-biophysical domains

Category	Scale	Soil unit	Examples of moisture availability factors
Global	1:25000000	Suborders	Soil moisture regime Climate class
Continental	1:5000000	Great groups	Soil moisture regime Length of humid seasons
National	1:250000to 1:1000000	Great groups	Rainfall amount Incidence of dry periods
Regional	1:250000	Subgroups	Evapotranspiration Depth of water table
Country/ Province	1:20000	Series	Daily precipitation data Particle size distribution
Farm	1:5000	Phases of series	Effective solum depth/ Field capacity
Field	1:500	Production factors	Slope aspect Rainfall intensity

At the domain level, the suitability of a specific crop can be evaluated using the methodology of the FAO Framework and Guidelines (FAO 1976, 1984); the principles of which can be applied at all scales. The Agroecological Zones (AEZ)

Project of FAO employed this approach at a continental scale. Volume 1 of the AEZ report (FAO 1978) contains a description of the methodology and the results for Africa. The maps delineate the generalized agroclimatic suitability assessment for the rainfed production of pearl millet, sorghum, maize, wheat, soybean, sweet potato, white potato, cassava, and cotton. The areas represent, in fact, the small-scale agrobiophysical domains of these crops in Africa. At the next level of assessment, soil properties are taken into consideration to demarcate areas with high potential and to signal areas with constraints. Figures 1a, and b, illustrate the sorghum and maize domains in Africa. This analysis only shows the potential for the land-use. The crops may be grown in other areas, where they may not be the most productive, or because of availability of management inputs such as irrigation. At a continental scale, the socioeconomic conditions

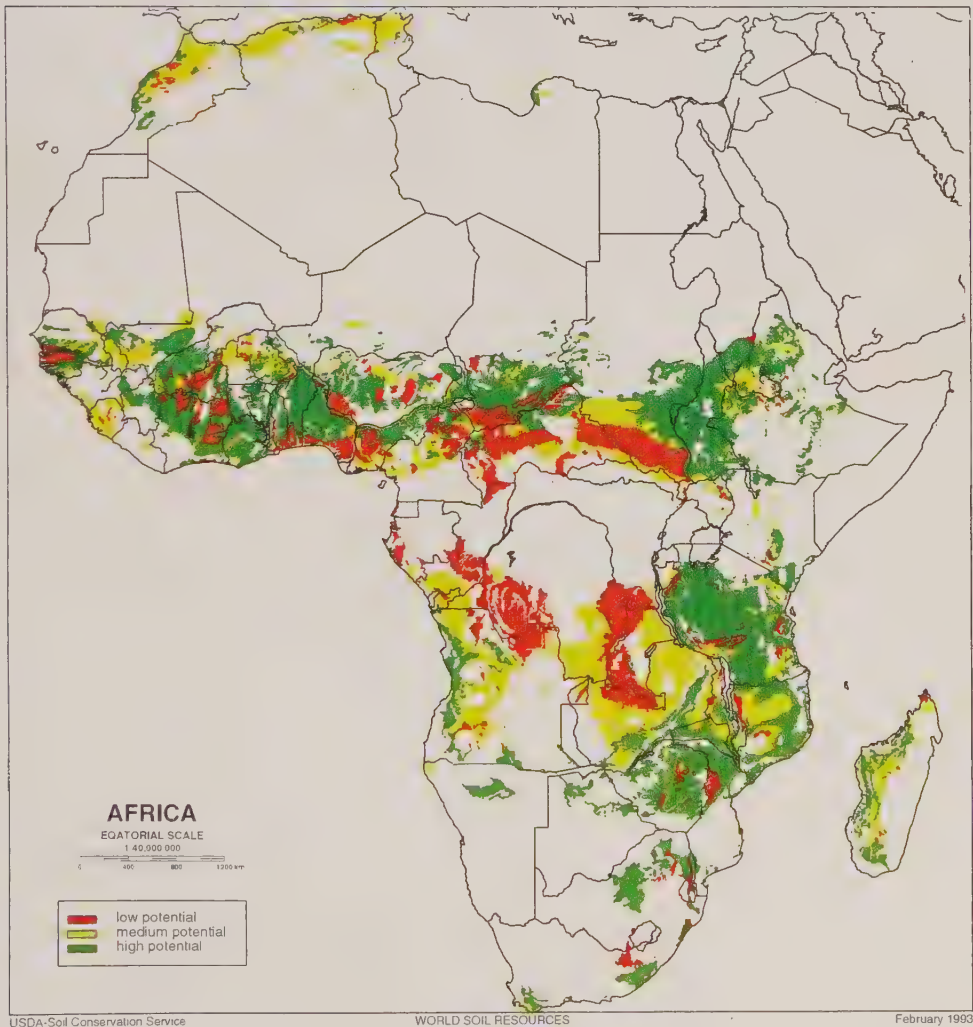


Figure 1a. Agrobiophysical domains for sorghum

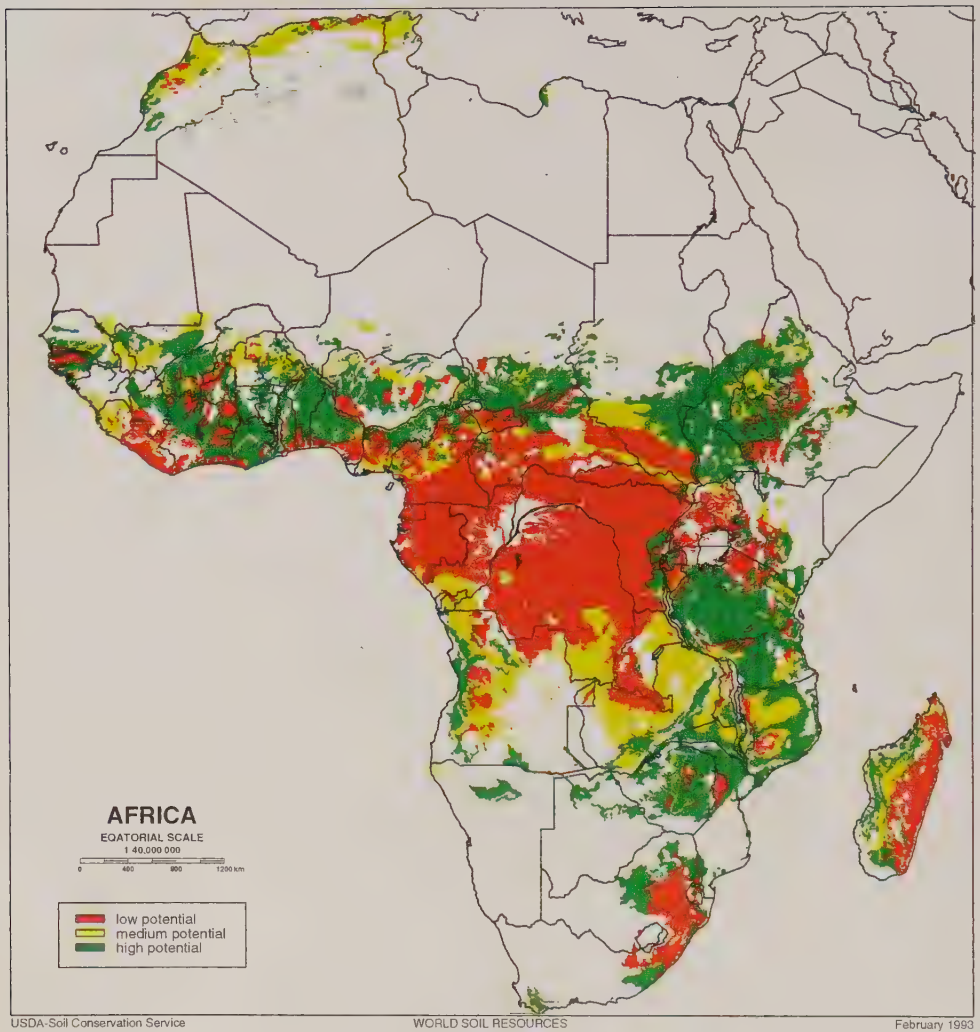


Figure 1b. Agrobiophysical domains for maize

of the countries becomes an important consideration in the domain analysis. Such preliminary assessments are important for targeting research and developmental activities for international donors and research centers.

A similar approach was used to establish crop-specific agrobiophysical domains for the Cimanuk Watershed in West Java, Indonesia. Figures 2a, b, and c, show examples of the different steps in the domain analysis procedure. In Figure 2a, the soils and their distribution is shown. A companion database provides the constraints of the soils within each map unit. An analysis of the constraints results in Figure 2b, showing the biophysical constraints. Matching the potentials of the soil and climate to the crop results in a map showing potential suitability. Figure 2c shows, for example, the agrobiophysical domain of upland

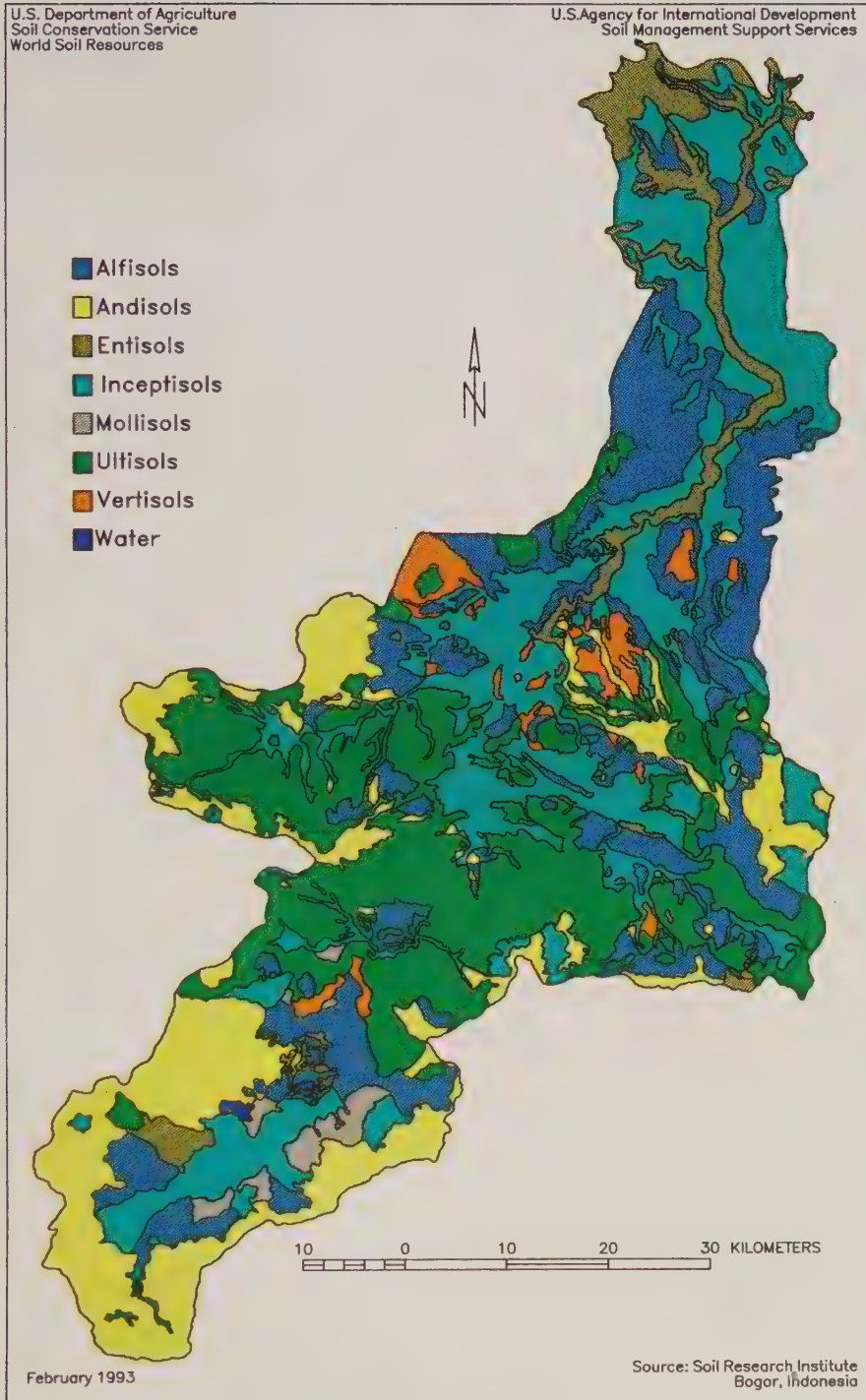


Figure 2a. Soils classified according to order Cimanuk watershed, West Java, Indonesia

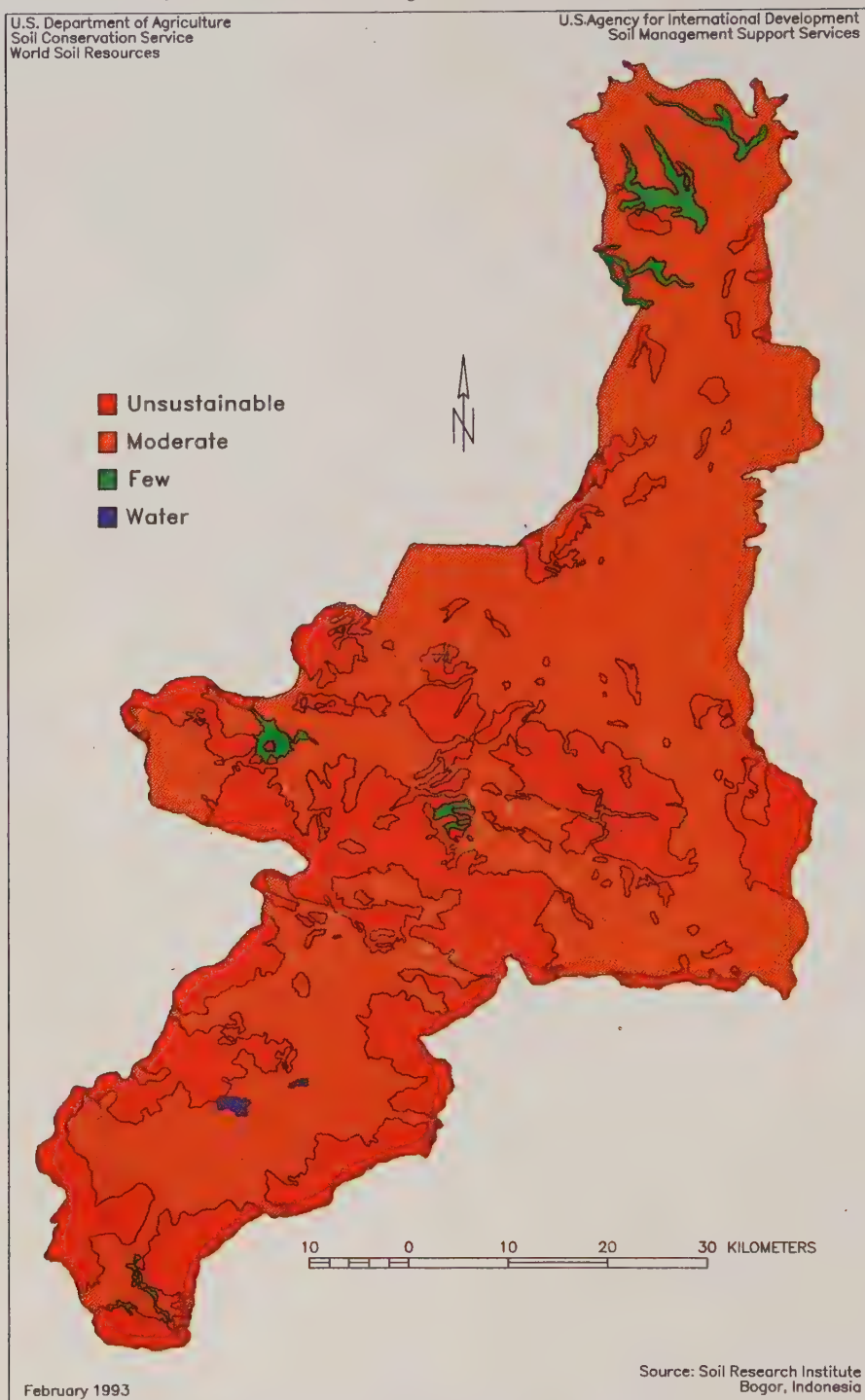


Figure 2b. Biophysical constraints to implement sustainable agriculture, Cimanuk watershed, West Java, Indonesia

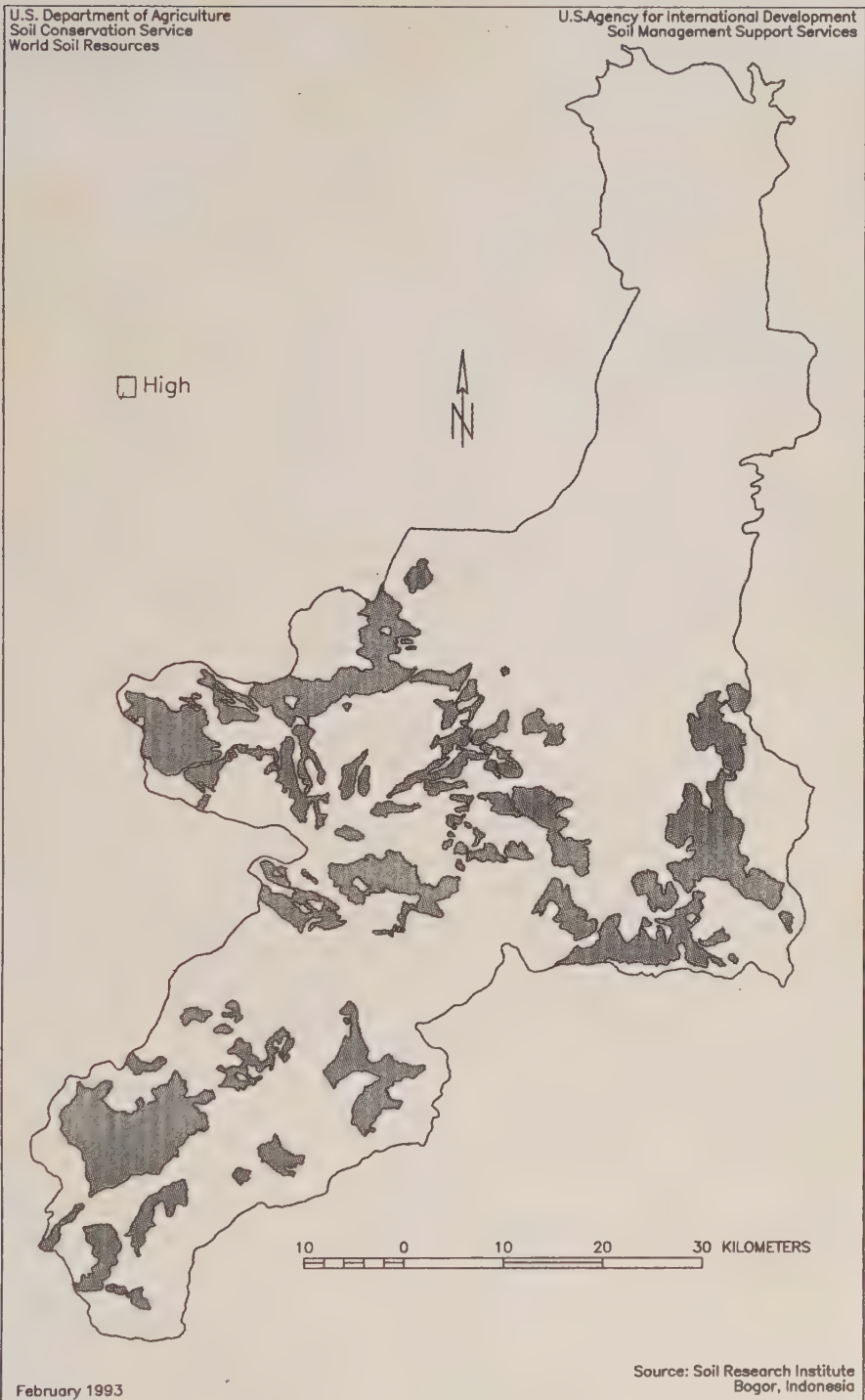


Figure 2c. Potential for upland rice (*Oryza sativa*), Cimanuk watershed, West Java, Indonesia

rice in the watershed. The biophysical analysis may be coupled to a socioeconomic evaluation together with analysis of market and transport facilities, to divide the domains into finer units for extension and management.

Implications

Information technology such as relational databases, soil and crop simulation models, expert systems, and decision support systems have all contributed to transforming land resource evaluation from an art to a science. The greatest impact, however, came through advances in two areas: (1) the scientific and commercial development of geographical information systems (GIS) and companion digital terrain models (DTM), and (2) the development of crop and environmental simulation models and related rule-based systems.

A GIS is a set of tools that permit the collection, storage, retrieval, transformation, manipulation, and display of spatially referenced data. The capacity of GIS to explore a variety of 'what if' type questions using different scenarios, is obviously of great importance to land-use planning and management. Similarly, the modeling of agrosystems has added new dimensions to land evaluation. Deterministic crop simulation models, for example, can predict the performance of a crop in a part of an agrobiophysical domain where it has not been grown. For a comprehensive review and discussion of land information systems and modeling of land resources, the reader is encouraged to consult Davidson (1992).

However, these and other relevant information technologies are merely tools, it cannot be overemphasized that the quality of the output they produce depends on the availability of adequate primary data. (Scarcity of such data caused what has been called the "parameter crisis"—too many models chasing too few data). A serious problem in this regard is that government funding for soil survey or meteorological monitoring is often inadequate or is being reduced. One reason for this may be that in the past soil survey and climatological information have not been efficiently used. The new information technology has changed this entirely as it can process huge amounts of data into useful information in very short periods of time. In our judgement, this should result in a renaissance of soil survey rather than a reduction.

The subject of spatial variability of land characteristics also requires attention. Stein et al. (1988) showed that this issue is best addressed by incorporation of soil survey data into geostatistical analysis with kriging. Another new development that warrants further study is the application of fuzzy set theory in land evaluation (Wang et al. 1990). According to Davidson (1992), still another avenue for research is the application of artificial neural networks which can deal with incomplete or inadequate data.

These scientific and technological advances, in conjunction with adequate primary environmental characterization data, facilitates an integrated approach to land resource issues that can play a key role in promoting the wise use of land resources that may help to prepare the groundwork for "the transition to sustainable life on earth", as envisioned by Agenda 21.

Conclusion

On a global scale the land resources of the world have the proven potential to produce more food at a faster rate than the growth of the population. That may be so, but many countries will have to confront an escalating problem of feeding their rapidly increasing populations while their agricultural growth rates are flat and their land resources are constant at best. However, while sound land management is extremely critical in these countries, it is of crucial importance all over the world. We believe that the judicious husbandry of land resources requires:

- the generation, mobilization and integration of environmental data and process knowledge for scientific land-use planning that takes full advantage of the latest advances in information science and digital information technology;
- a shift in research imperatives to future-oriented issues, such as the identification of indices of sustainable land management, and the long-term on-site and off-site consequences of agricultural practices; and
- visionary scientific and political leadership that precipitates public policy and action programs that ensure a healthy future for the land.

A major challenge in the coming decades will be to manage the interactions between land-use and the environment to increase the prospects for environmentally, economically, and socially sustainable improvement in the quality of life.

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Climatic Resource Characterization in Stressed Tropical Environments: Constraints and Opportunities for Sustainable Agriculture

S.M. Virmani

Abstract

Climatic resource endowments play a major role in the sustainability of agriculture in stressed tropical environments. Climate interacts intimately with the nature and quality of soil resource, that on human time scales, is nonrenewable. In rainfed areas climate imposes serious limitations on agricultural productivity, soil conservation, and enhancement of biodiversity. The dilemma of developing, and transferring sustainable land-use technologies that are adaptable in the resource-poor environments is a major challenge. Evidence suggests that the geographical and climatic resources of the stressed ecosystems vary significantly and require unique agricultural systems to sustain their production.

The climatic pattern of the stressed environments in the tropics is characterized by a strongly seasonal and highly variable rainfall. The rainy season may extend to less than 2 months in the arid tropics, and up to 7 months in the semi-arid tropics. Thus in the dryland stressed ecosystems, there is a short wet season followed by a relatively long dry interval of 5 to 10 months.

The land mass that dominates the areal distribution of soils in the stressed tropical environments is characterized by low organic matter, low available water-holding capacity, and hard setting surface-sealing soils. Under conventional cultivation surface horizons have plow pans. Thus the quality of land in the stressed environments is poor. This together with the overall variability of the seasonal rainfall, high potential evapotranspiration rates, and high volume short-duration tropical-rain storms seriously reduce the agricultural value of whatever little rain that is received. The available growing season varies considerably, at any given location, from year to year. Unpredictable droughts or floods may occur at any time during the cropping season. The time series nature of the rainfall interacts with the hydrological properties of the soil and this interplay governs the intake, storage, and distribution of the available water and nutrients in the root profile.

Agroclimatic studies of the stressed tropical environments have shown that by analyzing long-term data, it is possible to estimate stochastically the variability of rainfall. Robust-water balance models are now available which

can be used advantageously to determine the length of the crop-growth season and its variability. By estimating the rainfall variability and growing season lengths, as the two key agroclimatic determinants of the stressed dryland ecosystem, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) developed crop calendars for sustainable land-use systems. Emphasis in such a scheme is on inter- and relay-cropping, and on diversified land-use by incorporating agrohorticultural or agroforestry systems suited to the available soil quality. Thus a fundamentally useful method of agroclimatic evaluation which can be used to suggest alternate management practices that will sustain productivity and enhance the soil resource base is available. A minimum data set requirement to use this Eco-pedo transfer function for research and development in the semi-arid tropics has been developed. Such an evaluation also incorporates opportunity cropping potentials rather than underscoring the climatic constraints.

The climatic resources of the world are dynamic both spatially and temporally. Due to the increased pace of industrialization and extension of cultivation into ecologically fragile regions, the sustainability of dryland agriculture in the tropics is at crossroads. In some regions (e.g., Sahelian Africa), the rainfall has reduced considerably during the past 2 decades. The length of the growing season has also shown a marked decrease. In India the rainfall has shown an exceptional variation during the last decade. Thus the climatic resources that control the agricultural performance in the stressed ecosystems are becoming more variable and scarce.

There is an urgent need to create a user-friendly packaging and delivery system for agroclimatic information. A framework which can be used for organizing and conducting agricultural development programs based on agroclimatic qualities of the land at various levels (international, regional, local) needs to be evolved. A long-term planning perspective has to be taken. It is necessary, that decision makers and planners take into account climatic resources, while attempting to alleviate the constraints to increased productivity and while introducing sustainable agricultural practices. The challenge before the resource-related researchers in the future is two-fold: one, to relate future agenda for farming system research with a sustainability perspective; and two, to help decision makers recognize long-term planning needs by supporting production systems that avoid further degradation of the environment and contribute to the restoration and enhancement of productive capacity of the available agroclimatic resources. The choice between preserving and upgrading scarce natural resources for future use or exploiting these now to meet current needs is tough and is the key issue to be resolved by the people living in these stressed environments.

Introduction

Any discussion about the future of the agricultural development in the world's stressed tropical environment, and dryland agriculture in particular, ranges from euphoric optimism on the one hand to pessimism on the other. The pessimists assert that the arena of future agricultural development for global food security lies in currently irrigated and potentially irrigated lands. Food in these areas could be produced relatively cheaply under intensive agriculture. Dryland agriculture

does not have the capacity to sustain large populations. The optimists feel that drylands have sustained flourishing agriculture in the past, and that land degradation and declining productivity are only a passing phase. Science and technology would be able to offer attractive solutions to increased agricultural production in dry areas on a sustained basis.

This chapter examines the agroclimatic features of semi-arid tropical (SAT) agriculture in the context of its ecological endowments for sustainable agriculture. No attempt has been made to catalogue the diversity of soils and climates of the SAT, but the principles underlying the climatic analysis and synthesis for sustainable agriculture are highlighted. Sketching of a broad mosaic of agroecological possibilities of the SAT, would perhaps assist in the process of technology development.

SAT: A Broad Definition

Geographically, all areas situated within the Tropics of Cancer and Capricorn receiving the principal amount of their annual precipitation within a short, well-defined rainy season are called semi-arid tropics. Climatologically, all areas where the mean annual temperature exceeds 18°C and the rainy season extends from two to seven months are semi-arid tropics. For at least five to ten months, little rainfall is received. Ecologically, the vegetation associated with such a region is semi-desert and thorn savannah in tropical dry climates, and dry savannah woodlands in the wet-dry climates (Troll 1965).

The land mass that dominates the areal distribution of soils in the SAT environments is characterized by low-organic matter, low available water-holding capacity, and hard setting surface-scaling. Under conventional cultivation the SAT soils have plow pans under surface horizons. Thus, the overall quality of land in these stressed tropical environments is poor. The soil pattern is complex in many areas. The nature of the parent material and geomorphic characteristics have resulted in a high proportion of SAT soils being shallow and stony on moderately steep slopes, and considerable areas have sandy Alfisols and related soils.

The climatic resources of the SAT are continuously in a state of flux due to inter- and intra-annual variability of weather. The sustainability of agriculture is threatened by the increased pace of industrialization, large-scale removal of forests, and extension of cultivation into ecologically fragile regions. In some regions (e.g., Sahelian Africa), the rainfall has considerably reduced during the past two decades and the growing season has shown a marked departure from the long-term normal (Sivakumar 1989). In India the rainfall has shown an exceptional variability during the last decade (ICRISAT 1988). Thus, the climatic resources that control the agricultural performance in the stressed tropical systems are becoming more variable and scarce. A re-examination of the natural resource endowments is necessary for evaluating sustainability of farming systems and practices that are conservation-effective, and that enhance the productive capacity of the available resources.

Climatic Analysis and Sustainable Agriculture

In the stressed SAT environments, the total annual rainfall varies from about 500 mm in northwestern India and Botswana to 1400 mm in eastern India (Table 1). Sivakumar et al. (1983) have shown that the annual distribution of rainfall and the persistent recurrence of a specified amount of rainfall over a short-term is more important than the quality of rainfall in a given season. Hargreaves (1971, 1975) observed a linear relationship between mean annual rainfall and the amount of rainfall at the 75% probability level. He was thus able to create a moisture availability index (MAI), defined as dependable precipitation (PD)/potential evapotranspiration (PE) where PD is the precipitation which has a 75% probability of occurrence based on an analysis of long-term monthly data and PE is estimated potential evapotranspiration. Virmani et al. (1978) carried further the work of Hargreaves by estimating MAI in terms of both initial and conditional probabilities.

Table 1. Rainfall and PE at some selected locations in SAT

Location		Rainfall (mm)					Rainy season	Annual PE (mm)
		Annual	Seasonal	Maximum	Minimum	Range		
Hisar India	29° 10'N	446	317	1048	158	890	Jul-Sep	1616
Dakkar Senegal	14° 42'N	498	479	923	191	732	Jul-Sep	1753
Mahalapye Botswana	23° 06'S	502	415	769	285	484	Nov-Mar	1613
Anantapur ¹ India	14° 41'N	562	116 327	778	233	545	May-Jun Aug-Oct	1858
Coimbatore ¹ India	11° 02'N	574	146 255	880	224	636	Apr-May Oct-Nov	1620
Maiduguri Nigeria	11° 54'N	650	583	888	444	444	Jul-Sep	1936
Kurnool India	15° 50'N	674	568	1096	281	815	Jun-Oct	1828
Hyderabad India	17° 27'N	764	663	1431	455	976	Jun-Oct	1758
Kano Nigeria	12° 00'N	830	805	1117	580	537	May-Sep	1852
Nairobi ¹ Kenya	01° 18'S	941	540 248	1429	542	887	Oct-Dec Feb-May	1342
Raipur India	21° 14'N	1388	1290	2181	689	1492	Jun-Oct	1723

1. Bimodal rainfall areas.

It is suggested that to characterize the rainfall environment apart from the annual and seasonal rainfall, short-term rainfall statistics in terms of MAI and probability analysis are important for defining dependability of rainfall (Table 2).

Table 2. Probabilities of selected events at three locations¹

Event or operation	Probability (%)		
	Solapur	Hyderabad	Bhavanisagar
Possibility of at least one off-season tillage in May	38	54	92
Success in early sowing	77	92	15
Occurrence of one 21-day dry spell during June to September rainy season	92	54	100
Occurrence of three 21-day dry spells in the rainy season	15	0	77
Occurrence of three 14-day dry spells in the rainy season	62	38	100

1. Source: Huda et al. (1988).

Length of the Growing Season

Incorporation of rainfall, plant, and soil-water balance parameters results in some form of length of growing season (LGS). The LGS, with some estimates of probability based on actual rainfall records, is recognized as the most useful single parameter for judging suitability of a given production system. As an example, if the LGS of 90 days' duration occurs at a location with 75% probability and the LGS of 120 days' duration with 25% probability, the drought risk to a 90-day duration crop is minimal but a 120-day crop may be exposed to drought stress particularly at the maturity stages. Intercropping a short-duration (90-day) crop with a medium-duration (120-day) crop in the proportion of 3:1 is indicated. Agronomic feasibility, economic factors, and farmers' preference influence the proportion of the intercrops used in the field. The agroclimatic analysis could provide the first approximation data in this regard.

Characterizing Agroecological Yield Potential and Yield Gaps

Virmani and Alagarswamy (1993) have tried to link crop models, agroecological data, and geographical information system (GIS) so as to estimate the agroecological potentials of a crop (Figure 1). In the study reported here, we estimated potential sorghum yields in some agroecological (AE) subregions of peninsular India using the CERES sorghum crop growth model and compared it to on-farm yields to:

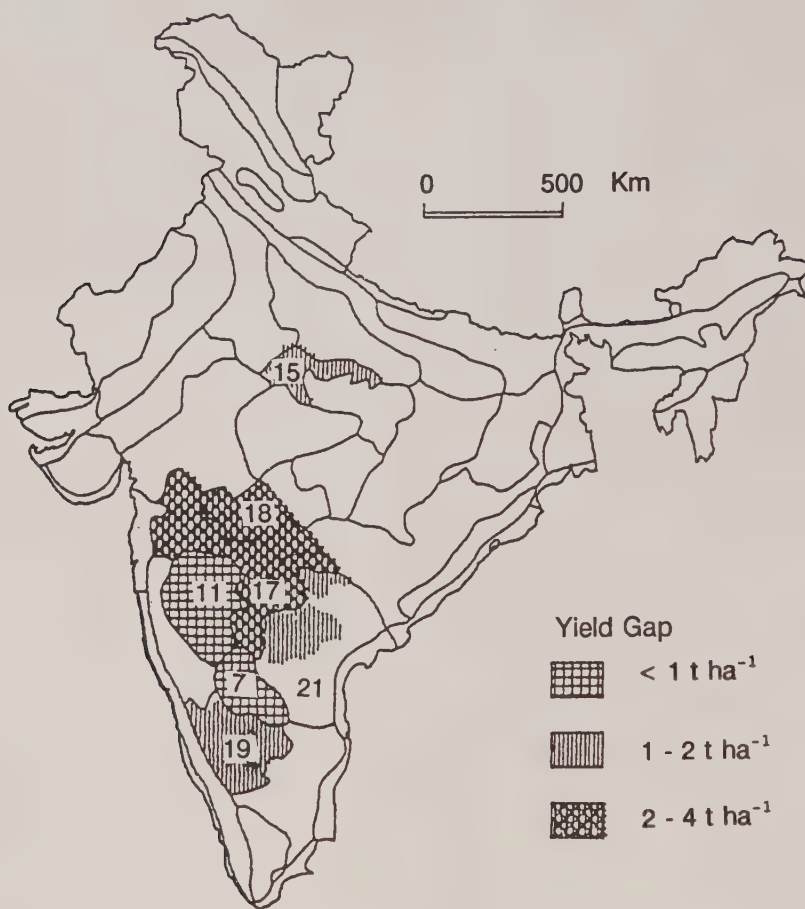


Figure 1. Yield gap analysis of sorghum production for selected agroecological subregions

- define agroecological potentials for sorghum across some agroecological subregions;
- estimate yield gaps;
- evaluate risks to dependable crop production using historical weather records;
- characterize “untapped” potential across various agroecological subregions in which sorghum is an important crop; and
- make suggestions for using the technique for priority setting for sorghum research.

Sorghum Production in Peninsular India

Although sorghum is grown on 15 million ha across several agroecological subregions of India, the primary production areas lie in peninsular India. The

crop is grown in the rainy season extending from June to October in hot semi-arid and subhumid peninsular India and northern plains with Vertisols and associated soils and Alfisols. In this region [AE subregions 11, 17, and 18] the length of the growing season is 90 to 180 days. The sorghum-growing regions in the peninsular India are characterized by a semi-arid tropical climate, with 500–900 mm seasonal rainfall and LGS varying from 110 to 150 days. The sorghum crop is mainly grown in red (Alfisol) and black soil (Vertisols, verticsoils) with variable moisture holding capacities in the root profile. Typically the crop is grown in soils with 100–150 mm available water-holding capacity during the rainy season, and in soils that can hold over 200 mm available water as far as a postrainy season crop is concerned.

Model Description

The CERES sorghum crop-growth model was used in this study. The model operates on a daily time step to simulate crop development, water and nitrogen balance, growth and yield based on soil, climate, management and crop genetic inputs. This simulation model has been tested with several independent data sets from India, Australia, and the USA, and has been found to be fairly robust. It was coupled with the Decision Support System for Agrotechnology Transfer (DSSAT) software developed by the International Benchmark Soils Network for Agrotechnology Transfer.

Simulation Study Methodology

The simulation study in cooperation with the International Fertilizer Development Center (IFDC) was conducted for several major sorghum-growing locations. These included eight benchmark locations in peninsular India. Some agroecological characteristics of the eight locations are given in Table 3.

Table 3. Agroecological characteristics of selected benchmark locations used in the yield gap study

Location	Temperature (°C)		Rainfall (mm)	Soil type	Length of growing season (days)
	Maximum	Minimum			
Hyderabad	31.7	20.0	764	Mixed red and black	120–150
Parbhani	33.7	19.9	903	Shallow and deep black	120–150
Pune	32.0	18.0	715	Shallow and deep black	150–180
Akola	34.0	20.4	876	Deep black	120–150
Hebbal	29.6	18.6	819	Red loamy	120–150
Gwalior	32.5	18.8	900	Mixed red and black	120–150
Solapur	33.7	20.5	742	Shallow black	90–120
Bellary	32.9	22.2	518	Mixed red and black	60–90

Historical weather data obtained from the India Meteorological Department (IMD) were used to make simulation runs. The weather records extended for a period of 15 to 25 years. Standard soil profile data for each of the sites were obtained from Benchmark Soils of India (ICAR 1982). Input data for running soil water balance were calculated from the soil physical characters using DSSAT. The soil water-holding capacity among the locations varied between 163 and 180 mm. Four N fertilizer rates from 0 to 90 kg N ha⁻¹ were simulated.

As a test crop, a standard sorghum cultivar (hybrid CSH 1) was used for this study. Although this cultivar is not popular now, most crop coefficient data required for the model are readily available for it. The results of the study would not change greatly if appropriate crop coefficients of any other sorghum cultivar maturing in about 105–110 days were used. Based on data from ICRISAT Center, initial soil moisture of the entire soil profile was set at 25% of potentially extractable water. The initial mineralized N was set at 30 kg ha⁻¹, and the amount of crop residue available per hectare for potential mineralization was set to 500 kg of straw and 100 kg of roots. The sowing date window was set between 1 June and 15 July and the crop was sown on the first day in this period when adequate soil moisture in the top 30 cm layer was available. If the sowing condition was not met by 15 July, the season was assumed to be a failure (mainly based on the shoot-fly damage and crop running out of water during grain filling). It was assumed that nutrients other than N were not limiting and biotic stresses were not present.

Simulation Results

The four N fertilizer rate scenarios simulated for four selected benchmark locations are presented in Figure 2 as Cumulative Probability Distribution Functions (CPDF).

Water-limited simulation results show that in all the four locations a standard application of 30 kg N ha⁻¹ at the time of sowing resulted in a clear response to the added N. Beyond this level the prospects of a large positive response to N fertilizer were not marked. In 8 out of 10 years the potential yield in Patancheru would be more than 4 t ha⁻¹, and in Pune and Parbhani it is likely to be above 2 t ha⁻¹. In contrast in Solapur potential yield would be above 2 t ha⁻¹ in only 7 out of 10 years.

The farm-level yields are regularly monitored by the Departments of Economics and Statistics through well-established crop cutting schedules and the data district-wise are easily available. Estimates of actual yields obtained at the farm level for these seven locations were derived from total area sown and total production district-wise. The differences between potential yield predicted by the model and estimates of yields obtained at the farm level constitute the yield gap.

Yield Gap Analysis

The difference between the agroecological potential of a crop and what the farmers realize in a given region is termed as the “yield gap”. It is a popular way of characterizing the “untapped” potential and of defining the “opportunity”

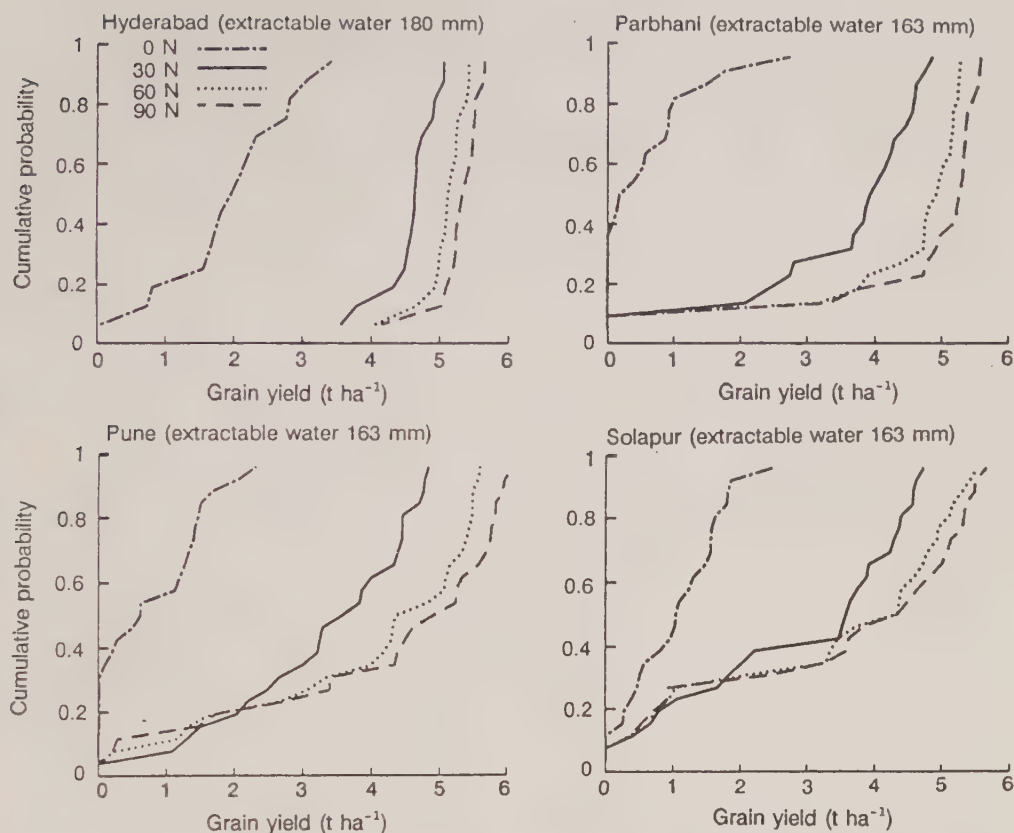


Figure 2. Cumulative probability distribution function (CPDF) for grain yield of sorghum at selected benchmark locations for different levels of N fertilizer applied at sowing time

that can be exploited if all constraints are removed. Yield gap analysis can be a major tool in the hands of a researcher in defining priority research domains within a broad crop growing region. In the recent years with the availability of “robust”, well-tested crop growth and the development of simulation models and geographical information tools, it has become possible to estimate the agroecological potential of a crop across different environments, so long as minimum weather, soil, and management data and cultivar-specific coefficients are available.

Simulated potential yield at given probability levels, estimates of yield at farm level and the yield gap for the eight locations are given in Table 4. We used a Geographic Information System (GIS) to extend the yield gap data of a given benchmark location (from a point data) to the whole of the agroecological subregion (on a spatial basis) in which the benchmark location is situated. Extrapolation of point data to a spatial basis is justified by the assumption that each agroecological subregion represents fairly uniform soil and climatic conditions, LGS, and physiographic resources.

Table 4. Simulated potential grain yield (t ha^{-1}), distribution, mean, estimated mean farm-level yields¹, and yield gap² at selected locations (fertilizer rate 30 kg N ha^{-1} applied at the time of sowing)

Location	Potential grain yield probability level (%)					Mean	Farm-level yield	Yield gap
	10	25	50	75	90			
Hyderabad	3.7	4.5	4.6	4.9	5.1	4.6	0.4	4.2
Parbhani	0.4	2.8	3.9	4.5	4.7	3.5	0.4	3.1
Pune	1.2	2.3	3.9	4.5	4.7	3.5	0.4	3.1
Akola	1.8	2.5	3.1	3.7	4.0	3.0	0.9	2.1
Hebbal	0.0	0.46	2.3	3.6	4.5	2.2	0.7	1.5
Gwalior	1.1	1.5	2.0	3.3	4.1	2.3	0.4	1.9
Solapur	0.16	0.46	0.69	0.77	0.89	0.62	0.45	0.17
Bellary	0.5	0.65	0.83	1.29	3.11	1.15	0.66	0.49

1. Source: Agricultural situation in India (Oct 1990).

2. Difference between mean simulated yield and farmers' yield.

The agroecological subregions 17 and 18 are characterized by a large yield gap of 2–4 t ha^{-1} . Sorghum is cultivated over 4.4 million ha in these subregions representing 29% of total sorghum growing area in India. In subregions 15 and 19 and part of subregion 21 (constituting hot semi-arid central highlands and deccan plateau with loamy Alfisols and mixed Alfisols and vertic-soils, and LGS of 120 to 150 days), the yield gap is from 1–2 t ha^{-1} and in these subregions sorghum is grown on 6% of the total sorghum area.

Sorghum is mainly grown as a postrainy season crop in agroecological subregions 7 and 11 (constituting hot arid and semi-arid Deccan plateau with Alfisols and vertic-soils, and LGS of 90 to 120 days). In these subregions the yield gap is low (less than 1 t ha^{-1}) indicating that they are water-limited, marginal sorghum production environments. However, area sown to sorghum in these AE subregions represents 23% of the total sorghum growing-area of India (about 3.4 million ha).

Conclusions

Planning for sustainable productivity of stressed environments should consider important resources such as climate, soil, and plants in different agroecologies. Information on the climatic resources provides a general idea of the distribution of rainfall and cropping or land-use potentials. This information should, however, be combined with the crop and management inputs.

The example given in the chapter demonstrates how the crop models and GIS could be linked for priority setting. In India, in the agroecological subregions 17 and 18, the yield gap is large and there are indications that hybrid adoption rate is about 50% and that rainfall is adequate. The research portfolio in these subregions should be directed to explore the causes of such large yield gaps.

Subregions 7 and 11 are the core postrainy season sorghum-growing areas of India; but here the yield gap is also very low. Analyses suggest that the use of improved technology coupled with modern high-yielding cultivars is unlikely to result in major improvements in these subregions unless an increase in availability of water is achieved.

These preliminary analyses illustrate how the integration of crop simulation models with GIS can serve as a powerful tool to study yield gaps. The development agencies can then extend sustainable technological options.

There is an urgent need to create a user-friendly packaging and delivery system for agroclimatic information. A framework which can be used for organizing and conducting agricultural development programs based on agroclimatic qualities of the land at various levels (international, regional, local) needs to be evolved. A long-term planning perspective has to be taken. It is necessary that decision makers and planners take into account climatic resources, while attempting to alleviate the constraints to increased productivity and for introducing sustainable agricultural practices. The challenge before the resource-related researchers in the future is two-fold: one, to relate the future agenda for farming system research with a sustainability perspective; and two, to help decision makers recognize the long-term planning needs by supporting production systems that avoid further degradation of the environment and contribute to the restoration and enhancement of productive capacity of the available agroclimatic resources. The hard choice between preserving and upgrading scarce natural resources for future use or exploiting these now to meet current needs is the key issue to be resolved by the people living in the stressed environments.

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Managing Extreme Stresses in Arid Zone of Western Rajasthan (India)—CAZRI Experience

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Abstract

In India the hot arid ecosystem occupies 31.7 m ha of which 61% lies to the west of the Aravalis in Rajasthan. This arid ecosystem is being subjected to stress due to increasing biotic pressure. Economic activities like mining and textile industry are degrading the resource base. At least 2.5 million Adult Cattle Units (ACUs) would be in excess of the available fodder by 2000 AD. So alternate income generation through systems like arid horticulture and fisheries has to be adopted.

Wind erosion is a major problem. It can be partly mitigated by sand dune fixation and shelter belts. Some of the ideal and feasible technologies for these are presented.

Ground water is being overexploited. The static water table has been receding @ 1.0 m year⁻¹ Even the quality of water is affected in the hinterlands leading to high sodicity. Limited/conjunctive use with canal water and correction of sodicity with gypsum are needed to live with this problem. Recharging of ground water with checkdams on ephemeral streams may be attempted.

Misuse of canal water has to be minimized by reducing inflow of water, using drip/sprinkler irrigation and improving vertical/horizontal drainage wherever possible.

Mining leads to overburdens and/or dugouts. Vegetation of the overburdens is needed and exploiting dugouts for fish culture has also to be attempted.

Industrial effluents contain dyes, salts and sodicity. By correcting sodicity, this water can be used for agricultural activities.

Introduction

The hot and relatively cold arid lands in India cover about 39.0 m ha of which hot arid ecosystem occupies 31.7 m ha. Of this 61% lies in western Rajasthan, to the west of the Aravali range followed by adjacent areas of Gujarat (20%). The other areas are in Punjab and Haryana (9%), Andhra Pradesh (7%), Karnataka (3%) and Maharashtra (0.4%). The Central Arid Zone Research Institute (CAZRI) has been addressing research problems for the overall development of the arid regions particularly, western Rajasthan. There has been little research effort for

the cold arid ecosystem. This chapter discusses the technologies for combating stresses to sustainable agriculture in the western Rajasthan.

Stresses in the Hot Arid Environment

By and large the stresses in relation to resource base can be grouped as anthropogenic and technogenic. The anthropogenic stresses include biotic pressure, overexploitation of ground water and misuse of canal water. The technogenic stresses arise out of mining activity and industrial effluents.

Biotic Pressure

The arid region of western Rajasthan can be classified into four zones based on the annual precipitation. Statistics on their extent, rainfall, population and livestock are given in Table 1.

Table 1. Some rainfall and population indices in arid zone of India

Zone	Area (m ha)	Annual precipitation (mm)	Population ¹ [Density 100 ha ⁻¹]	Livestock ² (ACUs) [Density 100 ha ⁻¹]
I	3.84	< 250	9	8
II	7.63	250–300	83	37
III	6.80	320–380	102	45
IV	2.60	380–425	188	85

1. 1991 Census.

2. 1988 Census.

The population has increased from 9.5 million in 1971 to 17.4 million by 1991. The annual growth rate in the last decade had been 2.9%. However, it was 4.5% in the zone I.

Similarly the livestock population (ACUs) has increased from 6.8 million in 1953 to 9.6 million by 1983 and to 8.6 million by 1988 even after a very severe drought in the preceding year (1987), when starvation deaths to the tune of 5.5 million animals were recorded.

The rapid increase in both human population and livestock has led to enormous biotic pressure on the already fragile ecosystem.

The Climate of the Arid Ecosystem

The annual rainfall in the region varies from less than 100 mm in the West to a little over 400 mm in the East. This meager rainfall is ill distributed and the growing season extends from less than 8 weeks to about 20 weeks depending on the amount of rainfall and soil type. High temperatures in May and June (43°–45°C) with high velocity winds (25–30 kmph) and low atmospheric humidity, lead to dust storms with considerable soil movement.

The soils are coarse textured with low water-holding capacity and low productivity. Soil crusting is a common problem. Crusting at sowing time causes poor seedling emergence of small seeded crops like pearl millet and moth bean. It also promotes runoff. Breaking of soil crust is essential to facilitate in situ rainwater storage and proper crop stands.

Land Use

In Rajasthan's arid region, the cropped area is 67% of the reporting area. Fallowing for long- or short-duration is common. At least 45% area is cultivated in any given year. The present land use in a good rainfall year is presented in Table 2.

Table 2. Land use in arid zone of India

Land use	Reporting area (%)
Net area sown	49.9
Pasture	26.3
Fallow land	13.7
Forest	1.5
Area not available for cultivation	8.6

From various studies it has been found that only 36% land was properly used, 42% not properly utilized and 13% misused, the rest lying as unused.

Fodder Needs

In the arid region of NW India, with the increase in population (human and livestock) more area has been brought under cultivation. It rose from 7.4 m ha (1957–58) to 10.2 m ha (1988–89), a 37.8% increase. All of this expansion has come from the conversion of relatively more productive communal pasture lands. In a case study in Jodhpur district, it was observed that there was a decrease of 25% in area of grazing lands over a period of 28 years—between 1958 and 1986. Mostly alluvial plains and interdunal plains have been put under cultivation.

Because of the change in land use pattern and a sharp increase in ACUs the fodder availability has been seriously affected. The requirement and supply of fodder from all sources—pasture, top feed from trees and crop residues of the agricultural crops—in a normal year is shown in Table 3.

Table 3. Fodder supply and requirements

Year	Requirement (t)	Supply (t)	Deficit (%)
1982	23.9	9.0	62
2001	28.2	11.2	60

CAZRI has conducted a desk study. It has been found that it is possible to enhance the fodder availability by another 10.69 t. Some details are presented in Table 4.

Table 4. Estimated additional fodder through different systems

System	Additional fodder (t)
Improved cropping system (crop residue)	2.3
Improved grazing lands	4.2
Improving productivity of the current fallows	1.9
Shift of 15% of arable area to pasture land	2.3
Total	10.7

Based on forage availability estimates it is found that at least 2.5 million ACUs would be in excess by 2000 AD despite all possible improvements in fodder production. This calls for a new strategy. Training of farmers to seek alternate source of income, and reduction in livestock number to the desired levels are essential components of this strategy. Some examples of alternate source of income are arid horticulture and salt water fish culture. Central Arid Zone Research Institute (CAZRI) showed that cultivation of ber (*Zizyphus nummularia*) along with annual legumes would generate adequate income from the 4th year of the plantation (Table 5).

Table 5. Relative yield—some best legume pasture systems

Component	Yield (kg ha ⁻¹)
'Ber' fruits	1500–2000
Grain yield of legume	400–500
Fuel with prunings of 'Ber'	1000–1500
Fodder through leaves of 'Ber'	700 (grazing days)

Overexploitation of the Basic Resources

In the arid ecosystems in India, with an increased biotic pressure, and subsequent increased cultivation and overgrazing, has increasingly exposed the structureless soils of the region to wind erosion. Soil loss is a serious problem as the pastures degrade. Some data on the extent of soil loss under different conditions of pasture are given in Table 6.

Table 6. Soil loss under pastures of different stages of degradation

Condition of the pasture	Soil loss (t ha ⁻¹)
Excellent	Nil
Moderately degraded	140–280
Highly degraded	430–970

The arid ecosystems of India has seen a substantial increase in the use of tractors. Currently almost 50% of the arable area is cultivated and sown with tractors. This is affecting the ecosystem in two ways. Firstly the valuable bushes that provide fodder (e.g., *Zizyphus nummularia*) are getting eliminated in the fields. Secondly there is enhanced wind induced soil erosion. Some details are given in Table 7.

Table 7. Soil loss due to wind erosion under 3 tillage systems

Tillage system	Soil loss (t ha ⁻¹)
Fallow	407
Tillage with country plough	832
Tillage with tractor	2892

The soil loss in tillage treatments using tractor is three-to-four-fold compared to the conventional tillage. The tractors loosen the surface, but compact the subsoil. While compaction proved beneficial under irrigated conditions; it led to adverse effects on crop yields in rainfed situations of arid ecosystems. However tractors have come to stay. CAZRI is therefore engaged in research on the problem of checking wind erosion through strip cropping. The details of this research are discussed elsewhere in the chapter.

Wind Erosion and Control

With increased pressure on land, more stable dunes are being brought under arable farming. Thus increased cultivation of marginal land, combined with overgrazing and tractorization have aggravated wind erosion. The barchan dunes also known to contribute to the sand movement and dust storms. To combat this problem two goals have to be aimed at; fixation of mobile dunes, and arresting the high speed wind action through wind breaks. Extensive research has been done on these issues at CAZRI. In our studies we have found that sand dune fixation involves the following steps:

- Provision of secure enclosure to the area,
- Establishment of microwind breaks on windward side of the dune, in a 3–10 m chess board pattern or as parallel strips,
- Planting of grass strips or sowing grass seed,

- Planting of trees with the onset of rainy season, and
- Continuous, and proper management for about 10–15 years.

In our research we have identified a number of trees, shrub and grass species suitable for sand dune fixation (Table 8) for various rainfall regions.

Table 8. Suitability of some vegetative species across rainfall zones

Rainfall (mm)	Tree	Shrub	Grass
Up to 300	<i>P. juliflora</i> <i>A. tortilis</i>	<i>C. polygonoides</i> <i>Z. nummularia</i>	<i>L. sindics</i>
300–400	<i>A. tortilis</i> <i>A. senegal</i>	<i>Z. jujuba</i> <i>C. polygonoides</i>	<i>C. ciliaris</i> <i>C. setigerus</i>
Above 400	<i>A. tortilis</i> <i>P. cineraria</i>	<i>Z. jujuba</i> <i>C. auriculata</i>	<i>C. ciliaris</i> <i>S. munja</i>

Our survey has revealed an interesting feature. Mere 50% of the area covered by sand dunes is owned by the farmers, *A. tortilis* is not widely accepted by the farmers because it does not allow arable crops to grow under its canopy. CAZRI has now identified *Cordia rothii* and *Colligonum polygonoides* as alternatives.

Strip Cropping

Our studies have revealed that farmer owned sand dunes are partly (30%) cultivated under arable crops. Similarly areas receiving less than 250 mm rainfall also are put under arable farming. These areas are however more suitable for pastures. Arable cropping involves presowing cultivation and opening up of sand/sandy soils which leads to considerable wind erosion.

To cope up with this problem, strip cropping techniques have been developed by CAZRI. These systems ensure biomass production, even during the low rainfall years. For instance, in 250 mm rainfall area strip cropping of clusterbean with *Lasiurus sindicus* helped in producing the vital biomass, and in reducing the wind erosion (Table 9).

Table 9. Strip cropping of legumes and grasses

Year	Average rainfall (mm)	Grain yield of cluster bean		Forage of <i>L. sindicus</i>
		With strip	Without strip	
1981–82 (good rainfall year)	296	503	418	3430
1984–86 (low rainfall years)	191	Nil	Nil	726

Desiccating Winds

Hot winds. The hot desiccating winds lead to higher water demands. Shelter belts evolved by CAZRI include planting of 3- or 5-row belts of trees and shrubs across the main direction of winds. A 3-row shelter belt is more common. Staggered planting of tree/shrub seedlings in a pyramidal shape is recommended. *A. lebbek* is the suitable tree to be located in the central row.

Shelter Belts

The shelter belts reduce wind speed (Table 10). They also decrease evaporation by 5–14% during the premonsoon period. The soil loss due to wind erosion is expected to be reduced by 40 to 60% with *Acacia tortilis* and *Cassia siamea*, respectively over bare soil without shelter belt. *Cassia siamea* shelter belt retained more moisture in the soil as compared to *A. tortilis* or *P. juliflora* under irrigated conditions.

Table 10. Percentage reduction of mean wind speed at different distances in the leeward side of different shelter belts

	Summer			Monsoon		
	Distance from the shelter belt 2H ¹	5H	10H	Distance from the shelter belt 2H	5H	10H
<i>Prosopis juliflora</i>	33	17	12	38	26	21
<i>Cassia siamea</i>	36	17	13	46	36	24
<i>Acacia tortilis</i>	36	25	13	46	36	20

1. H = Average height of the shelter belt.

This strategy was extended as microshelter belts to grow vegetables. A three row pearl millet shelter belt was used to grow okra and cowpea (vegetable). The yield with microshelter belt was enhanced by 41% and 21%, respectively compared to control (without shelter belt).

Alternatives to Shelter Belts

Although shelter belts are the most convenient method of reducing soil erosion these have not been adopted by farmers in the recommended form. As an alternative, CAZRI is advocating planting of single row trees on the field boundaries across the wind direction. For the purpose locally popular trees have been suggested. The predominant tree species suitable for zones I to IV are: *Zizyphus nummularia* – *Prosopis cineraria* – *Acacia nilotica* var. *Cupressiformis* and *A. nilotica* var. *Adiana* – *Prosopis cineraria* + *Acacia leucopholia*.

Overexploitation of Ground Water

In the arid ecosystems the exploitation of ground water is fairly high. Irrigation through ground water covers 37% of the total irrigated area. Ground water exploitation was 45.0% (in 1987–88) as against the national average of 35%. In pockets of overexploitation the static ground water table is decreasing by about 1 m year⁻¹. In general, it has been noted that with the increase in rainfall the area under arable cultivation increases and so is ground water exploitation. Some idea of the overexploitation can be obtained from the data given in Table 11.

Table 11. Annual draft of ground water across some rainfall zones in arid ecosystem of India

Rainfall zone (mm)	Annual draft (1988) [Utilizable recharging (%)]
< 250	1
250–320	22
320–380	37
380–425	82

Estimates show that at the present level of exploitation, the overall exploitation of the ground water will rise to 66% from the present level of 45%. The exploitation in higher rainfall zone could be 100–140% of the utilizable recharge—a serious situation. To overcome such a situation a three pronged approach has been suggested. First, the recharging of ground water can be done through check dams on the ephemeral streams, combined with various soil and water conservation measures. Such an attempt has shown 5 to 27% increase in recharge over a 3-year period. This incidentally also reduces the salinity. Second, low water demanding crops (e.g., rapeseed/mustard as against wheat) are recommended for cultivation. Conjunctive use of ground water with canal water, wherever possible should be encouraged. Lastly to minimize water use; drip and sprinkler irrigation should be put in place. Sprinkler irrigation systems are already adopted in the region, drip systems which need considerable financing have not become popular.

In our efforts to conserve water, recently ground level reservoirs have been constructed which are fed by tube wells located at long distances. This water is meant for both human and livestock consumption. With an increasing use of ground water for domestic as well as industrial purposes, the traditional water harvesting systems like *Tankas* and *Nadis* are losing ground. Many of them are already dysfunctional. But due to unwise exploitation of ground water the tube wells are becoming dry and supplies are becoming limited. In order to avoid human suffering in urban areas, all attempts are made to provide water by linking drinking water supply systems with the canals. Thus the hinter lands now stand in urgent need of reviving dysfunctional traditional water harvesting

systems. The National Drinking Water Mission has put in practice some of the improved technologies evolved by CAZRI for reestablishing *Tankas* and *Nadis*.

In the arid ecosystem of western India the quality of ground water is generally of poor quality. Either the water is saline, or sodic or both. As an example, in the Luni basin, the waters are moderately saline ($2\text{--}4.5\text{ dSm}^{-1}$), having high RSC^1 ($8\text{--}20\text{ me l}^{-1}$) and SAR^2 ($25\text{--}50$). The soils have $3\text{--}5\%$ silt and $5\text{--}8\%$ clay. Continuous irrigation with these waters promotes high Ph ($9\text{--}10$) and ESP ($50\text{--}80\%$), but the soil does not develop salinity ($\text{EC: } 2\text{--}4\text{ Dsm}^{-1}$). Because of high sodium content, these soils become compact, are usually hard when dry, and have low water infiltration rates. Correction of such soils is not difficult. Gypsum can be used with advantage. It corrects the existing sodicity in the soil. When added to irrigation water it balances sodium in high RSC waters.

Misuse of Canal Waters

In order to sustain agricultural production in the arid ecosystem of India, a major canal system (Indira Gandhi Canal) has been laid out to utilize 1.044 m ha meters of water. The main canal having a length of 649 km provides irrigation in the arid region in two stages. Stage I is having 189 km long main canal with a 2950 km long distribution system. It commands 0.525 m ha . The corresponding figures for stage II are 256 km , 5132 km and 1.012 m ha .

The impact of this canal on the agriculture development has been mixed. Water table has risen @ 0.9 m year^{-1} during the period 1981–90. By 1990, the area under waterlogging (water table between 0.6 and 1.5 m from surface) covered 0.198 m ha , i.e., 25% of the command area in Stage I. A sizable area (0.026 m ha) is already waterlogged/submerged. Further perched water table has developed in areas situated 2 to 7 km on either side of the canal where a hard pan at shallow depths underlies the light soils. There is an added risk of soil salinity development with the rise of water table. Salt concentration in the ground water is high ($3000\text{--}5000\text{ mg l}^{-1}$).

To mitigate this emerging problem, we have suggested that as a first step to reduce the water allowance from $3\text{ cusecs } 400\text{ ha}^{-1}$ to 1.5 cusecs in areas where soils have a hard pans. Water use also can be minimized by use of drip irrigation system wherever feasible. The lining of canals to reduce the seepage losses should be enlarged. Improvization with horizontal and vertical drainage, wherever possible, also reduces water table and use. In order to slow down buildup of salinity in ground water, the conjunctive use of canal water with ground water is suggested. In areas with severe drainage problems “biodrainage” is suggested. This would help to siphon off as much water as possible through evapotranspiration by fast growing trees.

Mining Activities

Mining is an important economic activity in this arid ecosystems. The area affected by mining and overburdens of mine spoils is about 2.2% of the geographical area of the region. The mine spoils are heaped irregularly and vary in height from 10 m or more.

Mining is done for metallic minerals like copper and tungsten, nonmetallic compounds like clay, gypsum, fuller's earth and bentonite, fuels like lignite and gas and building materials like sandstone, marble, granite, and limestone.

The mining activity leaves overburden of very low grade minerals. The soil materials is generally devoid of organic matter and is very low in available nutrients. Overburdens also lead to salt buildup. The dugouts become storage pits for polluted water. The loose overburden sometimes drifts to the adjacent productive soils due to high velocity winds.

To rehabilitate the overburden in mining areas, CAZRI has suggested schemes to vegetate the land. For this purpose, in situ rainwater harvesting through ridges and furrows and semi-circular structures is taken up along with planting of selected bushes and trees. Even grasses are also suitable. The pits (60 cubic meters) are filled with top soil and farmyard manure (FYM) @ 4.0 kg pit⁻¹. About 4–5 kg of bentonite pit⁻¹ is an useful supplement. Till the seedlings establish, protective irrigation for 1–2 years would be needed. The dugouts be used as useful water harvesting and recycling structures or for developing fish culture.

Effluents from Textile Industries

The arid ecosystem of India has a well developed textile industry. It is an important economic activity. However, industrial effluents to the tune of 2.2 million L are discharged daily into the ephemeral streams. The problems associated with the effluents are primarily related to the fact that the dyes have a high salt content and sodicity (600–3500 ppm Na). These waters have also a high RSC (11.90 me L⁻¹). Such waters, when discharged into the ephemeral streams, make the adjacent and neighboring wells dysfunctional. The cultivated area commanded by the wells gets severely reduced. Due to rapid industrialization the small stakeholders are losing their water resources and a sustainable livelihood security.

Researchers at CAZRI have observed that the microbial population is also adversely affected. For instance the bacterial population was 7.2 (million g⁻¹) with normal irrigation, it measured 18 with effluent irrigation water and 14 in areas which are now abandoned. Similar trend has been noted with fungi, actionmycetes, free living nitrogen fixers and nitrifiers.

The problem of sodicity can be corrected by the use of gypsum. However it results in water becoming saltier by about 1.0 Dsm⁻¹. Still such waters can be used in the light textured soils with caution as is being practiced by the farmers of the region.

After neutralizing the sodicity these waters can be successfully used for raising tree plantations of *Eucalyptus camendulensis*, *Acacia tortilis*, *Azadirachta indica*, *Hardwickia binata*, *Tecomella undulata*, *Acacia nilotica*, *Prosopis juliflora*, *Prosopis cineraria* and even horticultural plantations like *ber*. The dye colors in the effluent water can be adsorbed by passing them through fly ash.

Thus, the management of effluent waters can be made possible by (1) application of gypsum and FYM to soil @ 3–5 kg pit⁻¹ in alternate years, and (2) irrigation in the outer ring of pit avoiding direct contact of these waters with

the saplings. Thus even the abandoned lands under the presently dysfunctional wells can be brought to cultivation by correcting the sodicity in soils and treating the effluent or well waters with gypsum before use.

Genetic Diversity and Sustainability

V.L. Chopra and R.S. Rana

Abstract

Indian agriculture called for a new paradigm in the approaches to sustainability related research. It is suggested that in the future research approaches the socioeconomic realities of the farming systems in different agroecological zones must be considered, and the potentials and limitations of the resource base should be given due importance. It is envisaged that attainment of the goals of sustainability will require that technologies generated and promoted have the full involvement of the people.

It is noteworthy that the pace of increase in agricultural production, overtook that of population growth in India, during 1981–1991 as revealed by the last census survey data. A large share of credit for this remarkable achievement goes to agricultural research and extension work pertaining to development of high yielding crop varieties better suited to intensive agriculture under irrigated and crop protection technologies. Although these painstaking efforts during the last two decades or so have substantially added to food security measures, the disparities between the farmers engaged in crop production under favorable and limiting environments have disturbingly increased during this period. Intensive agriculture also now faces stresses in many ways. Indian agriculture in stressed environments has depended traditionally on highly diversified but integrated farming systems making full use of locally adapted annual and perennial crop plants. Utilization of native biological diversity, supported by cultural practices evolved by successive generations of farmers, has played a key role in sustaining such systems under a variety of ecological situations. Understanding and improvement of this indigenous wealth has not yet received the level of research effort that is required in this context.

Sustainability of Crop Production Systems

Sustained growth in agricultural production is essential for human survival and welfare. Sustainability denotes a 'steady state' between what is harvested and what is replenished. Adequate availability and efficient use of water and plant nutrients as well as proper soil health care are the basic considerations.

A critical look at the Indian experience during the last four decades is relevant here. Farmers having access to irrigation facilities were encouraged to adopt intensive and high-input agriculture. The law of diminishing returns began to operate soon. Furthermore, poor water management coupled with inadequate

drainage measures quickly led to soil degradation, resulting in yield reductions in many situations, due to build up of salinity, waterlogging, etc. While application of organic manures did not receive much emphasis, fertilizers were often used without due consideration of specific crop requirements, leading to not only wastage of costly inputs but also pollution of groundwater resource. Micronutrient deficiencies became severe limiting factors in many areas. High density biomass production due to excessive fertilizer application provided favorable growth conditions for disease and pests which had made crop yield increasingly dependent upon use of fungicides and insecticides. Practice of summer fallows had nearly disappeared. Short-term economic gains became a major decisive factor in the choice of crops rather than scientific principles of crop rotations. It is amazing that we experienced this sad turn of events and decline in production, in a short span of just one generation. In my view, diversification of agricultural systems and more diversity in crops and their varieties are highly relevant in the reversal of the present worsening trend as well as in ensuring sustainability of crop-production systems in our country.

Biodiversity and Its Relevance to Stressed Environments

Biological diversity refers to the variation among all living organisms and includes diversity within species, among species and also among ecosystems. Agricultural component of plant diversity comprises gene pools of cultivated plants including landraces, primitive cultivars as well as their weedy and wild relatives.

Farmers' reliance on use of biodiversity in ensuring stability of reasonable levels of agricultural production in desert ecosystem, hilly areas and coastal belt illustrates the basic relationship between genetic diversity in the farming systems and sustainable agriculture in such fragile systems. For example, human populations settled in arid zones make use of estimated 682 species belonging to 352 genera of 87 families of native flora for food, fiber, medicinal and many other uses. Farming too, is of a highly diversified kind. It is subsistence farming in a way but it is sustainable.

Likewise, farmers operating in hilly areas traditionally grow a large number of cultivated plants including amaranths, chenopods, buckwheat, small millets, spices, condiments and medicinal plants integrating them judiciously with the cultivation of cereals, grain legumes, vegetables, fruits and forages besides raising plantation crops and multipurpose shrubs and trees. The diversified systems not only meet daily needs of human populations and livestock but also promote better soil health care. Mixed cropping is commonly practiced under these conditions. A large number of species are endemic. Variability in soil status and agroecological situations combined with farmers' preferences for taste, flavor, color and use in sacred rituals have led to an amazing spectrum of genetic diversity in native species. Even in introduced crops like maize, remarkable diversity has arisen owing to expression of latent genetic variability under new environments and has been stabilized by successive generations of farmers, leading to cultivars having specific adaptations to local conditions and resistance to prevailing diseases and pests.

The recent experience of the National Bureau of Plant Genetic Resources (NBPGR) exploration team, that went on a collection of maize germplasm (in 1992) to numerous sites in the northeastern states after an interval of over 20 years, is both revealing and relevant. The team was apprehensive, fearing that most of the traditional cultivars would have been replaced and lost during the long interval of two decades. Interestingly, they found that very little had been substituted by modern varieties and hybrids. That speaks volumes for the merit of specific adaptations and consumers' strong preferences as well as the challenges faced by breeders.

Collection, Conservation, Evaluation and Utilization of Genetic Diversity of Cultivated Plants

Plant breeders in India have easy access to immense genetic diversity in the gene pools of cultivated plants. Out of 240,000 known economic variety of plants, 160 species evolved in the Hindustani Center and these are distributed in eight diverse phytogeographical regions of this country. The endemic plant wealth has also been enriched by introductions from abroad beginning in the remote past. The National Bureau of Plant Genetic Resources [formerly, Plant Introduction Division of Indian Agricultural Research Institute (IARI)] has facilitated germplasm exchange in recent years with a view to support crop improvement programs. Over 10,000 seed samples of indigenous cultivars and their wild relatives are collected every year through well planned explorations. In addition, nearly 60000 seed samples/propagules are introduced annually from other countries and international agricultural research centers.

In situ conservation of wild plant genetic resources is being done by the Department of Environment & Forests through protection of habitats and ecosystems. Seven biosphere reserves have already been established (Table 1) in addition to over 400 sanctuaries and national parks. Ex situ conservation of germplasm assemblages has been undertaken by Indian Council of Agricultural Research (ICAR) in a network of thirty nationally active germplasm sites (Table 2) linked to base collections in the National Gene Bank operated by NBPGR (Table 3).

Table 1. Ecosystem conservation: in situ conservation in India

Biogeographic region	Biosphere reserve	Area (km)	States involved
Himalayan highlands	1. Nanda Devi	1560	Uttar Pradesh
Burma monsoon	2. Nokrek	80	Meghalaya
Bengalian	3. Manas	2837	Assam
Rain forest	4. Sundarbans	9630	West Bengal
Coromandel	5. Gulf of Mannar	555	Tamil Nadu
Malabar	6. Nilgiri	5520	Karnataka, Kerala and Tamil Nadu
Andman & Nicobar Islands	7. Great Nicobar	885	A & N Islands

Table 2. Directory of nationally active germplasm (NAG) sites, in India

Crop	NAG site	Number of accessions
Wheat	Directorate of Wheat Research, Karnal 132001 (Haryana)	18000
Rice	Central Rice Research Institute Cuttack 753006 (Orissa)	42000
Maize	All India Coordinated Maize Improvement Project, Indian Agricultural Research Institute, New Delhi 110012	2500
Barley	All India Coordinated Barley Improvement Project, IARI Regional Station Karnal 132001 (Haryana)	—
Sorghum	National Research Center for Sorghum, Rajendranagar, Hyderabad 500030 (Andhra Pradesh)	5160
Pearl millet	All India Coordinated Pearl millet Improvement Project, College of Agriculture, Pune 411005 (Maharashtra)	—
Small millets	All India Coordinated Small millets Improvement Project, University of Agricultural Sciences Bangalore 560065 (Karnataka)	8572
Pulses	Directorate of Pulses Research Kanpur 208024 (Uttar Pradesh)	9310
Soybean	National Research Centre for Soybean Indore 425001 (Madhya Pradesh)	2500
Oilseeds	Directorate of Oilseeds Research Rajendranagar, Hyderabad 500030 (Andhra Pradesh)	15629
Rapeseed and mustard	All India Coordinated Crop Improvement Project (Rapeseed & Mustard) Haryana Agricultural University Hisar 125004 (Haryana)	8082
Groundnut	National Research Center for Groundnut Timbawadi P.O., Junagarh 362015 (Gujarat)	6432
Sugarcane	Sugarcane Breeding Institute Coimbatore 641007 (Tamil Nadu)	3979

(contd.)

Table 2. (Contd.)

Crop	NAG site	Number of accessions
Cotton	Central Institute for Cotton Research P.B. No. 125, Nagpur 440001 (Maharashtra)	6896
Jute and allied fibers	Central Research Institute of Jute & Allied Fibres, Barrackpore 743101 (West Bengal)	3226
Vegetables	National Bureau of Plant Genetic Resources Pusa Campus, New Delhi 110012	16139
Potato	Central Potato Research Institute Shimla 171001 (Himachal Pradesh)	2375
Forages	Indian Grassland & Fodder Research Institute Jhansi 284003 (Uttar Pradesh)	6267
Spices	National Research Centre for Spices Marikunnu, Calicut 673012 (Kerala)	2847
Tobacco	Central Tobacco Research Institute Rajahmundry 533105 (Andhra Pradesh)	1500
Plantation crops	Central Plantation Crops Research Institute Kasargod 671024 (Kerala)	307
Medicinal and aromatic	All India Coordinated M & AP Improvement Project, NBPGR, Pusa Campus New Delhi 110012	375
Agroforestry plants	National Research Centre for Agroforestry Jhansi 284003 (Uttar Pradesh)	40
Fruits (Semi-arid)	All India Coordinated Project (Semi Arid Fruits), Bikaner (Rajasthan)	541
Fruits (Subtropical and temperate)	NBPGR Regional Station Phagli, Shimla 171004 (Himachal Pradesh)	454
Fruits (Tropical)	Indian Institute of Horticultural Research 255, Upper Palace Orchards Bangalore 560080 (Karnataka)	13118
Citrus	National Research Centre for Citrus Seminary Hills, Nagpur 440006 (Maharashtra)	51
Fruits (Northern plains)	Central Institute of Horticulture for Northern Plains, Lucknow 226016 (Uttar Pradesh)	587
Tuber crops	Central Tuber Crops Research Institute Sree-kariyam, Trivandrum 695017 (Kerala)	3586
Pseudo cereals	NBPGR Regional Station Phagli, Shimla 171004 (Himachal Pradesh)	3682

Table 3. Base collections in National Gene Bank at NBPGR (as on 31 August 1993)

Crop groups	No. of accessions
I. Long-term storage (−20°C)	
Cereals	51182
Pulses	26159
Millet and minor millets	14599
Oilseeds	15647
Vegetables	6482
Fiber crops	3212
Narcotics	790
M & A.P.	179
Pseudo cereals	736
Improved varieties	904
II. Medium-term storage (+4°C)	
Ref. samples of indigenous collections	36137
Voucher specimen of exotics	20760
Total	176787

Characterization and evaluation of these vast collections are in progress but there is need to speed up this activity. Collaboration between NBPGR and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in this effort is commendable. ICAR is also funding several schemes/projects aimed at upgrading, evaluation, screening, multiplication and distribution of large germplasm collections of rice and wheat. With the development of some strong biotechnological research centers in the country, greater and more effective utilization of crop gene pools is expected in the near future.

Prospects

Tribal people and farmers engaged in crop production under stressed environments have known for a long time that their success, and also their survival, is linked to genetic diversity in crop and forest resources available to them. Modern researches have also established that shrinking genetic diversity among improved varieties of crop plants may lead to an increase in their vulnerability to widespread epidemics and pest outbreaks. Diversification is obviously the key to sustainable agriculture in stressed environments as it provides reasonable chances of success under threat of uncertainties and also promotes soil health status. It includes diversity of crops (a judicious mix of compatible annuals and perennials) as also genetic diversity among varieties within crops.

One group of crops that deserves more and sustained attention comprises of small millets or minor coarse cereals, namely, finger millet, foxtail millet, proso millet, kodo millet, little millet, and barnyard millet. They have proved

their indispensability in dryland agriculture and their desirable attributes include high nutritive quality, easy cultivation and nearly assured harvest. Tumba (*Citrullus cococynthis*) and jatropha (*Jatropha curcas*) hold promise for development aimed at seed oil. Multipurpose trees like *Prosopis cineraria* are highly prized in arid farming systems.

Indigenous cultivated species adapted to hilly areas in the country also offer vast scope for improvement and greater utilization. Pseudo-cereals like amaranths, buckwheat and chenopods as well as valuable legumes like rice bean and winged bean may be mentioned by way of illustration. Forage legumes, numerous native fruit plants and bamboos also play a significant role in hill agriculture besides indigenous vegetables and medicinal plants.

Soil microflora have not yet been studied properly and the time has come for us to devote more research effort on this vital aspect.

Socioeconomic Structures and Sustainable Agriculture in Stressed Conditions

Y.K. Alagh

Abstract

Operational strategies for land and water development in fragile or stressed conditions are discussed. The emphasis is on developing experience-based, replicable strategies. Economic policy rules which support such strategies and supportive state intervention systems are emphasized. The examples are from India, although more general application possibilities exist.

Bank finance and community labor have to be integrated with the rural employment program. Therefore, an attempt was made to permit local communities to undertake the kind of land development and water management works that are central to the efforts of turning around the subregional agricultural economies. Many feasible investment strategies have been developed for alternative agro/economic peoples. These have now to be implemented. The investment packages for different regions are different and the development strategy has to provide for this differential focus. The land and water development strategies will require a multipronged approach using alternative management strategies most suited to each region. Traditional water harvesting structures, canal improvement systems, and improved planning procedures have been established but need to be implemented. Successful experiences in land management in watersheds and difficult ecological regimes need to be duplicated faster in terms of community organizations, interfaces with local governmental institutions, and subsidies and market support. Economic policies have to address the question of reform of delivery systems.

A scheme of agroclimatic planning was developed by the present author in the Indian Planning Commission (Alagh 1988, 1989; India: Planning Commission 1988, 1989). This chapter discusses the issues relating to planning of arid regions as well as some successful related projects. The purpose of the listing of planning for different zones was to emphasize that land, water, infrastructure, processing, and extension support systems for the regional agricultural systems in India are very different and require alternate approaches. The Economic Survey sums up the strategy as follows:

"Land and water development strategies and cropping patterns suitable for each region have been worked out as also non-crop

based agricultural activities like forests, animal husbandry and fisheries have been taken into account. Agro-processing activities are to be emphasized. An attempt is being made to develop a package of more appropriate projects for each region, as also to involve the financial institutions more directly in the agricultural planning process. The studies/surveys undertaken in these zones would be the basis for the formulation of the 8th Plan" (India: Ministry of Finance 1990).

Investment Planning, Policy Frameworks and Institutional Issues

The agroclimatic plans for the different agronomic conditions should not be seen as a technoeconomic exercise alone. A crop-based approach or an approach which treats the country as a single unit would not adequately address the major issues for agricultural development in different conditions. Watershed development, or alternatively drainage, flood control, and conjunctive use of surface and groundwater, or again a more appropriate management of hill- and forest-based agriculture, are alternative regimes. Each would have a different investment- and policy-support strategy. In fact, one advantage of agroclimatic planning is that it builds up investment and infrastructure options for alternative agricultural and farming systems and thus removes the shortcoming of a favored crop/region approach, as say wheat based on canal irrigation. Also, the locked-up resource potential of different regions which can be released with marginal investments, for example, improvement of existing canal systems or traditional irrigation structures, can be realized. Yet the central question is not the listing of possibilities but the consideration of feasibility and this requires discussion of organizational, institutional, and economic policy issues.

The mindset underlying the theorizing on agricultural development consists of three kinds of alternative approaches. In one approach, the issue is considered as that of spreading available technologies for agricultural development through the implementation of an "appropriate" framework of institutions and adjustment to incentive prices. From this angle the process can be thought of as that of operationalizing the framework of neoclassical economic rules. The peasant is essentially rational, and if institutions are developed which permit him to respond to economic stimuli he quickly internalizes the available technology, and the gains are shared between those who have access to land and those who sell their labor. Technical innovations lead to labor absorbing change and employment opportunities rise fairly rapidly. In a more extreme version of this view, international markets and adjustment to changing international prices provide the stimuli to trigger such development. In another view, rural development is conceived essentially as a facet of statist planning. Institutions and economic incentives play a part in such a view, and yet the problem is conceived as that of operationalizing the impact of agricultural and rural development technology at the farm or village level, and that of setting up para-statal and other institutions which support the extension of technology to this level as well as agricultural marketing and processing. In such a view, a benign state plays

the role of energizing different components of the growth process, in terms of both input complementarities arising from technology and adjustment to wider factors such as economy level or international demands. In an alternative to this approach, the role of the state and/or other forms of political action is important but arises from the class nature of the principal agents in rural societies. In this context, feudal modes of production have first to be destroyed before economic incentives and economic organizations can play a role in transforming rural society.

In fact, in many rural areas examples of successful agricultural development or rural development experience, particularly under somewhat difficult resource endowment conditions, tend to follow a very different experience path. If sufficient irrigation water is available and the soil regime is suitable for a crop for which technology is well known, such as wheat or paddy, market-oriented prescriptions have great possibilities of success since almost all the preconditions of this paradigm are fulfilled in terms of the atomistic nature of peasant proprietorship and the response of the peasantry to economic incentives. Thus, in many countries, including India, thinking took a somewhat "linear" direction. The emphasis was on irrigation and the new biotechnology and in many cases only on this.

In many parts of the country, however, the problem is far more complex, as seen for example in the plateaux and hill regions and the Himalayan region. Land and water resources are meager. Population pressure is rising. Commercialization in many cases tends to lead to the short-term exploitation of resources, and costs of soil degradation and water erosion are not fully reflected in market prices. Traditional, socioeconomic systems working at low levels of equilibrium are collapsing and newer methods of sustainable development are not emerging.

There are, on the other hand, a number of successful experiences where the basic food and energy requirements of poor rural communities have been met through the application of state-of-the-art scientific knowledge and technology at the cutting edge of the interface of man with land and water. In the programs of work designed on agroclimatic planning, an attempt was also made as a part of the development of such plans to document success and failure stories in land and water management as well as in more optimal land-use and cropping patterns. Such success stories thus studied were under alternative agroclimatic regimes which include low rainfall areas where, for example, the level of water availability on an average is 50 cm and the coefficient of variation is 40 to 60% in the dry regions of India. In other words, in some years the water availability could be less than 20 cm. A second kind of agroclimatic problem occurred where the availability of water was greater, around 100 cm, but the variation is again 40 to 60%, in the context of a hill slope and a valley. Unregulated commercialization invariably means soil erosion, and precipitation instead of becoming a blessing becomes a curse since it flows down the hill, erodes the land of the region, and leads sooner or later to the collapse of the socioeconomic system in terms of food and energy. A third problem can be one where past development of an unplanned type or of a badly planned type has led to resource loss.

Invariably, the technology to overcome these problems is well known. It is also generally well known in university and research environments not far from the area where the particular problem exists. The interesting point is that just as there are a number of failures of development efforts to resolve such problems of scarce resource endowment, there are also many instances of success. These are no longer pilot projects in the sense of designed attempts on amelioration by the state or by international agencies, but are serious attempts to solve the local problems at the community level. The Planning Commission has initiated studies on a set of these experiments by independent social science institutions. The results of these and other studies are of interest in terms of the paradigms involved (Chopra et al. 1989). These experiments have some common characteristics. Firstly, they definitely involve effort at the community level but the basic technology is well known. In the case of a dry area, the question is that of water harvesting techniques. Traditional practices of storing water now require larger economic incentives, since the cost of community labor has gone up due to commercialization. Areas with good rainfall require watershed development. This involves soil conservation techniques such as contour bunding, ridge plowing, water harvesting, gully plugging on the soil slopes, and the use of village and percolation tanks to stop soil erosion. Once the land development and water harvesting is done, an optimal crop combination is possible in the agroclimatic plan. The land reclamation problem invariably involves more complex technology including pumping of water and the use of soil amendments. Since it involves application of the technology at the level of an aquifer, community involvement is important (Singh and Bajaj 1988).

The second aspect of these success stories is invariably the importance of leadership. There is no uniform pattern of leadership. In cases such as Sukhomajri in the Punjab and the Pani Panchayats (water collectives) at Ralegaon Sidhi, voluntary organizations mattered. In other cases, it was some concerned official who initiated the process. Generally, the leadership groups involved people below 45 years of age. All those who succeeded had scientific and technological training. Also, initial successes were sustained and replicated.

The third feature of these kinds of success stories is the high rate of measurable "economic" return and at the same time low market prices (Table 1). In all the successful cases, participative methods mobilized the labor resources of the community. At the 1986 or 1987 prices when these experiments were evaluated, the investment costs varied between Rs.9000 and Rs.11,000 ha⁻¹ (USD = Rs.30) for land. This money was made available for agricultural or orchard crops after reclamation. The investment lost was between Rs.2500 and Rs.4000 ha⁻¹ for social forestry purposes. As far as the economics was concerned, between 38 and 53% of these resources were bankable once the community was involved because many of these efforts were labor-intensive, particularly the investments in land development and water management. The internal rates of economic returns to these investments were in the range of 18 to 27% a year, making them some of the most socially profitable investments in the Indian economy. Yet, at going market prices, many of the families ended up with losses. A counterpart to these losses was a deficit in energy or food requirements of many of the families

Table 1. Selected characteristics of watershed development projects¹

Name	Land/water development cost (Rs ha ⁻¹)	Current input (Rs ha ⁻¹)	Annual return		Remarks
			(Rs ha ⁻¹)	(%)	
Naigaon	11364	2809.56	212		1984/85
Sukhomajri	22221		7979	19	1986/87 benefits include those of villages and government agriculture, dairying, fisheries, fodder, etc.
Samithed	1500	NA	NA	—	Returns are in terms of plantations, rise in water table and fodder in 312 acres of land; 78000 saplings.
Ralegaon Sidhi	9689	NA	NA	—	Drinking water available within 100–150 meters of each household
Tejpura	4246	Additional 816.8	3764		Doubling of pearl millet and sorghum yield 70 cross bred cattle: Plan for 200000 trees.
Mitemari	2030	NA	NA		Incremental income of Rs.2540 per household as compared to control village.
Sikundarpur and Kotpurva	11220	10825	255 days of grain requirement for a family plus 400 days of fodder for a pair of animals.		Ussar Reclamation Project

1. Source: SPWD (1988); For Row 7, Singh and Bajaj (1988).

involved. There is, therefore, no guarantee that with the given structure of international or national markets, a financially viable development will result. The paradigm question in this kind of development is important. None of the known methods of thinking correctly interface with the available institutions in the kind of development being described. Decentralized working of markets is

important and they do not necessarily provide automatically for the application of the available technology towards sustainable development in terms of the interface of humans with the scarce resources of land and water. Also, the income levels generated at existing prices may not meet subsistence requirements. A measurable kind of economic or social intervention is necessary, and yet it must not lead either to the suffocation of local initiatives or to a neglect of the great vitality of rural markets.

The socioeconomic rules that permit this participatory kind of development are very complex. It is quite clear that an estatist type of cooperation does not solve the problem. Neither does a technocratic regime that relies on the so-called transfer of technology paradigms through centralist auspices. For example, land development projects financed through international financial institutions have led to low rates of returns also. Perhaps the answer lies in social control on a part of the resource endowment. When water is harvested in a watershed, a set of community rules has to be evolved. For example, the Pani Panchayats give rights even to landless laborers on a part of the harvested water. Yet the peasant does not have to give up his rights to land. Socialization and cooperative institutions do not have to be holistic or either/or propositions with individual initiatives. It is possible for individuals to cooperate for limited and well-defined purposes.

Market Functioning: Limits and Opportunities

It is being suggested that in most rural or agricultural situations in our country the application of state-of-the-art technology to develop the slender resource base of the area requires community organization at the level of watersheds or aquifers. However, such requirements can be for limited purposes and the "institutions" challenge is to mesh such community requirements with the advantages of factor and commodity markets working essentially with functioning atomistic peasants. Such community requirements are a precondition for better use, for example, of lands in hill slopes or sandy areas with dune formation or at the level of an aquifer, either for reclamation of saline land or the development of water harvesting or aquifer exploitation methods.

Will an overall policy framework set in the context of competitive domestic and international markets be consistent with and support the kind of developments discussed earlier? In other words, how will community-based systems which meet the technical requirements of resource use relying on the labor endowment of the area interface with the rest of the economy? Experience suggests that at current market prices many of these experiments are financially not viable at least for those peasants who have a slender resource base. These losses have been estimated both as calorie or fuel gaps from a minimum biologically determined requirement for a section of the labor force (8 to 17.5%) and as financial losses if labor costs of development are fully accounted for (13.2 to 27%). The nature of such "losses" can help in appreciating the interface of markets with labor institutions. Such losses can be minimized by the development of domestic and international markets, which raise the value of agricultural, forest, or residue

produce and also reduce input costs. The price of a modern water-harvesting or energy-saving technology may be lower than a domestic substitute, for example, energy-efficient pump set, a modern seed or pesticide, a more efficient sickle, seed drill or power tiller, or the use of photovoltaic cells for providing energy in remote regions. It has to be appreciated that in many cases initial costs may be high, and so the case for selective nonmarket forms of intervention may be good since capital markets are poorly developed. In many land-development or reclamation schemes, particular crop combination cycles are technologically recommended for soil consolidation or improvement. For example, a fodder crop or a tree crop may have to be grown in reclaimed land to prevent relapse into degradation. At going market prices such a crop may be unprofitable. Again, invariably under such conditions in initial years input rates are high, for example the number of waterings required, seed rates, or soil amendment requirements will decline as the organic composition of the soil improves. Thus, initial subsidies or public intervention mechanisms may be required.

The conventional theoretical answer to such "low" carrying capacity of land features is to suggest migration and transfer of populations to the nonagricultural or urban sectors. While useful as a long-term guideline, the immediate relevance of such advice is not very clear. Also, improvement in land productivity is anyway a precondition of such a desirable outcome, and in any case if soil improvement is a dynamic process excessive migration may be the wrong answer. The upshot is that market-oriented rules need considerable modification when applied to realistic rural development possibilities. In fact, the "suboptimal" policy alternatives, for example, preference of input subsidies over output subsidies, may need to be experimented with, given the fragmented nature of labor markets. Having said this, however, two guidelines are important and may be stated firmly. Generally, markets are efficient methods of getting across to farmers and, other things remaining the same, should be used as the preferred form of delivery of inputs or output collection and processing. Secondly, development of markets and communication and processing infrastructure must get high priority for rural reform. In fact, the heart of institutional reform is to evolve a policy regime which uses fiscal and investment packages which unleash the power of properly functioning markets for generating higher incomes and employment and, wherever necessary, use direct intervention methods also.

To sum up therefore, the direct involvement of village-level beneficiary-oriented organizations is required since:

- The experience is that totally officially sponsored schemes have limited effectiveness (around 40% as per the Concurrent Evaluations of the Indian Rural Development Scheme).
- A part of the cost of land and water development schemes becomes bankable and this really means that through the kind of mechanics described earlier the labor assets of the community, instead of being a drag on employment, lead to asset creation.
- It becomes easier to channel structured subsidies to poorer beneficiaries through this method. Such subsidies are required for land development,

water-harvesting methods, and also vegetative and crop cover on such lands. At going market prices of outputs and inputs, studies show that such schemes are not financially viable. Instead of accepting such "market failures," the challenge is to channel public funds to energize the community to also contribute its bit and foster such schemes on a larger scale.

- Such organizational changes lead to the very exciting possibilities that assetless persons can share in the rewards of community efforts. For example, in the Pani Panchayat, landless laborers have a share of the water saved, and in many watershed schemes, energy entitlements are given to all. No wonder, in many such cases, we are in the somewhat happy state that practice is running ahead of theory and that the practitioners are explicitly unhappy with the social scientist and the planner.

The kind of agricultural development discussed above would require a very detailed link with technological and industrial progress. The growth of nonagricultural employment opportunities in rural areas has to be accelerated. Agroprocessing and input supply to the agricultural sector through development of marketing and service centers will need to complement a diversified planning strategy.

New Investment Strategies

When this new kind of planning is done for each region of India, new investment and policy strategies emerge for the country as a whole. Features such as watershed development, soil conservation, accelerated groundwater development, and tank irrigation are initiated. Operational targets are described below.

As the Integrated Watershed Development Program (IWDP) is based upon a multidisciplinary approach, the organization implementing this program will also have to be structured accordingly, so that the desired results are achieved. The beneficiaries covered in a micro-watershed should be actively involved right from the planning stage. They should also share the cost. Employment programs such as the Jawahar Rozgar Yojana must be integrated with watershed development programs. A part of the total cost of land and water development should be met by the beneficiary, a part could be raised through bank finance, and the balance could come from subsidies from the government.

Extensive areas in some zones suffer from soil problems such as salinity, alkalinity, and acidity. These problems are natural and also arise out of human intervention. Some soils have natural salinity or acidity due to their formation from basic material having proportionately high clay content and sodium salts. On the other hand, because of imprudent use of irrigation water or saline groundwater, secondary salinity may develop. All these situations badly constrain the achievement of higher yields possible through the application of improved technology. Physical targets and associated benefits as worked out in the agroclimatic plan for watershed development soil reclamation are shown in Tables 2 and 3.

Table 2. Agroclimatic zonal targets for integrated watershed development

Particulars	Zone: Area ('000 ha)					Total
	VII	VIII	IX	X	XIII	
Geographical area	39500	37000	33100	39500	19600	168700
Net sown area	17400	16900	15900	18900	9800	78900
(%) of geographical area	(44)	(46)	(48)	(48)	(50)	(47)
Area needing soil/water conservation measures	15800 (40)	12800 (34)	13200 (40)	15800 (40)	10700 (54)	68300 (40)
Area likely to be treated by the end of VII Plan [cumulative (assuming 20%)]	3100	2500	2600	3200	2100	13500
Area remaining to be treated	12700	10300	10600	12600	8600	54800
Assuming 20% will be attended by farmers themselves	2500	2100	2100	2500	1700	10900
Remaining balance	10200	8200	8500	10100	6900	43900

Table 3. Agroclimatic zonal targets for soil reclamation

Particulars	Zone					Total
	V	VII	XI	XII	XIII	
Estimated area under problems soil ('0000 ha)	991	9532	432	37	82	11802
Time frame for implementation (years)	5	25	5	5	5	
Cost of work (Rs ha ⁻¹) (tentative)	1500	600	1500	1500	1500	
Returns estimated as additional yield after soil conservation (%)	30	25	30	30	30	
Average yield kg ha ⁻¹	1993 (Wheat)	743 (Wheat)	1905 (Rice)	727 (Sorghum)	996 (Pearl millet)	
Value of additional production ha ⁻¹ (Rs)	1166	363	1985	338	463	

A regular program to sink wells, shallow wells, or tube wells is required in various hills and plateau region zones where groundwater development is low and the runoff problem is more acute.

In the Eighth Plan, a management strategy has been recommended. This program should be under the public or cooperative sector as well as the private sector, and liberalized institutional finance should be linked to it, making it a bankable proposition. A suggestion that merits attention in strengthening the groundwater development program is that the beneficiaries be encouraged to form groups and be financed by banks for group irrigation. Many lift and other irrigation cooperatives have successfully demonstrated this approach. The other dimension that merits attention is the proper enforcement of regulations with regard to exploitation of groundwater. This is of urgent importance in some zones (e.g., zones 6 and 13) where already there are signs of overexploitation. The high priority given to groundwater development in recent years will have to be continued. It is expected that a considerable part of the groundwater potential of the country will be utilized in the next decade or so. Special studies have been started to develop integrated management systems of groundwater aquifers. Particular attention needs to be paid to saline areas, coastal belts subject to salinity ingress, and other special problem areas to promote optimum conjunctive use. Satellite imagery in conjunction with further ground surveying can be used to update available information relating to groundwater. The existence of groundwater markets will have to be recognized and the institutional and procedural constraints on them removed. Where the nonownership of the land by share croppers precludes their access to institutional credit, a way must be found to overcome this difficulty in cases in which the existence of a groundwater market ensures the viability of an individual proposal. Similarly, for the purpose of funding by financial institutions, the viability of a groundwater installation should not be assessed on the assumption that its command is restricted to the holding of the prospective owner if a market for groundwater exists or is possible. Where groundwater markets have not developed and any institutional system acts as a constraint, the state will have to play a more direct role in meeting the requirements of marginal farmers.

Tanks are an important source of irrigation in the southern plateau region and the coastal region of eastern India. A large concentration of tanks as irrigation sources occurs in zones 3, 7, 10, and 11 (subzones 2 and 6). This system has degenerated over the past few decades in terms of area irrigated and stability of water supply due to silting up of tanks, weakening of bunds and weirs, and encroachment for cultivation purposes. These irrigation tanks should be restored, as such a step can not only substantially increase agricultural production but also raise the level of living of millions of marginal farmers. Components of tank restoration are: (1) desilting and using the excavated earth for augmentation of fertility of fields, (2) strengthening of bunds and raising of embankments, (3) afforestation of foreshores, and (4) improvement of water courses. The Zonal Planning Teams have suggested tank restoration as one of the strategies to augment irrigation in zones 3, 7, 10, and 11. The Eighth Plan targets this regionally.

Conclusion

Indian agricultural planning and policy has to meet a number of challenges in the years ahead. After a distinct deceleration of output growth and investment efforts in the mid-1980s, the end of the Seventh Plan again saw a greater priority being given to the sector in terms of resource allocation and policy focus. These priorities have to be maintained, since the sector is critical to India's developmental objectives.

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Farmers' Perception of Soil Erosion Stresses and Solutions: Analysis of a Case from the Philippines

S. Fujisaka

Abstract

Research was conducted at a sloping acid upland site in the Philippines. Farmers defined favorable and unfavorable characteristics of their soils, reported crop yield declines which they attributed to soil erosion and soil nutrient depletion. Farmers knew of several, but had tried only a few solutions to soil erosion. They viewed fertilizer use as the solution to soil nutrient depletion. Several farmers were trained in contour hedgerow soil erosion control. They trained others who adapted the technology to fit local conditions and reduce labor costs. Green manures from hedgerows were rejected in favor of grassy strips for stopping soil movement. Adoptors saw that hedgerows slowed soil erosion and, among others, allowed them to apply fertilizers to the alleys. Farmers who learned about the technology but did not establish contour hedgerows had higher proportions of flat lands or off-farm opportunities compared to adoptors. The study supports the idea that farmers clearly know about their lands and soils and problems of yield declines due to resource degradation, and that solutions can and should be built upon such perceptions.

Introduction

More than 100 million ha of the uplands in southeast Asia are characterized by sloping land, high soil erodibility, strong acidity, and low availability of phosphorus. Often following commercial logging, small, mostly resource-poor farmers have settled in these areas to produce subsistence cereal crops. The sustainability of such land-use systems is problematic due to soil nutrient depletion and soil erosion. Scientists from the International Rice Research Institute (IRRI) and the Department of Agriculture (DA) of the Philippines conducted research at Claveria, Misamis Oriental, the Philippines, to develop improved rice-based farming systems on flatter lands and to develop methods to slow down soil erosion on cropped sloping lands. Farmer perceptions—of soils, yield declines, soil nutrient depletion and soil erosion, potential solutions, and their own adaptations of solutions—have played a major role in attempting to build upon farmer perspectives.

Methods

In 1987, 55 Claveria farmers were randomly selected and interviewed about their soils, lands, and perceptions of related problems and of potential solutions. After it was determined that many farmers saw soil erosion as a problem, six farmers and two researchers were trained in contour hedgerow soil erosion control methods by farmers in a neighboring island (Cebu). These farmers in turn trained another 175 farmers from 1987 through 1989. Contour hedgerow technology adoptors were monitored over time to examine their adaptations of the technology and were interviewed periodically to determine their perceptions regarding the technology itself. Farmers who had learned about but did not subsequently adopt the technology were interviewed to determine the reasons for it.

Site Description

Claveria, Misamis Oriental Province, the Philippines, is an on-farm research site located at 390 to 550 m above sea level. Soils are Oxic Dystropepts ranging from clays to silty clay loams, and are acidic (pH 4.5–5.8) with low available P (1.3–4.7 ppm), low CEC (6–12 meq (100 g⁻¹), high Al saturation (11–51%), low to moderate organic matter (3.16%), and low exchangeable K (113.1 ppm). Rainfall occurs in 5 to 6 wet months (> 200 mm month⁻¹) and 2 or 3 drier months (< 100 mm month⁻¹). Average rainfall is 2200 mm year⁻¹ with greatest rainfall from July to December. Soil erosion is largely due to heavy rains in the wet months and because 59% of the semi-permanent plow-based cropping occurs on lands of slope > 15%.

Findings

Farmer Perceptions of Lands and Soils

Farmers readily described their lands and soils (Fujisaka and Garrity 1991). They characterized lands by slope and relative elevation and soils by fertility, color, texture, acidity, and friability (Table 1). For example, farmers considered red (*puwa puwa*) soils to be poor (*niwang* or “thin”) and acidic (*aslom* or “sour”); while dark (*itom*) soils were viewed as fertile (*tambok*) and usually friable (*humok*). Farmer descriptions were not incongruent with researcher analyses.

Farmer Perceptions of the Problem of Yield Declines

Ninety percent of the farmers reported yield declines of their main crops of rice and maize. Many farmers could recall their actual crop yields over the past several years; and such accounts often showed linear declines over time.

Farmer Perceptions of the Cause of Yield Declines

Farmers reporting yield declines were unanimous that the causes of their yield declines were soil erosion and soil nutrient depletion. Farmers described erosion caused by rainwater runoff (e.g., “soil slides down and fertility is washed out”

Table 1. Farmer characterization of lands and soils, Claveria, the Philippines

Soils		Lands	
Name	Description	Name	Description
Undesirable characteristics			
<i>Puwa puwa</i>	Red	<i>Bakilid</i>	Sloping
<i>Niwang</i>	Poor	<i>Buntod buntod</i>	Hilly
<i>Umau</i>	Thin	<i>Baton</i>	Rocky
<i>Aslom</i>	Sour	<i>Nagasgasan</i>	Washed out
Desirable characteristics			
<i>Tambok tambok</i>	Rich	<i>Patag patag</i>	Flat
<i>Itom itom</i>	Dark	<i>Bunkag</i>	New field
<i>Bukakhaon</i>	Holds water		
<i>Pughay/humok</i>	Friable		
<i>Bonbon</i>	Rich silt		

or "fertility is collected in lower lands due to the rains," Table 2). They pointed out parts of their fields damaged by erosion and identified different types of erosion (i.e., sheet, rill, and gully) in local terms. More than 50% of the farmers described a process in which, over time and with cultivation and erosion, darker and more fertile surface soils were lost, exposing infertile red subsoils. About 15% of the respondents reported that noncontour plowing contributed to soil erosion.

In terms of soil nutrient depletion, farmers made such observations as "the soil is now weak," "soils are getting older," "soil fertility has been used up," or "soil fertility is now spotty."

Farmer Perceptions and Practice: Solutions to Soil Erosion

Half of the interviewed farmers were able to name technical solutions to soil erosion. These included rainwater diversion canals, planting perennial crops on upper slopes, trees or bananas planted in gullies to trap soils and utilize eroded nutrients, contour plowing, and weedy strips. Other than 20% of the farmers who had constructed diversion canals, however, few had actually adopted such measures. Only one to three farmers had adopted each of the following: weedy strips between plots, weed and crop residue contour strips across plots, perennials planted on slopes, and perennials planted in gullies located in lower areas.

Table 2. Common farmer perceptions regarding soils, soil nutrients, soil erosion, and soil erosion solutions, Claveria, the Philippines

Topic	Farmer statements
Crops-soil nutrients	"Cassava adds soil acidity" "Cassava eats up soil nutrients" "Crops are vigorous on land last planted to tomato"
Soil nutrient depletion	"Soil fertility has been used up" "The soil is weak after cropping" "The soils are overtrained" "The soils are getting older" "Soil is poor if (<i>Imperata cylindrica</i>) dominates" "Weeds are thin on infertile soils" "Acidity increases where (<i>I. cylindrica</i>) dominates" "Soil is good where there are weeds with nodules"
Soil erosion	"Soil slides down and floats away" "Nutrients are drawn down" "Plants are washed away with the soil" "Soil was drawn downslope and nutrients washed away" "Land was 'shaved' after trees were removed" "Fertility is collected on lower plots"
Fallows	"Decomposing weeds help to enrich the soil" "Land is resting so the soil can store nutrients" "The land is rich because it is rested" "Fertility is added and the soil is made cool"
Soil erosion control	"Banana and coconut hold the soil" "Contour plowing reduces downslope soil losses" "Weedy strips can decrease soil erosion losses" "Trees above and below fields reduce erosion loss"

Farmer Perception and Practice: Solutions to Soil Nutrient Depletion

Of the 55 informants, 96% thought that inorganic fertilizers, lime, and chicken manure (used locally on vegetable crops) were needed to maintain or improve production. No farmer used green manures; and no one who had used a legume experienced soil nutrient benefits from the crop or biomass. Eight farmers had switched from burning to crop residue incorporation. Although 70% mentioned compost benefits, only 6 (9%) had compost pits. Labor, including hauling water, and lack of raw materials limited compost production. Although farmers commonly thought that animal dung increased soil fertility, they grazed their draft animals yet did not collect and compost the manure.

Farmers knew from past experience in other areas that field fallows led to nutrient regeneration. Thirty-five percent of the farmers commented positively regarding fallows. Among their comments were "The decomposing leaves of

weeds help to enrich the soil," "The land is resting, so the soil can store some nutrients," "Fertility is added and the soil is made cool."

The same farmers, however, had observed few positive effects of fallows in Claveria. We analyzed fallow weeds and soils and concluded that farmer perceptions were essentially correct. Vegetative succession no longer proceeds after grasses (*Imperata cylindrica*, *Saccharum spontaneum*, *Paspalum conjugatum*); soil organic matter increased very little by fallowing; and levels of nitrogen and phosphorus remained low.

Farmer Practice and Perception: Working with Contour Hedgerows

Farmer adaptation and adoption of contour hedgerows as a solution to soil erosion in Claveria is documented elsewhere [Fujisaka 1989, Fujisaka (In press)]. In terms of adaptation, hedgerow adoptors ($n = 71$) experimented with what they had learned from other farmers in order to: (1) match a basic contour hedgerow technology to local biophysical conditions by trying different combinations of hedgerow species—including grasses, perennials, or weeds, and (2) reduce labor costs by developing different hedgerow establishment methods.

Although *Pennisetum purpureum* (Napier grass) controlled soil erosion and provided animal fodder, farmers discovered that it was too competitive with the alley crop. Although several farmers had learned that *Gliricidia sepium* was a source of organic fertilizer, no farmer incorporated tree leaves and only one farmer applied an unincorporated mulch because of the labor required for cutting and spreading the biomass. Farmers were positive about mulberry (which 13 farmers adopted) when a silkworm project was initiated in the area, although the suitability of mulberry in terms of competitiveness with the associated alley crop was not known.

The original hedgerow establishment strategy consisted of using the A-frame to determine contour lines, double plowing to create a bund, shovel work to reinforce bunds, and planting of a double row of trees and a single row of grasses. Farmers reduced the labor required from 14 hours per 100 m of hedgerow in 1987 to 8 hours in 1989 by reducing plowing, eliminating most of the shovel work, planting either trees or grasses rather than combinations, or staking out of contour lines (usually but not always banded) which were then left to be covered by "weeds" or native grasses (i.e., *Chromolaena odorata*, *Digitaria setigera*, *Imperata cylindrica*, *Paspalum conjugatum*, *Sorghum halepense*, and others). Farmers further reduced labor requirements in 1990 by simply laying out contours using an A-frame and then preparing the land in the alley. The unplowed weedy strip also terraced and formed flat alleys after a second season's plowing.

Contour hedgerow adoptors ($n = 64$) assessed the technology and saw benefits in terms of reduction of soil erosion (mentioned by 78%), flattening of alleys for cropping (23%), and the possibility of apply fertilizers without loss of such inputs from erosion (25%), although neighbors sometimes allowed their cattle to graze the hedgerows, causing hedgerow and bund destruction (16%).

Farmers who did not adopt the new procedures after attending farmer-to-farmer training sessions provided reasons for non-adoption. These were lack of

labor (45% of interviewed trained nonadoptors) or of draft animals (27%) or competing demands for labor on nonsloping areas (67%) for farmers with large proportions of such lands or for off-farm and nonfarm activities. Although a few mentioned that their tenant status barred adoption, about 16% of adoptors were share tenants.

In light of the nonadoptors' responses, adoptors' and nonadoptors' lands were measured in terms of size and slopes. Differences between total land holdings and between percent slopes on sloping lands did not differ significantly between the groups, but a significantly higher proportion of adoptors' lands was sloping (> 7% slope) compared to that of nonadoptors'.

Discussion and Conclusions

Farmers in Claveria displayed clear perceptions (or farmer technical knowledge) regarding: (1) their local lands and soils, (2) their experience with the problem of yield declines, (3) soil erosion and soil nutrient depletion on their fields as causes of the problem, and (4) the use of organic and inorganic fertilizers as an answer to the problem of soil nutrient depletion. They correctly, for Claveria, had discovered that field fallows were of little benefit for soil nutrient regeneration. On the other hand, although they knew of several technical solutions to the problem of soil erosion, they had adopted only a few problem-solving approaches.

With assistance from researchers, however, farmers who perceived soil erosion as a problem, adopted and then adapted effective contour hedgerow systems after exposure to farmer-to-farmer technology transfer. Farmers adapted the technology to suit local conditions after they correctly assessed problems associated with what they had initially learned in a different environment. They also felt a need for the reduction of the labor needed for hedgerow establishment; and, in response, developed equally effective systems that required much less labor.

The randomly selected Claveria farmers who provided their perceptions prior to technology introduction, during technology adaptation, and in *ex post* technology assessments were "normal" in the sense of being small, resource-poor farmers with low levels of formal education. Nor had they any substantial exposure to researchers or extension agents.

Farmers elsewhere have similarly and clearly described land and soil resources (Richards 1985, Fujisaka 1991), related problems (Fujisaka et al. 1991, Thrupp 1981), and their problem-solving approaches (Buckles 1992, Rhoades and Bebbington 1991, RAPA 1989, Wilken 1987).

In short, this chapter maintains that the answer to "the all important question of how farmers or the users of the land perceive stresses" is "clearly and accurately," albeit in their own terms. The challenge is for researchers to elicit such farmer perceptions and related practices in order to determine where and how problem-solving research can build upon—i.e., take advantage of—such farmer perceptions.

Several guidelines are offered to operationalize the use of farmer knowledge, practice, and perception:

1. Researchers must realize that farmer knowledge pertaining to lands and soils is usually fairly complete and relatively accurate for their needs.
2. Such knowledge is based on farmers' practical local knowledge gained from season-after-season observation and experimentation.
3. Accepting the above, researchers can elicit farmer concepts and knowledge using simple open-ended interviews and discussions.
4. The key is to ask farmers a sequence of "why?" questions when discussing their practices.
5. Farmers' perceptions of problems and their problem-solving practices can then be discussed using farmer terms and concepts.
6. Researchers and farmers can benefit by starting work on a problem that farmers have tried to solve via their own experiments.
7. Researchers and farmers can benefit by starting work with farmers who are aware of a problem and who have tried to solve it.
8. Technology development can build upon farmer knowledge and practice via joint efforts by farmers and researchers.
9. Farmer-researcher partnerships begin with problem and research identification and prioritization and continue through cycles of technology development and evaluation.

The above statements imply that a key to working with farmers is building upon their knowledge and practice; and that the key to doing so is a researcher understanding that small farmers in marginal areas must have sets of knowledge and practice matched to their environments in order for them to survive. Eliciting such knowledge, understanding farmer practices, and developing sensible research approaches can be somewhat straightforward once such an understanding is reached.

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V. Resource Management

Nutrient Management Strategies in Stressed Environments

P.L.G. Vlek and K. Vielhauer

Abstract

The land endowment of the tropics is highly variable. Of the nearly 5 billion ha of tropical land, 43% is found in Africa, 28% in South America and 20% in Asia. Most developing countries are found within this region. FAO estimates that 57% of this land has a high potential for agricultural production due to good water supply. The remaining land is considered stress prone due to low and uncertain rainfall (21%) causing drought, or excessive rainfall (22%) leading to erosion, leaching and soil acidification. In this chapter we concentrate on these stressed environments.

The soils of the tropics are a key element determining the productivity of the land. They are widely different in their characteristics as a result of different parent materials and pedogenesis. An important part of what constitutes soil productivity is determined by the fertility of the soil, which in turn is largely determined by the organic matter and stored nutrients of the soil. In many soils, a significant fraction of the nutrient store is in the soil organic matter (SOM), an extremely important but fragile soil constituent, readily lost when organic matter inputs are drastically reduced following cultivation. The concomitant loss of topsoil and possible exposure of subsoil acidity may cause further soil degradation.

Estimates of nutrient depletion rates for sub-Saharan Africa, in soils are alarmingly high. The situation may be more favorable with respect to harvested and applied nutrients in Latin America and Asia, where fertilizer inputs exceed those in sub-Saharan Africa by a factor of ten. As much as 50% of the increase in agricultural productivity in the developing world is due to the adoption of fertilizer use. However, the rate of adoption of fertilizer, in stressed environments lags far behind that of the more favorable production areas. Over 60% of the urea consumed in South and Southeast Asia is used for irrigation of rice. Much of the remainder is used on irrigation of wheat and cash crops, whereas rainfed crops largely depend on biologically fixed, soil and residual N.

Environmental awareness is causing a shift in strategy for nutrient management towards soil fertility maintenance based on natural resource conservation, biological nitrogen fixation, and input efficiency, referred to here as integrated soil fertility management (ISFM). The concept of ISFM is equally applicable to stressed and favorable environments. Using the latest knowledge regarding cultural practices, cropping systems and nutrient cycles it aims at optimizing and stabilizing agricultural production within a given ecological and socioeconomic environment. The concept does not preclude

the use of fertilizers but weighs its use against the alternatives in terms of direct and long-term environmental costs in meeting the demand for food and fibre. The resulting strategies may differ considerably for similar ecosystems due to varying infrastructural, population or policy settings, resulting in different market conditions. Therefore, it is difficult to provide a blueprint for nutrient management in defined stressed environments without considering these externalities.

The agronomic information on which nutrient management strategies need to be based has been largely collected over the past decades. However, the combination of plant nutrients and stressed environments found in the tropics would factor to a set of scenarios that cannot be practically covered in a single chapter. Consequently, the principles of nutrient management in stressed environments are highlighted using the three major nutrients and one key stress environment relevant to this nutrient. The chapter discusses N management in the semi-arid tropics, P management in the highly acid soils, and K management in the high-rainfall tropics. These examples are used to clarify the strategy options as a function of the social and ecological setting.

Introduction

The land endowment of the tropics is highly variable. Of the land between the Tropic of Capricorn and the Tropic of Cancer (nearly 5 billion ha) 43% is found in Africa, 28% in South America and 20% in Asia. The vast majority of the developing countries fall within this region. A recent study by FAO (1989) concerning 93 developing countries, estimates that 57% of this land is of high quality with high potential for agricultural production due to good water supply. The remaining land is considered to be of low potential due to low and uncertain rainfall (21%) or problem land with excessive rainfall and/or prone to erosion (Figure 1).

The soils of the tropics are a key element, determining the productivity of the land. They are widely different in their characteristics as a result of different parent materials and pedogenesis. Most tropical regions have some representation of all soil types, but the dominant soil types are different in the different ecological zones. The distribution of soils by climatic regions is given in Table 1, (Sanchez 1976), showing the predominance of the highly weathered soils (51%) and dry sands (17%) in the tropics as a whole.

An important part of what constitutes soil productivity is the fertility of the soil, which is largely determined by the organic matter and stored nutrients of the soil. In many soils, a significant fraction of the nutrient store is in the SOM, an extremely important but fragile soil constituent.

The loss of soil productivity is often related to the loss of SOM. Jenny and Raychaudhuri (1960) studied 522 soils in India and calculated "cultivation indices N_x and C_x " reflecting the percentage loss of SOM as a result of cultivation. They found values for C_x ranging from near 100 for resilient paddy soils down to around 30 for the most fragile environments. N_x values were mostly following a similar trend. A number of studies since then have described the process of

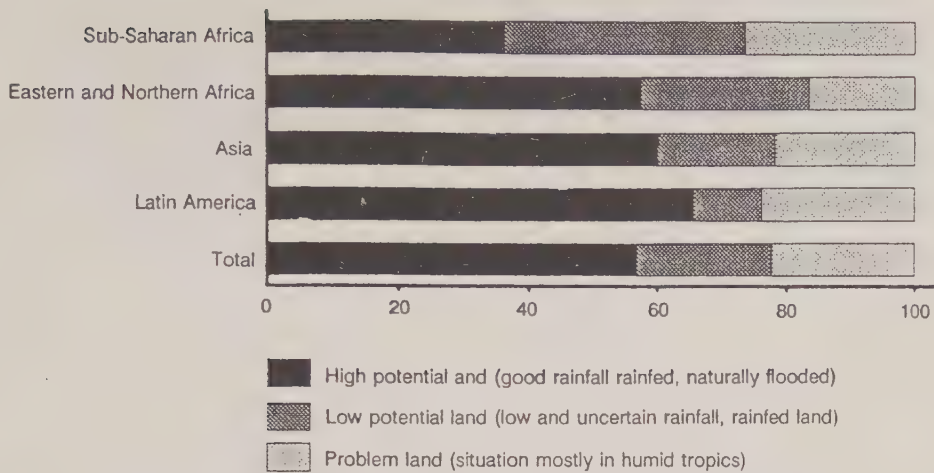


Figure 1. Shares of total harvested land of different potentials, 1982–1984 (93 developing countries). (Source: World agriculture: Toward 2000)

Table 1: Distribution of soils in the tropics by climatic regions (million ha)¹

Soil groups (soil taxonomy equivalents)	Rainy (9.5–12) ²	Seasonal (4.5–9.5) ²	Dry and desert (0–4.5) ²	Total	Percent of tropics
1. Highly weathered, leached soils (Oxisols, Ultisols, Alfisols)	920	1540	51	2511	51
2. Dry sands and shallow soils, (Psammments and lithic groups)	80	272	482	834	17
3. Light-colored, base-rich soils (Aridisols and aridic groups)	0	103	582	685	14
4. Alluvial soils (Aquepts, Fluvents, and others)	146	192	28	366	8
5. Dark-colored, base-rich soils (Vertisols, Mollisols)	24	174	93	291	6
6. Moderately weathered and leached soils (Andepts, Tropepts and others)	5	122	70	207	4
Total area	1175	2403	1316	4896	100
Percent of tropics	24	49	27	100	

1. Source: Sanchez (1976).

2. Numbers in parentheses refer to number of months with an average rainfall greater than 100 mm. Source: Adapted from the President's Science Advisory Committee (1967).

SOM loss. Siband (1974), demonstrated the process by sampling an unreal time series in Senegal. He noted a decline in topsoil SOM from 2,85% under forest to 0,84% after 90 years of continuous cultivation. Fölster (1992) studied the effect of intensification, on soil degradation in the Gran Sabana region of Venezuela. With increasing demand for land the natural vegetation declined from primary forest via Savannah to degraded grass-Savannah with concomitant losses in soil nutrients (Table 2).

Table 2: Changes in soil parameters (rounded) in the successively degraded landscapes of the Gran Sabana, Venezuela¹

	Above ground biomass t ha ⁻¹	In litter and 30 cm topsoil		
		C (t ha ⁻¹)	K (kg ha ⁻¹)	Ca (t ha ⁻¹)
Primary forest	330	220	285	90
Secondary forest	180	115	240	90
Matorral	10	85	160	190
Bush-Savannah	6	60	150	190
Grass-Savannah	4	45	80	40
Degraded Grass-Savannah	2	20	50	15

1. Source: Fölster (1992).

When the natural carbon recycling in natural vegetation is interrupted due to cultivation, the level of soil organic matter declines, and more rapidly so under tropical conditions (Jenkinson and Ayanaba 1977). Further losses in soil productivity will occur due to the acceleration in soil erosion when a year-long canopy is no longer present (Dunne and Dietrich 1982), leading to a possible exposure of subsoil acidity. Shifting cultivation techniques, involves the abandonment of such degraded lands in order to allow restoration of soil productivity (Sanchez 1976).

Quantification of nutrient losses from agricultural systems are risky. For sub-Saharan Africa (SSA) an effort was made to assess the depletion rates for the various countries and land/water classes (Stoorvogel and Smaling 1990). The results, summarized in Figure 2, deliver a compelling message: soils in SSA are losing their fertility at exceedingly high rates. Vlek and Koch (1992) estimated that a minimum of 4 million tons of nutrients are harvested annually in SSA while only one-fourth of it is returned in the form of fertilizer. As much as 0.3 million ton of nutrients are contained in exported products. The situation may be more favorable with respect to harvested and applied nutrients in Latin America and Asia, where fertilizer inputs far exceed those in sub-Saharan Africa. However, it is doubtful that the balance will turn out favorable when losses due to erosion and declining SOM levels are taken into account.

Classes of nutrient loss rates (in kg ha ⁻¹)				
	Class	N	P ₂ O ₅	K ₂ O
	Low	<10	<4	<10
	Moderate	10-20	4-7	10-20
	High	21-40	8-15	21-40
	Very high	>40	>15	>40



Figure 2. Soil nutrient depletion rate in sub-Saharan Africa. (Source: Stoorvogel and Smaling 1990)

According to FAO as much as 50% of the increase in agricultural productivity in the developing world is due to the adoption of fertilizer use. Statistics on fertilizer use clearly demonstrate the dependence on fertilizer for food security, of the tropics and subtropics. However, the rate of fertilizer adoption in stressed environments lags far behind that in the more favorable production areas. Over 60% of the urea consumed in South and Southeast Asia is applied to the irrigation of rice. Much of the remainder is used on the irrigation of wheat and cash crops,

whereas rainfed crops largely depend on biologically fixed, soil and residual N. The growing awareness in the West of the damage caused to the environment associated with indiscriminate fertilizer use is causing a shift in strategy for nutrient management towards soil fertility maintenance based on natural resource conservation, biological nitrogen fixation, and input efficiency, here referred to as integrated soil fertility management (ISFM).

The concept of ISFM is equally applicable to stressed and favorable environments. Using the latest knowledge regarding cultural practices, cropping systems and nutrient cycles it aims at optimizing and stabilizing agricultural production within a given ecological and socioeconomic environment. The concept does not preclude the use of fertilizers but weighs its use against the alternatives in terms of direct and long-term costs to the environment in meeting the demand for food and fibre. The resulting strategies for nutrient management may differ considerably for similar ecosystems due to varying infrastructural, population or policy settings, resulting in different market conditions. Therefore, it is difficult to provide a blueprint for nutrient management in defined stressed environments without considering these externalities.

In discussing nutrient management in stressed environments we have opted to treat the major nutrients N, P, and K in sequence, while focusing on selected stressed environments in which managing each nutrient is particularly cumbersome. We will restrict our discussion to abiotic stresses other than nutrient stress, even though we fully recognize the complex interactions between abiotic and biotic stress factors. It is further useful to keep in mind that stressed environments are often associated with high risk and low productivity, thus limiting the options for nutrient management unless associated with full scale reclamation/irrigation practices. In the process we hope to clarify the options available for nutrient management strategies in stressed environments in various socioeconomic scenarios.

Nitrogen

Probably the main stress in relation to nitrogen management is the uncertainty of rainfall. When excessive or very intensive, nitrogen is subjected to leaching or denitrification, while with draught it has a tendency to remain in soil unutilized by crop. Various symposia have dealt with soil water and nitrogen management in Mediterranean-type environments (Monteith and Webb 1981), in humid and subhumid tropical environments (Kang and van der Heide 1985) and in semiarid tropical regions (Christianson 1989). Nitrogen management for various African climatic regions nitrogen management was recently reviewed by Mughogho et al. (1986) and Christianson and Vlek (1991). In the current review we will concentrate on the semi-arid tropics.

The semi-arid tropics (SAT) stretch over 48 countries in four continents (El-Swaify et al. 1985) covering around 2000 million ha (Ryan 1974) supporting more than 700 million people (Swindale 1982). The major soil types in the SAT belong to the rather infertile and poorly buffered Entisols and Alfisols or to the fertile but difficult to manage Vertisols (Table 1). Nitrogen is generally deficient in these soils, irrespective of their depth (Finck and Venkateswarlu 1982). Fertilizer

use in the SAT regions of the world is negligible. In India, where the efforts to reach the SAT farmer are probably the most intensive, fertilizer consumption in the SAT increased 10-fold between 1970/71 and 1985/86 (Biswas 1989), but still amounts to less than 10% of the Indian N consumption.

The principle stress factor in the SAT is often considered to be water (Huda et al. 1988). However, the stochastic nature of precipitation in these areas is such that N or other nutrients may frequently be more limiting to crop growth and may lead to poor water-use efficiency, when rainfall is adequate. Moreover, soil nitrate can be left unused in the soil in the absence of rainfall or be lost through leaching by excessive rains (Huda et al. 1988). The complexities of these interactions give rise to highly variable yields, as well as use efficiencies of soil and applied N. Yet, fertilizer use in the SAT can be profitable, particularly if combined with improved cultural practices and high yielding varieties (HYV) (Venkateswarlu 1987). The response to fertilizer N in many soils of the SAT is spectacular in years of adequate rainfall, provided other nutrient deficiencies are taken care of.

The options for improving nitrogen management are relatively few. Soil nitrate generally accumulates over the dry season in quantities dependent on the amounts of readily decomposable organic matter left in the soil, and may be available for crop establishment. Conservation and build up of this valuable SOM is of critical importance to long-term productivity, particularly in the absence of fertilizers. Bationo et al. (1993) demonstrated the importance of the restitution of straw on improving SOM levels in soils of the Sahel. The benefits of combined use of fertilizer and straw were clearly better than each factor alone, and after four years was reflected in a 60% reduction in Al saturation of the exchange complex and tripling of available P. The incorporation of legumes in the cropping system is another important avenue open to achieve this. The experience in India in this respect was recently reviewed by Lee and Wani (1989).

Light textured soil. The majority of the soils in the African and Asian SAT consist of light textured soils. Nearly 500 million ha are found in sub-Saharan Africa alone (Sanchez 1976). Soil organic matter in these soils rarely exceed 1%, and declines with rainfall as follows:

$$\text{SOM} = 0.15 + 0.00085 \text{ Rainfall} \quad (\text{SE} = 0.20; R^2 = 0.48)$$

Under these circumstances, native soil N is unable to realize the yield potential of the crop when rainfall is not limiting crop growth. Figure 3 (Christianson et al. 1990) depicts the modeled response of millet in Niger under three rainfall scenarios. When rainfall is not limiting (350 mm mid-season rain) yields of millet do not exceed 1000 kg ha⁻¹ and N is clearly limiting as reflected by the excellent response rate (kg yield kg⁻¹ fertilizer N). The critical rainfall needed between sowing and mid-season in order to obtain a response to applied N lies above 200 mm. Our understanding of these nitrogen and rainfall interactions is of little help to the farmer as long as weather forecasting remains out of reach. The decision making for the farmer is made more complex due to the interactions of seasonal rainfall with sowing density, another factor that

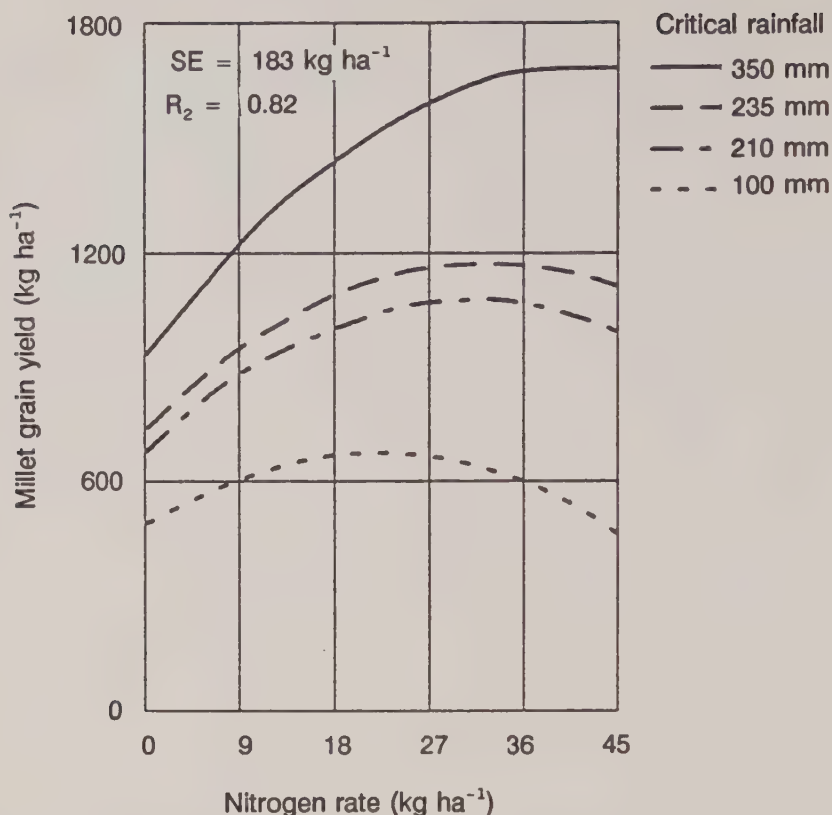


Figure 3. Nitrogen response of millet as a function of "critical rainfall." (Source: Christianson et al. 1990)

is decided before rainfall estimate are known. Bationo et al. (1990) summarized the relationship between millet grain yield (Y), nitrogen rate (N), plant density (D) and mid-season rainfall (R) for the Sahel in the following equation:

$$Y = 1085 - 8.65 N - 51.13 D - 2.73 R + 0.071 N \times R + 0.304 D \times R$$

$$R^2 = 0.75, SE = 283$$

reflecting the benefits of dense sowing and nitrogen use in years of adequate rainfall, while dense sowing with N fertilization in dry years may result in haying off. Again, this knowledge is not readily translated into recommendations for farmers.

Typical losses of applied urea for different SAT environments in Africa and India are provided in Figure 4. In the case of millet grown on lighter textured Entisols of the Sahel (500–750 mm rainfall) these losses amounted to around 40% when urea was split and banded in the wet year 1983 as well as in the dry year 1984, and were presumably due to ammonia volatilization. The plant recovery was around 20% in both years, but the partitioning of recovered 15 N by the plant was decidedly different, with equal amounts found in grain and

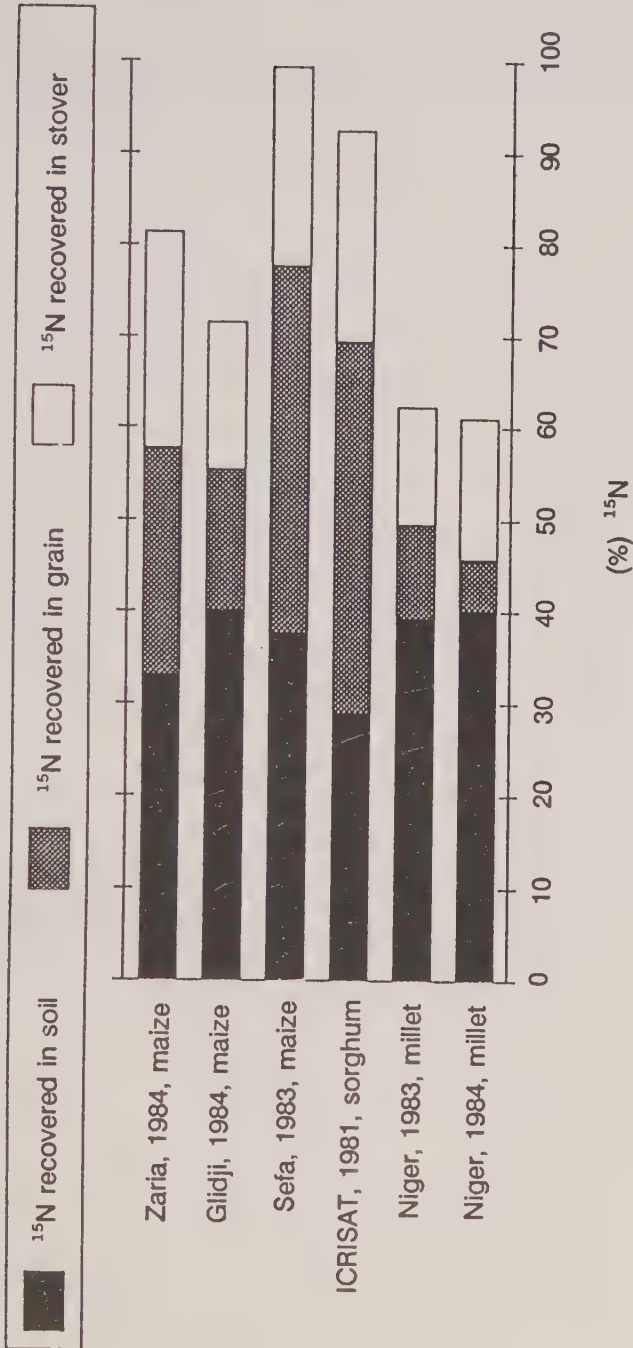


Figure 4. ^{15}N balances for split-applied urea on pearl millet, sorghum and maize in semi-arid tropical environments

stover in the wet year and only a quarter in the grain in the dry year (Figure 4). Similar results were also reported for rainfed wheat in the Mediterranean region (Buresh et al. 1990).

Nitrogen losses in Alfisols from the slightly wetter SAT (750–1000 mm) ranged from 20–28% for maize cultivation in Africa (Mughogho et al. 1986) and from 5–21% for sorghum in India (Moraghan et al. 1984). In all these studies split banding seemed the most suitable application method while calcium ammonium nitrate (CAN) appeared slightly more efficient than urea.

Heavy textured soil. Of the 257 million ha Vertisols world wide (Dudal 1965) most are located in the SAT. Vertisols with mean soil depths of > 100 cm, are commonly associated with soils exhibiting vertic characteristics, such as Ustochrepts and Ustropepts, but too shallow (< 50 cm) to classify as such. In India alone 20 million ha of these soils are found (Swindale 1982). Research over the past 15 years has indicated that response of sorghum on the Vertisols is good even under rainfed conditions (El-Swaify et al. 1985). For the shallow vertic soils, response to fertilizers is more erratic because of poor water storage characteristics (Randhawa and Venkateswarlu 1980). For Vertisols, placement of N in bands was found to be efficient, and losses were low (Moraghan et al. 1984).

Hong et al. (1992) studied the response of sorghum to applied N on a deep Typic Pellustert and a shallow vertic Ustochrept, and, using labeled fertilizer, traced the fate of N through the soil-plant system. Response to N for the two soils for the different years is depicted in Figure 5. Leaching losses of native soil N in these heavy clay soils of the Indian SAT reduced yields to half of their potential (Hong et al. 1992). Timely sowing might increase the chance of N interception by the crop, but sowing date options are often determined by the ability to cultivate land and thus by the onset of rain.

Nitrogen 15—balances were constructed for the various N sources applied at 60 kg N ha⁻¹ (Table 3). On the deep Pellustert, fertilizer use by sorghum was rather efficient with plant recoveries of 56% and soil recoveries of 35–37%, resulting in losses of 7–9% of the applied urea-N, irrespective of seasonal rainfall. Moraghan et al. (1984) conducted similar experiments at the same site in a similarly wet year (1070 mm total rainfall vs. 913 mm in 1983) and reported a total ¹⁵N loss of less than 6 % for split applied urea.

In the shallow Ustochrept, urea-N recoveries by the plant were substantially lower (36–41%) even though soil recoveries were similar to those obtained on the Pellustert (Table 3). Consequently, ¹⁵N losses ranged from 21 to 30% or nearly triple those experienced on the deeper Pellustert. Given that the top 50 cm of these two soils are nearly identical in character, the difference must have been due to applied N leaching into the zone below 50 cm where, in the shallow soil, it would be beyond the sampling zone.

The KNO₃-N included in the wet year on the Pellustert was as efficient as urea (Table 3). Moraghan et al. (1984) reported for an even wetter year (1070 mm rainfall) that NO₃-N applied to a deep Vertisol was indeed very efficiently (57%) taken up by the crop. In the Ustochrept, the behavior of NO₃-N was strongly dependent on rainfall. In the wetter years the ¹⁵N labelled NO₃-N was poorly

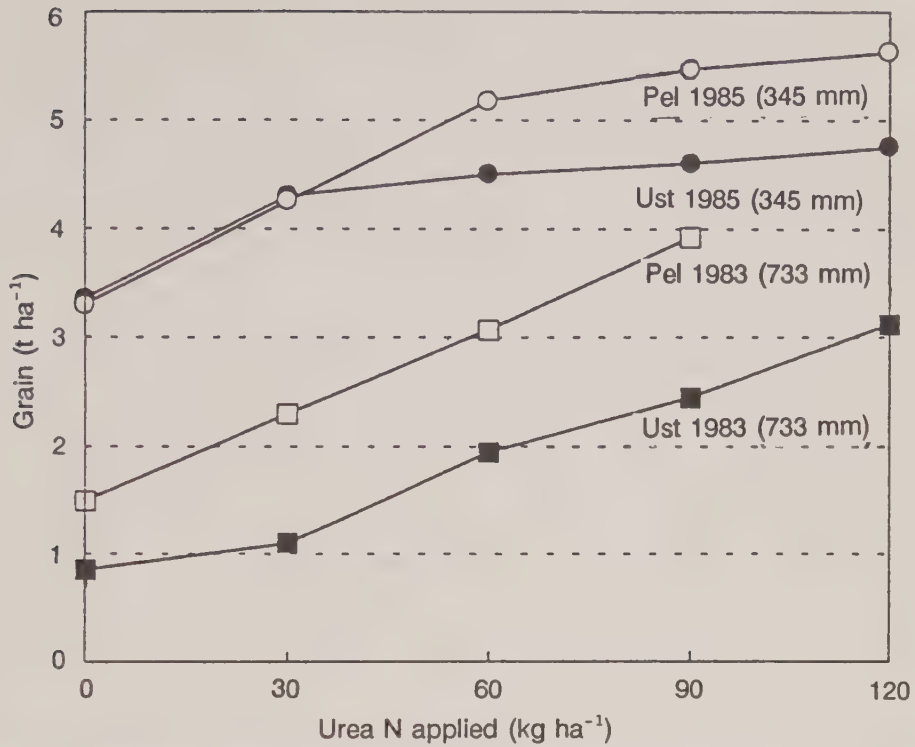


Figure 5. Response to urea-N on a shallow Ustochrept and deep Pellustert in years with different rainfall. ICRISAT, India

Table 3: Recovery of ^{15}N applied to two experimental soils cropped to sorghum in different years.¹ Pairwise comparison (LSD 95%) within years (significant difference within columns are indicated by different letters)

Soil	Year	N-source	Rain ² (mm)	¹⁵ N recovery			
				Plant	Soil	Total	Loss
						%	
Pellustert	1982	Urea	516	56 ^a	35 ^b	91 ^a	9 ^a
		KNO ₃		66 ^b	26 ^a	92 ^a	8 ^a
	1985	Urea	345	56	37	93	7
Ustochrept	1983	Urea	733	36 ^A	35 ^B	71 ^B	29 ^A
		KNO ₃		35 ^A	23 ^A	58 ^A	42 ^B
	1984	Urea	485	40 ^b	29 ^b	70 ^b	30 ^a
		KNO ₃		26 ^a	13 ^a	39 ^a	61 ^b
	1987	Urea	372	39 ^A	40 ^B	79 ^A	21 ^A
		KNO ₃		55 ^B	27 ^A	82 ^A	18 ^A

1. Source: ICRISAT, India.

2. Rainfall between June 1 and September 15.

utilized by the crop in comparison with urea-N. The lost ^{15}N amounted to 42%–61% of the applied N.

It appears that the great difference in susceptibility to loss of NO_3N is due to differences in soil depth, suggesting leaching beyond the rooting zones. Kissel et al. (1974, 1976) also reported leaching of nitrate in swelling clay soils. Such losses are not only determined by the accumulated rainfall, but also depend on the rainfall distribution. In years with heavy rainfall immediately following fertilizer application, NO_3 moves readily into the poorly rooted parent material. Smaling and Bouma (1992) demonstrated that much of the leaching in Vertisols early in the season occurred as bypass flow, utilizing cracks that formed during the dry season prior to their closure. As N leaching appears to be the predominant cause of N loss from the shallow soils, and given the unpredictability of the rainfall pattern following fertilizer application, NO_3 sources should be avoided on shallow soils of the SAT. Moreover, in order to minimize the risk of leaching, the fertilizer-N on shallow soils should be split as frequently as possible.

Thus, with the exception of the dry SAT and the shallow soils, response and efficiency of fertilizer N appears reasonably assured. Nitrogen adoption in these regions will, however, only commence when a secure market is available for the crops grown and the risks of regaining investment costs are limited to the vagaries of the weather only. Governments may have a role to play in establishing adequate price floors for these commodities.

In those regions where adequate markets can not be guaranteed, the farmer's options to increase long term crop production are rather limited. Bationo and Mokwunye (1991) argue convincingly that good organic matter management is the key to soil fertility management. Research results reported by them and those summarized by (Pieri 1985) show that quantities of around 15–20 t ha⁻¹ of manure are needed to obtain the effect otherwise achieved by chemical fertilizers. Young (1989) estimated requirements of crop residues to range from 2 t ha⁻¹ in the semi-arid zones to over 8 t ha⁻¹ for the humid tropical regions. With the many alternative needs for organic material such quantities are not generally available (Bationo and Mokwunye 1991). The best, one could probably hope for is, that organic matter levels be maintained, through a combination of crop residue restitution, fallowing or green manuring. An example from Zimbabwe (Table 4), summarized by Steiner (1991) shows the time investment necessary to assure sustainability of the system. Once the pressure due to land limitation does not

Table 4. Mean maize yields (%) in different crop sequences in comparison with alternative cropping of green manure and maize; A = 100%. (mean of 6 years)

Sequential cropping of maize and green manure (GM)	1	2	3	4
	year			
A. GM and maize, alternating	100			
B. GM followed by two maize crops	93.5	52.9		
C. GM followed by 3 maize crops	95.6	53.5	48.2	
D. GM followed by 4 maize crops	87.1	51.5	41.2	36.4

permit farmers to set aside land for recuperation, the productive capacity declines, often to the point of becoming wasteland.

Phosphorus

Most of the soils of the tropics are notoriously low in available P (Ssali et al. 1986). Often this is due to the inherently low P levels in the soil such as is common in the coarse textured Entisols and Alfisols of the semi-arid tropics, e.g., western Africa, southwestern Africa and northeastern Brazil. Initial available P in these soils following the onset of cultivation are largely stored in the soil organic matter which is readily depleted (Bationo et al. 1986). Even if the inherent P content of a soil is high, the high affinity of P for iron and aluminum oxides may immobilize any solubilized P and render it unavailable for plants. This is particularly the case in the acid Ultisols and Oxisols common in the humid and subhumid tropics. Various forms of calcium phosphates may maintain low P-levels under alkaline conditions typical for the arid and semi-arid environments (Lindsay et al. 1989). In this chapter we will restrict ourselves to the management of P in the highly acid soils of the tropics.

The acid soils of the tropics cover an area of 580 million ha of potentially arable land with udic moisture regimes. Acid soils are, however, not restricted to the tropics, and are found over large areas in the subtropics of the southern United States as well as elsewhere in the world. As a result, the management of such soils has been studied extensively. The key nutritional disorders in acid soils are related to the toxic manganese and aluminum levels and the associated lack of phosphorus and the secondary nutrients S, Ca and Mg. The universal solution to these problems is the liming of acid soils. The resulting pH increase precipitates soluble and exchangeable Al in the form of Al-hydroxides thus eliminating Al toxicity (Haynes 1984). The same would occur with soluble Mn which may be present at toxic levels in younger acid soils (Stumpe and Vlek 1991). Lime or dolomitic lime also serves as a source of Ca and/or Mg. Most recommendations are based on liming to pH levels around 6.5, where P availability is judged to be maximized (Lindsay et al. 1989). Yet, the effect of liming on P absorption and availability is often contradictory (Haynes and Naidu 1991), with the sorptive capacity reported to increase as well as decrease, and P availability going up, down or remaining unchanged with liming.

Haynes and Naidu (1991) explained these contradictions based on two mechanisms acting in parallel when soils are limed: an increase in negative surface charge due to a pH increase reducing P adsorption, and the formation of freshly precipitated Al-hydroxide surfaces which increase the P adsorption. The net result of these two mechanisms determines the overall P behavior upon liming (Haynes and Swift 1988). In soils with large initial P absorption capacities, the first mechanism is likely to dominate whereas in soils with limited P absorption capacity but high exchangeable P levels the second mechanism dominates (Figure 6).

The primary effect of lime is to reduce the free Al-species, which, as was shown for an acid Ultisol in Malaysia (Shamshuddin et al. 1991), correlates well

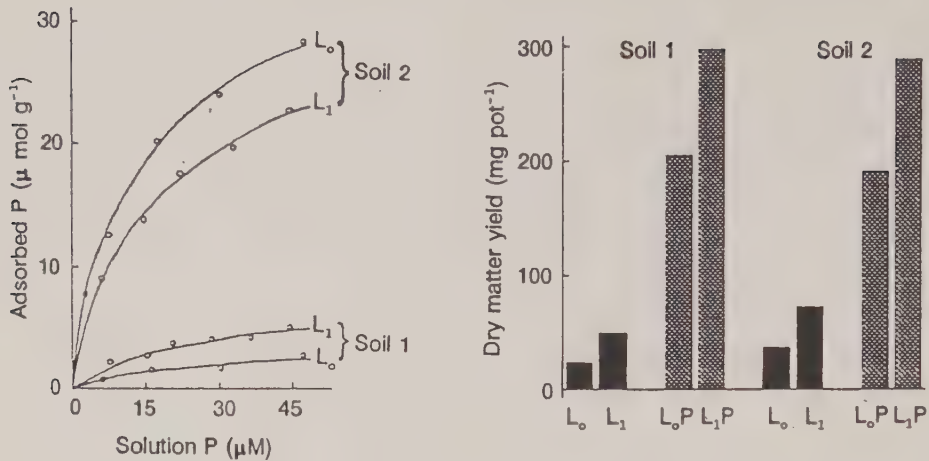


Figure 6. Effect of lime addition on adsorption of phosphate (left) and effect of lime and phosphate additions on cumulative dry matter yield of *Lolium perenne* (right) in two different soils. (Source: Haynes and Naidu 1991)

with crop yield (Figure 7). As a result, the effect of liming is often not related to the P availability or only coincidentally so. The soils 1 and 2 in Figure 8 above show opposite behavior with respect to P availability upon liming, yet crop yields improved with liming irrespective of P status.

Most commonly the liming rate is based on the titration curve established for the soil type in question. In the case of Oxisols, Reeve and Sumner (1970) recommended to base lime requirements on the exchangeable Al index. Responses to higher application rates are widely reported (Fagaria et al. 1991). Responses up to 10 tons of lime are not uncommon, while residual effects may last several years (Friesen et al. 1982). Such recommendations are of little use to small farmers that could ill-afford these investments without government support. They were, however, adopted by the Brazilian government as a condition of sale of Cerrado land together with substantial investments in P and Zn. Thus, 50 million ha of land were opened up for agriculture, mostly for mechanized farming on larger farm holdings.

Application of small amounts of lime to acid soils is an unusual practice, but encouraging results were recently reported by Mamaril et al. (1991) for an acid Ultisol from the Philippines (Figure 8). In this experiment, which was continued for 6 years, annual lime applications were kept to 0.75–1.5 t ha $^{-1}$, levels considered affordable for the resource-poor farmer. Over the years of the experiment yield levels were sustained with either liming or a minimum of 18 kg P ha $^{-1}$ (Figure 8), but yield improvements required a combination of both.

Heavy lime applications do more than providing the desired pH change and concomitant changes in Al and P activity in the soil. Ca and Mg levels in the soil are greatly increased, particularly in the plough layer (Figure 9). At the higher

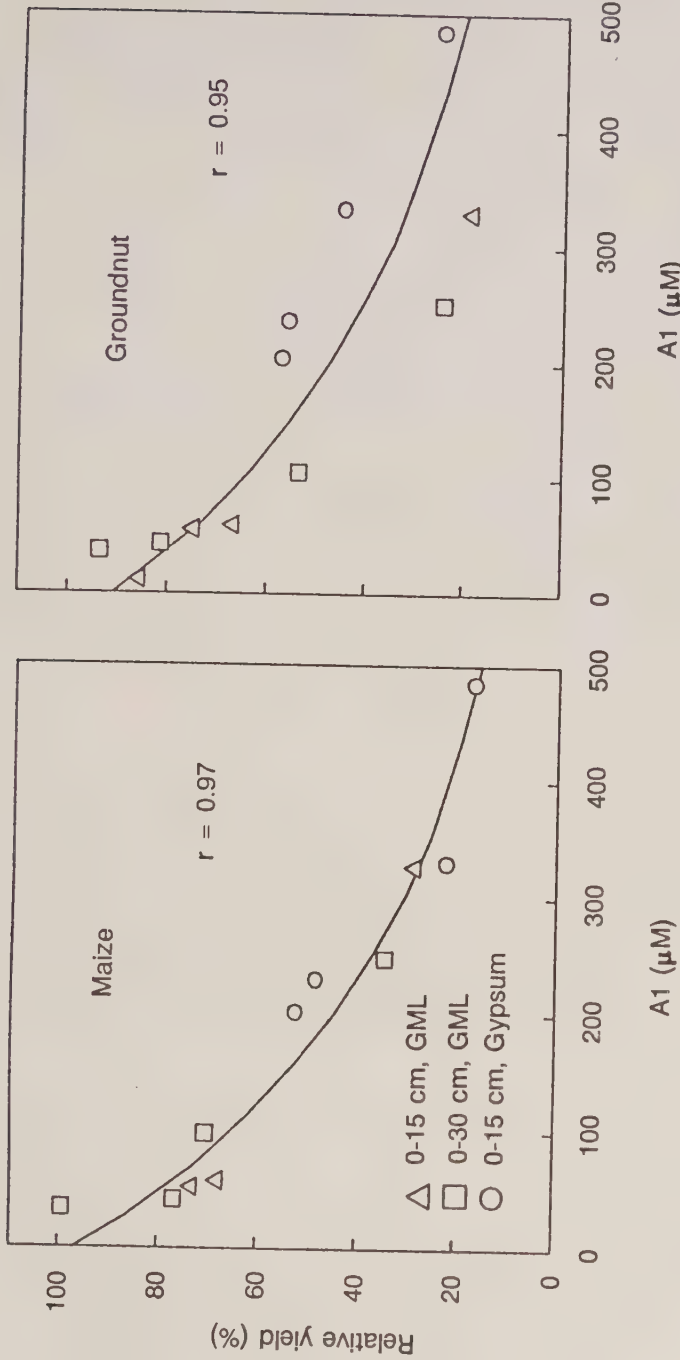


Figure 7. Relationship between maize and groundnut yields (%) and soil solution A1 concentration in 0–15 cm layer following incorporation of limestone (GML) or gypsum. (Source: Shamsuddin et al. 1991)

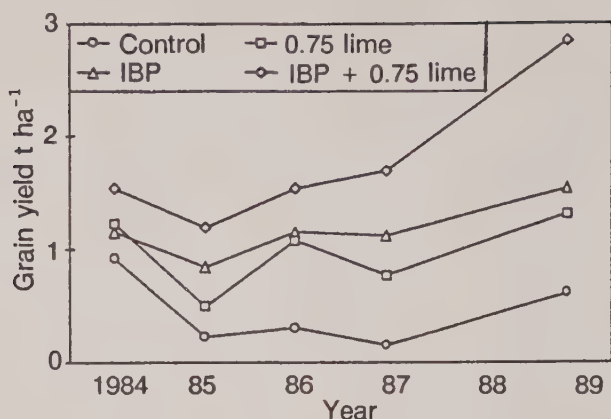


Figure 8. Grain yield trends for unfertilized control and for treatments involving P and lime as well as P in combination with lime, 1989 wet season. (Source: Mamaril et al. 1991)

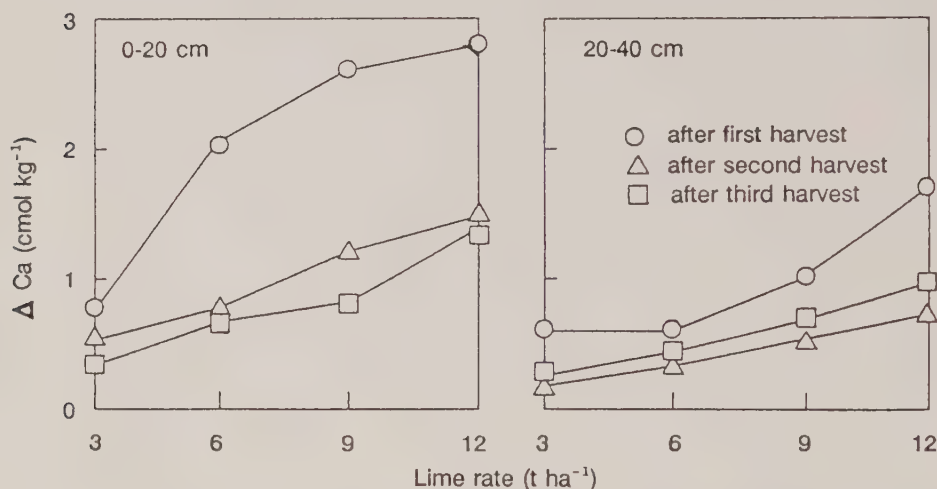


Figure 9. Changes in soil exchangeable Ca and exchangeable Mg with soil depth interval and time as a function of lime application rate. (Source: Gageria et al. 1991)

application rates these bases may move downward and reduce subsoil acidity, responsible for shallow rooting depths and thus improve soil and water exploitation in the acid soils of the tropics (Ritchie et al. 1980; Friesen et al. 1982).

Phosphate application rates needed to satisfy the fixing capacity of acid soils may vary considerably. The low-fixing acid soils of West Africa require as little as 30 kg ha⁻¹ P₂O₅ to adequately support crop growth (Bationo et al. 1986), whereas the high-fixing acid soils of Latin America will show little crop response with P rates below 200 kg ha⁻¹ P₂O₅ although much higher rates are not uncommon. The cost to the farmer may be prohibitive. One of the attractive options extensively studied in the past decades has been the application of

phosphate rock as a slow-release source of P and Ca for direct application on acid soils. The topic has been exhaustively reviewed by Khasawneh and Doll (1978) and Hammond et al. (1986). Although some details on the optimum management practices are still being argued, there is little doubt that direct application of phosphate rock, many deposits of which are found in the tropics, provides a low cost option to supply P to acid soils. The effectiveness of application not only depends on soil characteristics, but also on the quality of the phosphate rock (PR). The reactivity of tropical PRs vary widely, leading to differences in the availability of P from these sources (Hammond et al. 1986).

In situ acidulation of PR by soil acidity will render the phosphate available to the standing crop. The rate of acidulation and thus the P supplying power of the PR, depends on the PR's reactivity and the acidity and buffering capacity of the soil. The P availability is further dependent on the rate at which the soil immobilizes the released P. The net result of these P releasing and P fixing processes may differ substantially, dependent on soil type and PR source. For most PRs a certain contact time is needed to solubilize adequate amounts of P to generate a response. A comparison of five Brazilian PR sources on an Oxisol planted for six successive seasons showed the delay in P solubilization in the first season (Table 5), but residual effects of PR were similar to those of the soluble sources (Fagaria et al. 1991).

Table 5. The effect of P sources and rates on grain yield of rice and common bean (kg ha^{-1})¹

P added (kg ha ⁻¹)	TSP	P source ²		PR
		APPA	PPPA	
First crop (rice)				
Control	529	—	—	—
87	1958	2190	1743	518
174	2739	2046	2237	611
262	2217	2094	1455	829
Second crop (rice)				
Control	674	—	—	—
87	1509	1505	1819	1549
174	1897	2243	1960	1606
262	1588	1745	1728	1679
Sixth crop (rice following 2 seasons of beans)				
Control	1571	—	—	—
87	1764	1825	1961	1790
174	2142	2000	2161	1861
262	2013	1954	1767	1787

1. Source: Fagaria et al. (1991).

2. APPA = Partially acidulated Arafertil PR; PPPA = Same for Patos PR.

In high fixing soils it is often more effective to provide readily soluble P and place it near the seed in order to reduce the P-soil contact (Yost et al 1979). Intermediate solutions have been suggested through partial acidulation of PR or mixtures of PR and soluble P to satisfy the immediate plant needs and provide a long term source of P and Ca (Hellums et al. 1989) with substantial residual value (Chien et al. 1987). Both of these options proved effective in the Brazilian experiment reported in Table 5. A series of on-farm experiments on soils in India varying from slightly to strongly acid showed applications of Mussoorie phosphate rock (MPR) or mixtures with (1:2) of single super phosphate (SSP) and MPR, on average, to have benefit/cost ratios 3–4 times those for SSP (2.3) alone (Krishnappa et al. 1991). The responsiveness to MPR increased with organic matter content and soil acidity (Figure 10).

In contrast to nitrogen, there are no “free” sources of P to remedy the low P status of soils. If low P availability is primarily related to low native P levels in soil, P additions are unavoidable if soil productivity is to be restored. Whether this P originates from neighboring pastures and is added as manure, or from subsoil P reserves pumped to the surface through a fallow vegetation or from chemical fertilizers is the farmers option. In general he will be basing his choice, on land and resource availability considerations. In high fixing soils a number of alternatives are being studied. One of these options is to look for crops or crop varieties that have a greater tolerance for low soil P. Many plant species have developed mechanisms to help overcome the P constraint by reducing the distance to the P source through increased root growth, improved acid tolerance or with the help of mycorrhiza (VAM) hyphae (Gianinazzi-Pearson 1986). In addition, P stress conditions may induce an increased exudation of P solving acids or chelates (Nye and Kirk 1987). Plant adaptation to stress is the subject of another chapter in this book.

A large research effort has been made in studying the possibilities of exploiting the vascular arbuscular mycorrhiza (VAM) symbiosis to increase the availability of P and has led to high expectations from this fungus. However, VAM symbiosis has been reported to be beneficial to plants in one year, and parasitic the next, when competition for assimilates comes into play. The energy required to build and maintain a VAM infected root system needs to be offset by the improved nutrient uptake of the plant. This condition may apply to marginal soils or soils amended with slowly soluble nutrient sources such as phosphate rock, provided effective VAM species are present. Due to the omnipresence of VAM in cultivated soil and the problems associated with inoculum production, the scope for use of VAM as a management tool to enhance P availability in annual crops appears limited. May be the most promising approach is the selection or breeding of varieties that effectively engage in a symbiotic relationship with VAM (Manske and Vlek 1990).

Management options for P in stressed environments are thus relatively limited. In the strongly weathered Oxisols, the options range from the build up of soil organic matter (SOM) through conservative and cropping system measures, to the choice and placement of the P source with or without restrictive liming.

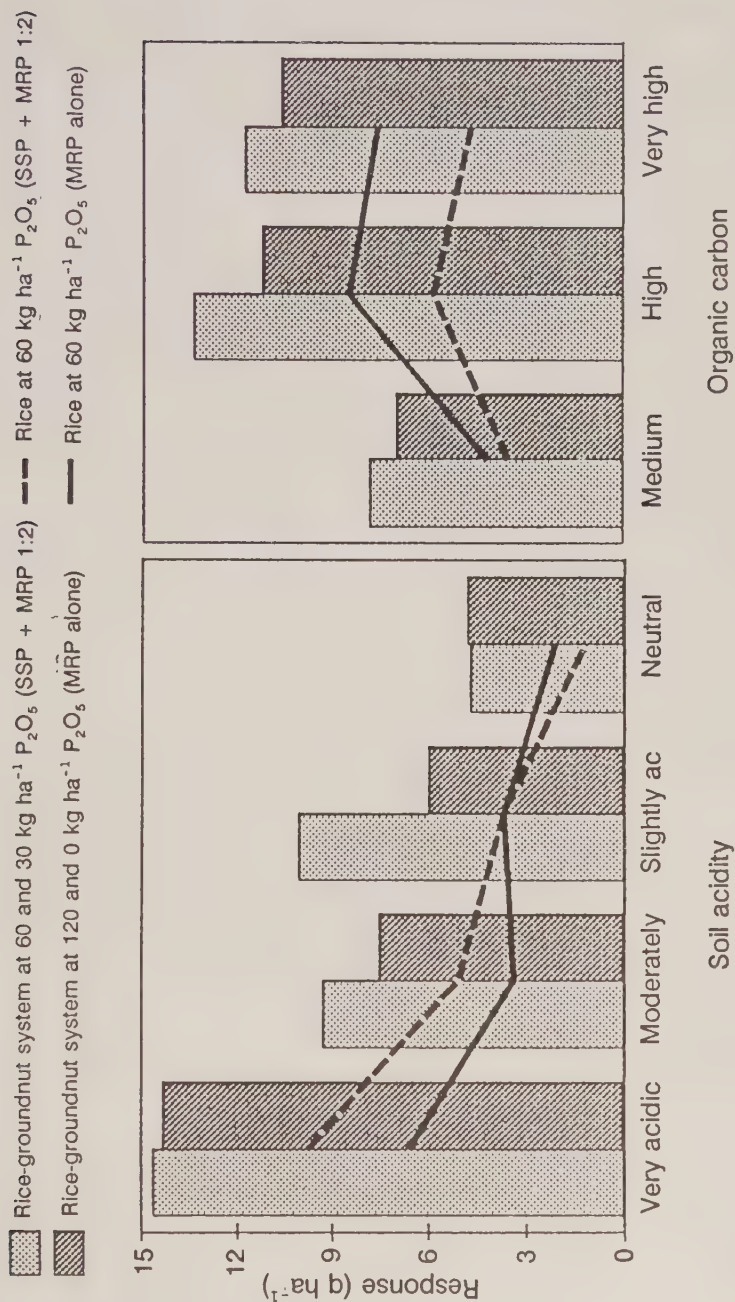


Figure 10. Response to sources of P at varying levels of soil acidity and of organic carbon. (Source: Krishnappa et al. 1991)

When larger investments are warranted, reclamation programs involving such measures as massive liming and deep ploughing might be considered.

Potassium

Of the three major nutrients, potassium deficiency in the tropics has received the least attention. Potassium deficiency is common in the tropics but is often masked by other nutrient deficiencies. As was the case with P, deficiency of K occurs due to inherently low K status of soils due to the absence or disappearance of K bearing minerals or as a result of K fixation by illitic clay minerals. A substantial amount of research was conducted on K fertilization in tropical soils, much of it supported by the trading companies or their international representatives such as IPI (International Potash Institute). Much of this work was reviewed by Munson (1982).

A large area of the tropics located in the perhumid zone comprises highly weathered soils and can be considered under excess water-stress. These soils are not only inherently poor in K, but many of these soils contain low-activity clays and have little or no ability to retain added K. The FAO estimates that fully 22% (see above) of the soils of the tropics are affected by excess water problems and, unless percolation is restricted through puddling, might pose a problem with respect to potassium management. In the Amazon basin alone, it is estimated that an excess of 240 million ha of land suffer from low K reserves (Sanchez 1983).

The common vegetation of the perhumid tropics, the primary forest or the mature fallow vegetation may accumulate substantial quantities of nutrients (Greenland and Okigbo 1983). Although the soils are inherently low in K, the amount of K cycling through the soil/vegetation system has accumulated over many years and little chance for losses exist, due to nutrient pumping by the roots. The large majority of soil K resides in the litter and soil organic matter of the top layer and may be equivalent to that in the standing vegetation (Nye and Greenland 1960). Upon clearcutting and burning, potassium, stored in the ashes is readily leached to lower layers. In the absence of a deep-rooting vegetation the K tends to leach beyond the rhizosphere of annual crops. In the perhumid Amazon region of Peru, Seubert (1975) found the K accumulated in the vegetation and stored in the top 50 cm of the soil following slash and burn clearing to have essentially disappeared due to leaching, after 6 months. According to Sanchez (1983), these K losses were reflected in K deficiency within 12 months.

Leaching losses of K under cultivated systems in the humid tropics have been scarcely measured. Lysimeter measurements under sugarcane fertilized at a rate of 250 kg K ha⁻¹ showed that losses could amount to 80% of the applied K (Table 6). Losses were higher in the first year than in the ratoon crop as the rooting system still had to be established. Leaching losses appear related to the leaching volume or rainfall (Ng and Deville 1984). A similar observation was reported by Sanchez (1976) based on the very limited data that was available at the time.

Table 6. Total K leached from soils in lysimeters planted with sugarcane in 1977 in Mauritius¹

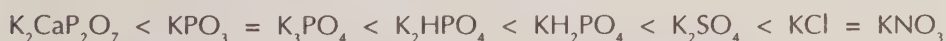
	Rainfall (mm)	Rock-free soil (kg ha ⁻¹)	Rocky soil (kg ha ⁻¹)
Belle Rive	3258	136	204
	2783	68	64
	4745	105	93
Reduit	1343	78	88
	1285	64	56
	2613	98	86

1. Source: Ng and Deville (1984).

A host of mixed cropping systems, incorporating deeper rooting tree crops or multipurpose trees have been developed to avoid these losses by root interception (Nair 1989). Many of these systems are successful in avoiding loss of K and are particularly suitable for the high-rainfall zones. Imbach et al. (1989) estimated nutrient balances in two agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and with poro (*Erythrina poeppigiana*) based on intensive measurements. They concluded that K leaching losses were negligible (1–1.5 kg ha⁻¹ per year) despite the abundant rainfall (2000 mm per year) and percolation of around 1000 mm per year. In comparing these values with other published data they conclude that these agroforestry systems behave like natural or artificial forests and protect better against leaching losses than annual crop systems.

Residue management in cropping systems plays a key role in the K balance of soils, as K contents in the residues generally far exceed those in the harvested products. Thus, restitution of straw may greatly improve the K balance in the system (Smaling 1992). Unfortunately, K leaching from mulch is rapid (70–80% within 2 weeks) and may be more efficient when applied repeatedly during the growing season (Schroth et al. 1992). Moreover, the selectivity of the adsorption sites of SOM is low and building up SOM levels does little to improve the K retention of the soil to prevent leaching.

The alternative to conservation of K is to fertilize regularly with one of the commercial sources of K, e.g., muriate of potash (KCl). Most commercial K sources are, however, highly soluble and easily subject to leaching. Munson (1982) lists the following order of susceptibility to Leaching:



The application rate in these soils can not be based on the concept of supplementation and maintenance fertilization promoted by the French (Chaminade 1973), but rather on strict elimination of the deficiency taking into account the efficiency of K uptake, given the anticipated losses. The efficiency can be substantially improved if multiple applications are practiced. Care should further be taken that no nutrient imbalances are induced on the soils with low exchange capacities.

One way to avoid both imbalances and leaching losses is through the use of slow release K sources. Some research was done on the use of K bearing minerals such as biotite, feldspars, mica, sepiolite or that are occasionally available on a regional basis. Ground biotite and biotite fused with phosphate rock gave agronomic efficiencies of around 20% as compared to KCl (Salcedo et al. 1982). A low solubility product called Kalsilita generated by thermal treatment of potassium-aluminium silicate (19% K) was less susceptible to leaching, yet agronomically as efficient as KCl or K_2SO_4 . More recently, Weerasuriya et al. (1993) did some preliminary testing of acidulated pegmatitic mica from Sri Lanka (5, 65% K) and found it potentially promising for high-leaching soils. These low grade products may have an important role to play as low cost inputs in stressed environments, particularly when their effects can be sustained over a number of seasons. The economics of the various alternatives, the recurrent application of commercial grade K or the use of lower grade slow-release alternatives has yet to be established. Given the fact that most other mobile nutrients are similarly subject to leaching, the use of "stones for bread" with the rock material serving as a source of Ca, Mg, as well as minor nutrients (Chesworth et al. 1983) deserves greater attention.

Conclusions

The foregoing presentation has dealt with nutrient management strategies, and in this context has elaborated in an exemplary manner on some of the principles that guide the decision making process. To us, the nutrient management strategy options for stressed environments can be separated into two extremes: (1) the case of the marginal environment with a lacking infrastructure and limited market opportunities. Nutrient management becomes a matter of avoiding or resisting excessive pressure on the land and utilizing conservation measures in order to at least maintain the soil resources available. Organic matter restitution, soil conservation, biological fixation and nutrient pumping are some of the principles that should be emphasized. They find their application in shifting cultivation and agroforestry systems. When these areas are put under pressure as a result of increasing population, the options are limited and catastrophes near at hand. Some regions in western Africa bear witness to our inability to cope with this situation; (2) the case of the stressed environment that has come under intensive pressure but is strategically located. The pressures may have caused good land to deteriorate (salinization) or the region may have come nearer urban centers through infrastructural development and may be essential to its support (Cerrado). In these cases, investments in the land may pay off handsomely, and the strategic options may involve reclamation measures such as the construction of drainage system, liming programs, terracing and fertilizer use. Whereas such measures may lead to durable improvements when applied to productive and resilient environments, they may yield only temporary improvements rather than sustainable production in stressed environments.

The arguments presented here were meant to show that an intermediate approach, referred to as integrated soil fertility management is an essential

component of a sustainable farming system when stress is a constant menace. It exchanges some of the capital investments against investments in time and or land which reduces risks. Production may decline somewhat when part of the land is set aside for fallow, but the conservation of soil productivity will more than compensate for this loss in greater yield stability and sustainability. Sustainable agriculture in stressed environments of the tropics and subtropics will require an integrated approach to nutrient management. Numerous examples exist to show that modern agricultural approaches based on fertilizers alone will eventually break down. However, for sustained and improved productivity, fertilizers will need to play a role in many stressed environments.

Agronomic research on crop configurations and cropping systems in maintaining or enhancing nutrient reserves in the soil is complex in nature and has led to relatively few, new technologies. This type of information is essential in order to tailor integrated nutrient management systems that can maximize economic returns while being environmentally sustainable. Numerous research efforts are underway, but site specificity is hindering rapid progress in this respect. A good example provides the alley-cropping research instigated by IITA in Nigeria with reportedly excellent results. Kerkhof (1990) after visiting 21 agroforestry projects in 11 sub-Saharan African countries concluded that on-station work was impressive but that farmers preferred more dispersed forms of intercropping. When transferred to the more acid soils of Latin America, alley-cropping results were disappointing (Sanchez 1983). The focus of future research endeavors in stressed environments should be based on ISFM with judicious fertilizer use within nutrient and soil conserving cropping systems.

Farmers cite various reasons for non-adoption of fertilizers such as risk, lack of credit, and untimely supply (Vlek 1990). These problems are particularly relevant in stressed environments and need the attention of governments. Most fertilizer management problems in stressed environments have been adequately addressed on a technological level. They are not restricted to the three examples discussed in this chapter. We might have included the problem of P or Zn fertilization on sodic and calcareous soils, Mo and S fertilization on sandy acid soils grown to legumes and improved pastures. The prescriptions are often site specific and require a research network in the tropics that can effectively define the nutrient needs of well-defined stressed ecosystems.

When market conditions preclude the use of fertilizers as an input, the emphasis should be placed on preventing further decline in soil productivity. Continued research investments should be directed towards low potential and stressed environments in order to arrest soil degradation and promote efficient types of extensive farming while simultaneously improving access to inputs and markets through improved infrastructure. Government policies should aim at protection of these lands and alleviate pressures by linking these zones with more resilient regions where opportunities for (off-farm) employment exist. Ignoring the problem may be costly, as history provides ample evidence that many flourishing civilizations have experienced a sudden decline when their agricultural base disappeared due to overexploitation and degradation of their land (Dale and Carter 1955).

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Organic Matter Management in Relation to Crop Production in Stressed Rainfed Systems

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Abstract

Maintaining an optimum amount of organic matter in soils is essential to sustain reasonable productivity. Soil organic matter appears to be a function largely of climate and soil management. The amount of organic matter is low in soils receiving annual precipitation less than 500 mm. Entisols and Aridisols have less soil organic matter than Vertisols and Alfisols.

Application of farmyard manure builds up soil organic matter (SOM). Cultivation of grain crops decreases SOM and fallowing in cultivated soils reduces it further. Burning crop residues often decreases the quantity and quality of soil organic matter.

Most benefits from soil organic matter are due to the ceaseless decomposition of plant and animal residues. However, the amount of nitrogen likely to mineralize and become available to crops during the year is sufficient for only low levels of crop production. Hence, it is necessary to periodically add substantial amounts of fresh plant residues and stimulate nitrogen fixation activity.

Experiments indicate that response to application of farmyard manure differs with crops and soils. In India, biogas slurry promises to progressively become a very significant source of fresh organic matter to soils. Crop responses to organic residues are small. The strawy residues can be more beneficial when applied with farmyard manure, biogas slurry or some nitrogen. Appropriate mix of farming practices to improve and maintain soil organic matter can be identified with the help of simulation models.

Introduction

Maintaining organic matter in soils at an optimal level is essential to sustain reasonable productivity of all stressed ecosystems. Organic matter improves water-holding capacity of light-textured soils and enhances the supply of nutrients particularly nitrogen, phosphorus and sulfur and at the same time makes them less susceptible to leaching. Organic matter makes heavy soils more friable, easier to work with, more porous, permits better aeration, and also reduces crusting, thus facilitating better plant stand. It absorbs calcium, magnesium and potassium on its colloidal surfaces and then gradually releases them through cation

exchange. The iron-organic complexes, such as iron-humate, make the iron more available. Adequate amounts of available boron usually exist in soils with high organic matter content, because organic matter protects the boron against leaching. Hence, it is desirable to maintain maximum amounts of organic matter in cultivated soils.

Organic Matter in Soils

Soil organic matter appears to be a function largely of climate and soil management. Hans Jenny showed that an inverse relationship exists between mean annual temperature and the amount of organic matter in regions of comparable rainfall. Besides climate, the type of vegetation, the nature of soils and the kind of soil fauna and flora may determine the kind and amount of organic matter. A significant decline in the amount and quality of soil organic matter occurs when virgin soils are first cultivated. In cultivated soils, the nature of crops—annual or perennial, row crops or meadows—influence the amount at which the organic matter will stabilize. When manure, fertilizers and necessary amendments are applied to soils, and an efficient plant cover is maintained, the decline in organic matter is minimized. A review of organic matter in benchmark soils of India indicates differences among soils and climates. These are summarized in Table 1—A,B,C.

Table 1 shows that where soils are subject to drought stress as in Rajasthan, India the amount of soil organic matter is the least (with a low of 0.33% in the surface soil). The organic matter content is more in soils of northern Karnataka and Andhra Pradesh (with a high of 1.37%). Amongst different soil orders Entisols and Aridisols have least amount of soil organic matter (with a low of 0.24%) and Vertisols closely followed by Alfisols, the most (with a high of 1.12%). Typic Pellusterts, Paralithic Vertic Ustropepts, and Lithic Vertic Ustochrepts among Vertisols and Typic Paleustalfs and Udic Rhodustalfs among Alfisols have more organic matter than others. The amount of organic matter is low (0.59%) in soils receiving annual precipitation less than 500 mm, and high (1.12%) in soils receiving annual precipitation between 500 and 1000 mm. Owing to small variations in temperature, this factor appears to be of little significance in organic matter differences in these soils. Variation in soil properties and vegetation, perhaps accounts for differences in organic matter content between soils otherwise similar in location and classification.

Cultural Practices and Soil Organic Matter Changes

Singh et al. (1980) observed that at Central Arid Zone Research Institute, Jodhpur application of farmyard manure (FYM) in amounts of 20 t ha⁻¹ every alternate year since 1975, led to a considerable (60%) buildup of soil organic matter over a period of 5 years. The effect of organic amendments on soil physical properties was particularly noticeable when the amendments were incorporated in the subsurface (20–25 cm depth).

Dormaer and Pittman (1980) have shown from long-term rotation plots at Lethbridge (Alberta) that organic matter decreased from 5% to 3.4% under

Table 1. Organic matter in the soils of different states, soil and climatic groups of India¹**(A. States)**

State	Soil series	Annual rainfall (mm)	Organic matter (%) in the indicated layer	
			Surface	Subsurface
1. Bihar	Pusaro	1090	0.45	0.40
2. Rajasthan	Thar, Chirai, Chomu, Pali	100–700	0.17–0.64	0.21–0.64
3. Gujarat	Adesar	350	1.38	0.69
4. Madhya Pradesh	Singapura, Sarol Marha, Chougel, Kamliakheri	900–1400	0.58–1.55	0.36–1.44
5. Maharashtra	Jambha, Linga Barsi	740–1125	0.79–0.91	0.79–0.89
6. Andhra Pradesh	Kadirabad, Kasireddipalli, Patancheru, Chinnaloni	730–760	1.22–1.57	0.93–1.55
7. Karnataka	Vijayapura, Tyamgondalu, Channasanodra, Hangund, Kagalgomb, Raichur, Jamkhandi, Achmatti	575–1000	0.76–2.15	0.72–2.08
8. Tamil Nadu	Coimbatore, Palathurai	570	0.60–1.14	0.69–1.27

(B. Soils)

Soils	Soil series	Annual rainfall (mm)	Organic matter (%) in the indicated layer	
			Surface	Subsurface
1. Entisols	Thar, Chomu	100–700	0.17–0.31	0.12–0.21
2. Aridisols	Chirai, Pali, Adesar	250–400	0.19–0.64	0.15–0.69
3. Vertisols	Sarol, Jambha, Marha, Linga, Barsi, Hangund, Kagalgomb, Kadirabad, Singapura,	660–1300	0.59–2.15	0.36–2.08

contd.

Table 1. contd.

Soils	Soil series	Annual rainfall (mm)	Organic matter (%) in the indicated layer	
			Surface	Subsurface
4. Alfisols	Coimbatore Kamliakheri, Chinnaloni, Kasireddipalli, Raichur, Achmatti	570–1400	0.45–1.77	0.40–2.01
	Pusaro, Vijayapura, Tyamagondalu, Channa sandra, Palathurai, Chougel Patancheru, Jamkhandi			

(C. Climate)

Climate Annual rainfall (mm)	Mean Annual Temperature (°C)	Soil Series	Organic matter (%) in the indicated layer	
			Surface	Subsurface
1. < 500 (100–400)	25.9–26.7	Thar, Chirai, Pali, Adesar	0.17–1.38	0.21–0.69
2. 500–1000 (570–1000)	23.6–27.9	Coimbatore, Palathurai, Jamkhandi, Hangund, Achamatti, Chomu, Kadirabad, Chinnaloni, Barsi, Raichur, Kagalgomb, Kasireddipalli, Patancheru, Tyamgondalu, Channasandra, Singapura, Vijayapura, Jambha	0.31–2.15	0.12–2.01
3. > 1000 (1050–1400)	24.4–27.2	Sarol, Kamliakheri, Pusaro, Linga, Marha, Chougel	0.45–1.55	0.40–1.44

1. Source: Murthy et al. 1982.

continuous wheat and 2.4% under a wheat-fallow system. Ancillary data show that fallowing in rotations deteriorated soil structure rapidly but continuous cropping and inclusion of legumes in rotation improved it. Other studies (Douglas et al. 1980) indicate that cultural practices like tillage and mixing of organic material in the soil speeded up decomposition.

To facilitate seed-bed preparation and seeding, some farmers continually burn off excess straw. The practice is nourished by the belief that extra nitrogen would be needed by soil microorganisms to decompose the straw (Spratt and Piloski 1977). Dormaar et al. (1979) found that burning crop residues generally reduced organic carbon, polysaccharides and water stable aggregates all of which are associated with soil productivity and erodability. Rasmussen et al. (1980) noted that although burning of straw did not accelerate carbon loss per se from the soil, it did significantly affect physical properties, such as soil color, aggregate stability and water infiltration rate, indirectly related to the organic matter balance in the soil.

Soil Organic Matter and Its Decomposition

Soil organic matter, perhaps, contains most of the naturally occurring organic compounds. In addition to the organic constituents present in undecayed plant and animal tissues, soil organic matter contains living and dead microbial cells, microbially synthesized compounds and an array of derivations of these materials. However, soil organic matter needs to be chemically characterized for understanding its role in soil productivity. The major constituents of organic matter are polysaccharides, lignins and proteins. Polysaccharides are natural carbohydrates such as cellulose, the hemicelluloses, starch and pectic substances. Lignins are complex, highly resistant materials, which occur in the woody tissues of plants. Proteins, the principal nitrogen-containing constituents, are formed by linkages of many amino acids, and most living matter consists of proteins.

Most of the benefits which accrue to soils from organic matter are due to the ceaseless decomposition of plant and animal residues, into simple inorganic compounds such as carbon dioxide, water, nitrate, phosphate, and sulfate. The polysaccharides, which constitute the bulk of mature plant tissues, are decomposed by several species of soil microbes. The products are carbon dioxide and water, and new cells of molds, actinomycetes, and bacteria. The result is that soil organic matter contains very little polysaccharide of plant origin, though it does contain some polysaccharide of microbial origin. Lignins being far more resistant to microbial attack than polysaccharides, accumulate as the decomposition proceeds but do not remain unaltered. When some of the side chains are split off and methoxyl groups are cleaved, the number of acidic groupings such as carboxyl, increase. These changes modify the properties of lignin; which can now retain more nutrient elements. Plant proteins contain the nitrogen essential for building microbial cells. Thus, nitrogen accumulates in soil organic matter not because plant protein is resistant to microbial attack but because nitrogen is an important constituent of microbial cells, and is used and reused as old cells die and new ones are formed. Organic nitrogen in soils appears gradually in soluble inorganic

forms because clay minerals exert a protective action on protein molecules, trapping them within the lattice of the clay crystal and also because of the formation of organic complexes resulting from reactions between proteins and lignin.

Estimated Release of N from Organic Matter

More decomposition occurs usually in soils high in organic matter than those that have low organic matter. Greenland (1986) has suggested that the amount of nitrogen released to a crop from soil organic matter can be calculated from the following equation:

$$y = A \times XYZ$$

Where y = amount of N released in inorganic form

$A = 4 \times 10^6$ kg (the weight of top soil per 10 cm hectare)

X = Fraction of soil present as organic matter

Y = Fraction of organic matter present as N

Z = Fraction of organic nitrogen mineralized per year

Assuming $Y = 5\%$ and $Z = 2\%$, the amount of N released in inorganic form per year in Indian soils is

$$4 \times 10^6 \times (0.24 \text{ to } 1.12\%) \times 0.05 \times 0.02 = 9.6 \text{ to } 44.8 \text{ kg N ha}^{-1}$$

Even if half of the N so mineralized is assimilated by a crop or sorghum or millet, this would be sufficient for the harvestation of less than a ton of grain per hectare.

Need for Addition of Fresh Plant Residues/Organic Matter and Its Benefits

The microbiological activity proceeds at a fast rate when fresh plant residues start decaying. As more material susceptible to decomposition is consumed, the microbial activity slows down. For this reason and also because the intrinsic supplies of soil organic matter are low in Indian soils, it becomes essential to add substantial amounts of fresh plant residues and stimulate nitrogen fixation activity if dependence on fertilizer use has to be minimized.

Farmyard Manure

Farmyard manure is a mixture of animal excreta and the soiled bedding of farm animals. Experiments carried out at various research stations of Coordinated Research Projects for Dryland Agriculture in India have shown that the response to application of farmyard manure differs with crops and soils. The material itself is so variable. Then, seasonal variations and differences in conditions of crop growth also influence the magnitude of response. Thus, at Kovilpatti (Tamil Nadu), pigeonpea benefited from application of farmyard manure, much more than sorghum. The increase in yield of pigeonpea with application of farmyard manure was 0.5 t ha^{-1} as against 0.36 t ha^{-1} with fertilizers. The figures for sorghum

were 0.14 t ha⁻¹ with farmyard manure and 0.38 t ha⁻¹ with fertilizers. Experiments conducted with pearl millet at Hisar (Haryana) and Jodhpur (Rajasthan) showed that at both places, application of nitrogen through inorganic fertilizers was much more beneficial to pearl millet than the application of farmyard manure to supply equivalent quantities of nitrogen, but the differences were more at Jodhpur than at Hisar. At both places, a positive interaction to the combined application of fertilizers and farmyard manure was noted.

Biogas slurry

Biogas slurry is the end product of biogas plants when organic material is converted into methane and carbondioxide. The biogas slurry is semi-liquid, with solids forming about 20–40% of the ordinary feedstock. The dry slurry powder is an excellent manure. The digested slurry contains about 1.5–2.0% N, 1% P₂O₅, and 1.0% K₂O, besides various micronutrients.

Kute (1992) described the results of field demonstrations conducted on various crops with biogas slurry by the Gujarat State Fertilizer Corporation. 17 field demonstrations with rainfed pearl millet using 5 t ha⁻¹ of dry biogas slurry gave an increase yield of 11–15%. At present, there are nearly 1.5 million family biogas plants in various parts of India, nearly 30% of which are in Maharashtra, 9% each in Tamilnadu and Gujarat, 7% in Andhra Pradesh and 5% in Karnataka. With a total potential of nearly 24 million biogas plants and plans of adding approximately 0.3 million plants each year, during the next 8 years up to 2000 AD, biogas slurry promises to progressively become a very significant source of fresh organic matter to soils.

Crop Residues, Green Manures and Green Leaf Manures

One of the suggestions, often made to maintain maximum amounts of organic matter in cultivated soils is to return all residues to the soils.

The effect of incorporation of farm residues, organic residues/wastes were studied in crop yields at several stations of CRIDA. At Akola (Maharashtra) and Kovilpatti (Tamil Nadu) incorporation of organic residues increased sorghum yield by 120 kg ha⁻¹ and 40 kg ha⁻¹ against 75 kg ha⁻¹ and 38 kg ha⁻¹ with fertilizers. Again at Akola, organic residues increased the yield of cotton by 30 kg ha⁻¹ against 15 kg ha⁻¹ with fertilizers. At Bhubaneswar (Orissa), blackgram, mung bean and cowpea legumes incorporated at flowering, increased the yield of finger millet from 0.87 t ha⁻¹ to 1.2 t ha⁻¹, 1.3 t ha⁻¹ and 1.4 t ha⁻¹, respectively. Similarly, at Bijapur, incorporation of 5 t ha⁻¹ of sunhemp or *Leucaena* increased the yield of sorghum to 1.6 t ha⁻¹, against 1.1 t ha⁻¹, 1.4 t ha⁻¹, 1.8 t ha⁻¹ and 1.9 t ha⁻¹ with sorghum stubbles, FYM (each 5 t ha⁻¹), 25 kg N + 12.5 kg P₂O₅ ha⁻¹ and 50 kg N + 25 kg P₂O₅ ha⁻¹, respectively. The results in Table 2 show that increase in wheat yield with green manuring ranged from 0.1 to 0.8 t ha⁻¹. Reddy et al. (1986) reported that in the USA, wheat production was significantly higher after the application of tropical legume green manures than after summer fallow. Mahler and Auld (1989) observed that incorporation of winter peas, green manure and residues after harvesting grains significantly increased

Table 2. Effect of green manuring on grain yield of wheat in India

Green manure crop	Age/Biomass	Wheat yield (t ha ⁻¹)		References
		-GM	+GM	
Sunhemp	56 days	1.6	2.1	Khan and Mathur (1957)
Sunhemp	49–56 days	2.0	2.3	Chandanani (1958)
Different green leaf manures	18.4 t ha ⁻¹ (fresh mass)	0.3	1.0	Singh and Sinha (1964)
Sunhemp/ Sesbania	5.6 t ha ⁻¹ (green matter) irrigated wheat (mean of 190 experiments)	1.1	1.3	Panse et al. (1965)
	Unirrigated wheat (mean of 46 experiments)	0.6	0.7	
Sunhemp/ Sesbania	—	0.5	0.6	Darra et al. (1968)
Sunhemp	19.3 t ha ⁻¹	1.6	2.1	Gupta and Gyan Prakash (1969)
Sunhemp	—	3.1	3.6	Kute and Mann (1969)
Sesbania/ clusterbean	—	1.3	1.6	Chela and Gill (1973)
Sunhemp	Unirrigated wheat (40 kg N + 17.5 kg P ha ⁻¹)	1.7	2.5	Verma et al. (1990)

wheat grain yield over spring barley treatment. The corresponding nitrogen fertilizer equivalents were 94 and 75 kg N ha⁻¹. Nitant (1990) noticed that *Leucaena* loppings applied as green leaf manure significantly increased the grain yield of wheat. Application of 50 kg N ha⁻¹ along with green leaf manure resulted in higher grain production than that obtained by the application of 150 kg N ha⁻¹.

That the value of farmyard manure has been known for a long time is axiomatic. However, the problem of organic matter management arises from its short supply. Supplementing it with crop residues, is both necessary and desirable. The residues of crops in the form of straw are rich in carbon and can be far more beneficial, when applied with farmyard manure or biogas slurry and in their absence with some fertilizer such as nitrogen and phosphorus. Estimation of appropriate mix of farming practices which can lead to improvement and maintenance of soil organic matter in different soils can be of immense help in

developing systems of sustainable agriculture. Choice of the ingredients of this mix should rest on their availability.

Paustian et al. (1992) used simulation model (CENTURY) of soil organic matter (SOM) dynamics to evaluate data from organic amended and nitrogen fertilized 30-year-old long-term plots. Large differences in total soil organic matter were elicited by the different treatments: after 30 years total C contents ranged from a low of 2.7 kg m⁻² in bare fallow to 4.8 kg m⁻² in the FYM and saw dust + N (SWN) treatments. Thus, changes in organic matter content ranged from a 30% decrease to a 30% increase from that present at the start of the experiment. The three treatments not receiving external organic matter inputs all showed net losses of SOM, while all treatments receiving external additions had increased. Differences in rates of SOM accumulation, among various amended treatments, were assigned to two factors, the quality of organic matter added and amount of N added in organic and inorganic forms. Both lignin content and N addition rate showed positive effect on organic matter accumulation and the relative influence of either factor was relatively constant across treatments. The ranking of treatments, in terms of organic matter accumulation were, in general, correctly predicted by the model. Hence, simulation models can be profitably used to develop appropriate mix of farming practices to ensure improvement and maintenance of soil organic matter.

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Water Conservation in Soils of the Semi-arid Tropics

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Abstract

Water conservation is important to agriculture in all environments, and relatively more so as climates become more arid. The renewed interest in rainfed agriculture as a solution to further food shortages has emphasized the need to maximize in situ water conservation. With this consideration our chapter will deal principally with the soil management aspect of water conservation on rainfed agricultural lands and specifically crop based systems.

Soil management for in situ water conservation aims to maximize the use of rainfall by increasing infiltration and storage, through protecting the soil surface with cover, increasing surface roughness to reduce runoff and increasing porosity for higher water intake. Practices which maximize soil organic matter tend to increase soil stability, while the utilization of the soil biological population to increase porosity is underdeveloped. We have chosen two regions to provide examples of management systems using these principles i.e., the Alfisols of the semi-arid tropics (SAT) of India and the northern cereal belt of Australia.

Our chapter identifies a number of biophysical variables important for water conservation. The use of simulation modelling to link these variables and predict the effect of changes has great potential. In addition, we identify biological practices including harnessing the soils biological population and straw management, and the utilization of indigenous knowledge as aspects requiring further study.

Introduction

Water conservation is vitally important to agriculture in all environments but relatively more so as climates become more arid. Implicit in a discussion of the term 'water conservation' are storage and efficiency factors. Water storage occurs in the soil and in natural or manmade surface structures. Efficiency relates to the effective utilization of a given quantity of water. A complete discussion of water conservation would therefore include coverage of water storage structures, in situ water management and water conservation at a plant cellular level, however this is beyond the scope of this chapter. Given the renewed interest in rainfed agriculture as a solution to further food shortages, we will deal principally with in situ water conservation on rainfed agricultural lands and specifically on crop based systems.

The basis for our discussion will be the water balance equation ($P = ES + T + R + D + \Delta SW$), where the abbreviations are precipitation (P), soil evaporation (ES), transpiration (T), runoff (R), drainage (D) and change in soil water storage (ΔSW). In situ water conservation aims to maximize transpiration and soil-water storage while minimizing soil evaporation, runoff and drainage. One qualification is that in some rainfed areas, small-scale irrigation depends on groundwater and hence drainage is acceptable to replenish the groundwater reservoir and some systems have been developed which utilize runoff collected in farm tanks. The interaction between the climate (particularly rainfall distribution, rainfall intensity and evaporative demand), soil properties (particularly infiltration rate determinants and soil storage), and plant properties (e.g., cover, phenology, root density) determine the amount and the effectiveness of in situ water conservation. We will consider soil management for maximum water intake ignoring the evapo-transpiration aspects.

Soil management for in situ water conservation aims to maximize the use of rainfall by increasing infiltration and storage. These objectives are achieved by protecting the soil surface with a cover and hence reducing the incidence of surface sealing and crusting, increasing surface roughness to reduce runoff and increasing porosity for higher water intake. The cover includes both contact cover in the form of crop residues and projected crop cover, that is speedy crop development or intercropping. Weeds are generally viewed as exploiters of water but could perhaps be managed so as to provide cover. Practices which maximize soil organic matter tend to increase soil stability, whereas, currently the utilization of the soil biological population for porosity development is underdeveloped. We have chosen two regions to provide examples of potential in situ water conservation management systems i.e., the Alfisols of the semi-arid tropics (SAT) of India and the northern cereal belt of Australia.

Alfisols in the Indian SAT

The SAT of India is characterized by variable rainfall and rainfed crops grown on the Alfisols in this zone often suffer drought stress. The cause is both low seasonal rainfall or within season dry periods and low soil water storage capacity of the Alfisols. Management practices to improve water conservation on cropping lands have been reviewed by El-Swaify et al. (1987). We will broadly categorize various alternatives as interbund management and bund management. Also indigenous practices and surface water storages will be briefly discussed.

Interbund Management

Many practices have been identified as having in situ water conservation benefits in Alfisols and these are either tillage or biologically based.

Tillage to increase surface roughness and porosity and to break surface crusts has been carried out traditionally either at the end of the summer crop season or/and after early rains prior to the cropping season, the perception being that subsoil and seedbed moisture will be improved for the subsequent crop. An animal drawn plow is the most commonly used tillage implement. Research to improve

the water conservation effectiveness of tillage has centered on the evaluation of various tillage depths and surface roughness practices.

Deep tillage has been shown to increase grain yields (Table 1) for a range of crops in normal rainfall years (Vittal et al. 1983). However, in above normal rainfall years (Table 1) only long season crops such as castor responded to deep tillage, while in subnormal rainfall years there was no crop response. Subsoiling to depths greater than 50 cm improved yields for up to 2 years in a project conducted between 1983 and 1986 (ICRISAT 1987). However, one difficulty with deep tillage and subsoiling is that the resource poor SAT farmer is unlikely to have easy access to machinery capable of performing this cultural operation.

Table 1. Effect of land management on runoff and crop yields in Alfisols at ICRISAT and CRIDA

Land management ¹	Runoff reduction (%)	Crop	Yield increase (%)
Deep tillage	46 NA ² 34 ²	Sorghum Sorghum Sorghum	31 10 28
Scoops (40 mm)	69	Sorghum	35
Tied ridges	39	Sorghum	NS
FYM (a) 15 t ha ⁻¹	51	Maize	56
Straw (a) mulch 5 t ha ⁻¹	76	Maize	53
Prior (b) perennial	79	Maize	36
Contour bunds (c)	37	Maize	NA
Graded bunds (c)	31	Maize	NA
Porous (d) barrier	66	Maize	NS
Sand (e) mulch (95%)	80	—	—

1. a = Effects after 4 years of continuous application, b = Effects are during the first year after removing a 4-year mixture of perennial pigeonpea, Cenchrus and Stylo, c = Average of 4 years, d = Porous barriers are 3 years old, e = Average of 2 years after bringing the sand content of the surface to 95%.
2. Data from CRIDA. Other data from ICRISAT.

Tillage results are presented as % increase over traditional practice. FYM, straw and prior perennial data are presented as % increase over an unamended control.

Shallow interrow cultivations to break the surface crust, during the crop, have also been shown to be effective in increasing infiltration and crop yields, and serve the dual role of weed control as well (ICRISAT 1984). In addition, contour farming and the use of dead furrows are effective water conservation practices (Singh and Rao 1988).

Surface roughness experiments on Alfisols, have been conducted under natural and simulated rainfall. A study (Pathak and Laryea 1992), on three levels of surface roughness, i.e., (1) scoops (or small depressions or cavities on the surface of the soil), (2) tied ridges, and (3) flat seed beds, indicated (Table 1) that, compared to flat seed beds, scoops reduced seasonal runoff by 69% and soil loss by 53% while the tied ridge system reduced runoff by 39% and soil loss by 28%. In a 40 mm storage capacity scoop, the increased infiltration as a result of reduction in runoff gave a significant increase ($P < 0.04$) in pearl millet grain yield (2.42 t ha^{-1}) over the flat seedbed (1.79 t ha^{-1}).

However, while tillage has been shown to have benefits in Alfisols, these have been reported to be short lived, both due to a decrease in porosity and due to a loss of surface roughness caused by raindrop impact. For example, Pathak and Laryea (1992) reported a reduction of more than 50% in scoop capacity over a cropping season. To maximize the in situ water conservation benefits of any form of tillage, therefore, it is necessary for speedy crop canopy development to occur so that the raindrop energy of future rainfall events will be dissipated and surface soil structure less damaged. However, if unfavorable soil surface conditions such as surface seals or crusts have developed, then infiltration (and water conservation) will be reduced regardless.

One practice found to reduce the incidence of crusting is sand mulching, which is used on some Alfisols in the Indian SAT. Significant increases in infiltration have been reported when the sand content of surface soil is more than 85% (Sachan et al. 1990).

Smith et al. (1992) note that while tillage has short-term benefits in improving soil water status and related processes, it may lead to long-term land degradation. They therefore suggested that biological methods of improving soil structure may be appropriate to improve among other things, in situ water conservation. These methods include reducing tillage and the retention or application of various organic amendments or inclusion of perennial legumes and/or grasses in a cropping rotation.

Crop residues are one such organic amendment that play a crucial role in ensuring that the disruptive force of raindrop impact does not destroy surface soil structure. This protection promotes infiltration and hence potentially increases water storage in the soil profile for crop uptake. A major parallel benefit is the reduction in runoff and soil and nutrient erosion. The benefits of residue retention for soil erosion control are well known in tropical and temperate agriculture (Unger et al. 1991), however benefits to crop yield are not always as clear. Some results in the SAT show large yield benefits with surface straw mulch. At ICRISAT Center, runoff was reduced by 76% by addition of 5 t ha^{-1} straw, and this corresponded to a 53% increase (Table 1) in maize yield (Cogle et

al. 1992). Numerous results also illustrate the reduction in runoff and increased infiltration that occurs with surface residue addition or retention (Yule et al. 1991).

In addition to straw retention, another common organic amendment is farmyard manure (FYM). FYM is often considered to supply nutrients, but it has also been shown to have beneficial effects in increasing infiltration (Yule et al. 1991), particularly after several years. These findings support Indian farmers' perceptions of the usefulness of FYM and its physical effect (Motavalli and Anders 1991).

A commonly held view is that crop and animal residue retention in the SAT is impractical due both to its value for other uses, such as fodder, fuel, and shelter. Unger et al. (1991) have listed possible alternative strategies to ensure the availability of straw for soil protection. Some of these could also apply to animal residue and include limited or selective residue removal, substitution of high value forages for residue, alley cropping, utilization of wastelands for forage and wood production, and the control of livestock numbers. We note that the use of farm residues as soil amendment will depend largely on its profitability and need for other uses.

To provide some idea of the value of straw in the farming system we studied returns from grain and fodder (straw) using data from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) economics group. They provided grain and fodder price data for hybrid sorghum which had a variable price ratio (grain/fodder) between 13.9 and 2.4 (with a mean value of 8.8) over the last 16 years. Using these figures we calculated the total yield increase (grain plus fodder) required for total returns to permit the retention of 3 t ha⁻¹ of straw, without loss of income (Table 2). The necessary yield increases were 17%, 25%, and 60% for price ratios of 13.9, 8.8, and 2.4. These yield increases can be achieved from the water conservation practices that we have discussed previously,

Table 2. Returns from grain and fodder combined for three¹ ratios of grain and fodder prices for rainy season sorghum

Yield Increase	Yield (t ha ⁻¹)		Total returns (Rupees)		
	Grain	Fodder	Ratio = 13.9	Ratio = 8.8	Ratio = 2.4
Base	1.0	3.0	1399	1180	2980
17%	1.17	3.51	1637	— ²	— ²
25%	1.25	3.75	— ²	1475	— ²
60%	1.6	4.8	— ²	— ²	4768

1. The ratios represent grain/fodder prices in different years. These are from 1984 (13.9), 1990 (2.4) and a mean of 16 years (8.8). The base unit in the example is 1 t ha⁻¹ grain and 3 t ha⁻¹ straw. The value of the base unit of straw (3 t ha⁻¹) in 1984, 1990 and the mean was Rupees 249, 1650 and 300 i.e., when the ratio was 13.9, the total return is Rs.1399 (Rs.1150 + Rs.249) for the base unit; if a yield increase of 17% occurred, the total return would be 1637 (or 1399 + 249).
2. These numbers are not presented.

and an added advantage is that the land resource will be protected for the future. However, this is a superficial treatment of a complex economic and cultural situation and there is no doubt that further study is necessary. One possibility would be to use calibrated crop models, which are responsive to water conservation practices, to provide probabilities of the amounts of grain and fodder produced in a region. Outputs could be linked with price information to provide a comprehensive risk assessment of the financial value of water conservation practices utilizing straw.

Pasture leys have been successfully used in the Mediterranean and temperate climates in southern Australia to provide nitrogen, and structural and disease break advantages to succeeding cereal crops. Similarly in the SAT of northern Australia attempts have been made to introduce the concept using tropical legumes (Jones et al. 1991), but with little success on a large scale. Research in Australia has concentrated on crop production and nitrogen aspects of the system. Recently, research to identify the structural benefits, as compared to the nitrogen benefits, was commenced at the ICRISAT Center (Smith et al. 1992). The initial results from this project show advantages in runoff and erosion control and subsequent crop yield in cereals following pastures—maize yield being increased by 36%, and runoff being reduced by 79%.

Soil management which includes reducing tillage and organic matter retention or addition, and pasture rotations, generally also favor soil fauna and flora. The beneficial effects of such managements have often been associated with changes in soil biology, but most of this work has been conducted in temperate climates. In the tropics and particularly in the semi-arid tropics, there has been little research about the effect of management on soil populations and of soil populations on production and stability. More research on these factors in the agriculture of the SAT is warranted. Similarly methodologies need to be developed which allow quantification of the impact of soil biology on productivity.

Bunding

Bunding has been a widely recommended soil conservation measure on Alfisols in India (Bali 1980). Bunds mainly serve as a precaution against high intensity storms, to reduce overland flow velocities and act as a means of safe disposal of excess water. Bunds are built across the slope and are either contour or graded types. Contour bunds act as a barrier to overland flow of water and ponding of water sometimes occurs behind the bund. Productivity gains result when ponding is limited and also occurs if appropriate crops are sown in the ponded area, e.g., upland rice. However, yield reductions have also been reported (Huibers 1985) and as a solution, Pathak et al. (1989) suggested a modification of the conventional contour bund to include gated outlets. These allowed control of water levels behind the bunds and resulted in yield increases over the conventional field bunds. The modification could be regarded as an extension of existing farmer practice of placing rocks at the bund overflow point, however the modification also allows greater control since water is released or retained as required.

In addition to physically constructed bunds, porous bunds have also been shown to be effective in both soil and water conservation. Porous barriers include grass barriers and stone bunds. Rao et al. (1992) studied porous barriers and found that grass barriers were more effective than stone barriers in runoff and erosion control. Vetiver grass, lemon grass and stone barriers reduced runoff by 43%, 20% and 10% respectively over that of a nonbundled control. Vegetative species, which have economic value through dry matter harvesting, may have a greater chance of acceptance. More work looking at the range of porous barrier possibilities in different environments is warranted. Other grass species include buffel grass, napier grass, bana grass, guatemala grass and makarikari grass. In addition, various agroforestry species such as *Leucaena* and *Gliricidia* may have a role in bund building.

Indigenous Water Conservation Practices

Studies of indigenous soil and water conservation practices question the role of conventionally advocated systems (Kerr and Sanghi 1992). These authors emphasize the importance of boundary bunds as a central part of the farm system in India and recommend that research and development programs should better integrate indigenous knowledge so that more effective and appropriate soil and water conservation practices are recommended to land-users.

Their survey listed farmer practices, many of which are similar to those found by researchers to be water conserving, but which are adapted to each site rather than following a countrywide standard. Broadly they also found that tillage (e.g., shallow interculture) was regarded as an important water conservation measure in red soils, as was short-term fallowing and stone mulching. That no biological interbund management practices were identified is worrying but it also provides us with the challenge to link in situ water conserving practices which we believe to have long-term land resource protection attributes with indigenous practices.

Tanks, Wells and Farm Ponds

Tanks and open wells are traditional sources for small-scale irrigation in India. Little work has been carried out to increase the efficiency of existing tanks and/or to increase the groundwater recharge to increase the yield from wells. In areas where the mean annual rainfall is more than 750 mm, runoff can be 20–30% of annual rainfall. A potential exists for collecting and storing this rainfall in farm ponds for irrigating crops (El-Swaify et al. 1987). Studies of this type have used harvested water to provide life saving irrigation during periods of stress or to grow high value crops such as vegetables in small areas near the pond or for rice gardens. The main problems noticed are the high costs involved in the provision of water storage and irrigation systems, evaporation and seepage losses and the uncertainty about the availability of water during periods of stress.

North Australian Cereal Belt

As a contrast to the Indian SAT Alfisols we have chosen to briefly discuss Vertisols of the northern cereal belt of Australia. In this region, water storage has historically

occurred over a preceding fallow period and within a crop season, rainfall was required for topping up of the profile at crucial times e.g., sowing, anthesis. The system required soils which can store relatively large quantities of water, for example, Vertisols, and good management during the fallow was crucial for success. Practices have since evolved from fallow storage over the summer for winter cereals, to the retention of crop residues and reduced tillage for water conservation for both winter and summer crops. Benefits to yield have been shown with this system and farmer acceptance has generally been high. However, in this region there is less requirement for fodder, hence it was relatively easier for the residue retention practices to be accepted. Tillage practices to promote surface roughness such as pitting (equivalent to scoops in the above mentioned Alfisol example) also are undertaken but these practices do not show advantages over straw management practices.

Simulation Modelling

The chapter has discussed soil management practices to increase in situ water conservation. However, a continuing problem for field researchers is how to extrapolate conclusions from data collected over short experimental periods, e.g., one or two seasons, or from specific locations, to information useful for understanding the long-term impact of both new and old practices. This problem is greater in environments with high coefficients of climatic variability, such as the SAT. Simulation modelling provides a tool for understanding the relationships between various factors and can be used for extrapolation. We earlier, provided one potential example for understanding the straw management story.

Using the simulation model 'PERFECT' (Littleboy et al. 1989), which was developed to simulate the dynamics of plant-soil-water management, three soil managements in two regions was compared. One region was relatively drier than the other and it was shown that in this region there was a smaller impact of soil management on yield. A further but preliminary example of PERFECT output shows reduced runoff and increased drainage following farmyard manure application for July planted sorghum in Hyderabad, India (Figure 1). The responses are attributed to increased stability of the surface soil, and can be considered to have both advantages (reduced runoff leads to less erosion, increased drainage can increase groundwater levels) and disadvantages (reduced runoff decreases potential tank water supply and drainage can cause leaching of nutrients from the root zone.)

Conclusion

To be successful, management systems must conserve and efficiently utilize water, however there are many other components of farming systems that determine the ultimate success of the system. These include markets, labor type, and culture. In many regions the perception and the preparedness to act against soil erosion is also associated with the degree of acceptance of water conservation practices. All these factors must be taken into account in identifying optimum in situ water conservation practices.

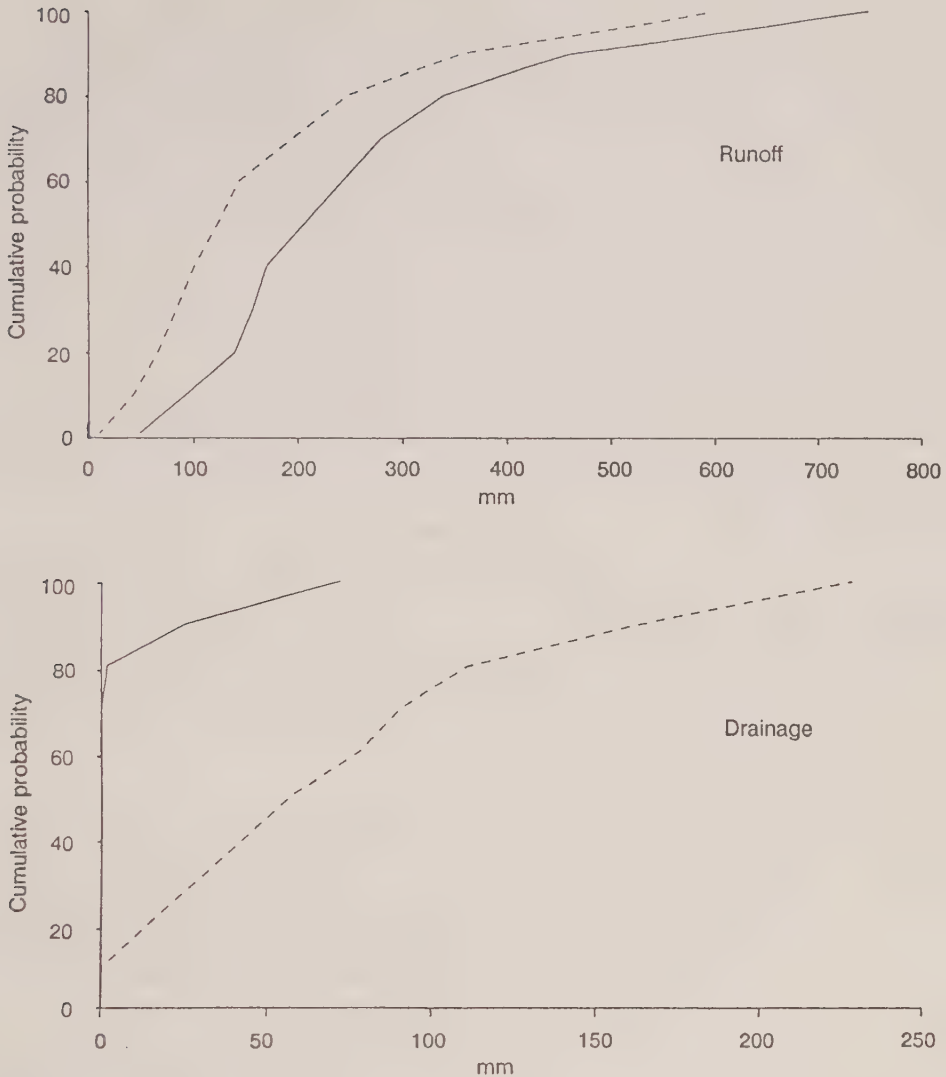


Figure 1: Cumulative probability for runoff and drainage from bare (—) and FYM (--) amended soils between 1901 and 1991 at Hyderabad, India using the simulation model PERFECT

Many biophysical variables are important for water conservation. These range from soil properties to climatic patterns. The use of simulation modeling to link these variables and predict the effect of changes has great potential. However, calibration of these models is imperative and requires the setting up of long-term experiments and the collection of the appropriate data. Much of this is yet to be done. In addition, we identified biological practices including harnessing the soils biological population and straw management, and the utilization of indigenous knowledge in developing acceptable water conservation practices, as aspects requiring further study.

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Optimizing Rainwater Use

B.A. Stewart, Zhu Zixi and O.R. Jones

Abstract

Irrigation played a particularly important role in the rapid increase in food production between 1950 and 1985. The world's irrigated land in 1950 totaled 94 million ha but increased to 140 million ha by 1960, to 198 million ha by 1970, and to 271 million ha by 1985. However, the current rate of expansion has slowed to less than 1% per year. The world population continues to increase and agricultural production by the year 2000 will have to be 50 to 60% greater than in 1980 to meet demands. This continued demand for food and fiber, coupled with the sharp decline in the growth rate of irrigation development, means that much of the additional agricultural production in future years must come from cultivated land that is not irrigated.

Agricultural production will be expanded in the arid and semi-arid regions because these regions make up vast areas in developing countries where populations are rapidly rising. Expansion of agriculture in these fragile regions presents a major challenge in crop resource management requiring efficient use of rainfall. Arid and semi-arid regions comprise almost 40% of the world's land area and are inhabited by some 700 million people. Approximately 60% of these drylands are in developing countries. Crop production is also hampered in many subhumid regions because of lack of sufficient water, particularly in years of below average precipitation.

For drylands, increased efficiencies are obtained using three technologies. The first kind of technology is to retain precipitation by minimizing runoff. This can be accomplished by using residue management with reduced or no-tillage systems to increase infiltration rates; by using tillage to control weeds and roughen the soil surface and destroy runoff-inducing soil crusts; and by use of specialized soil management practices such as furrow diking or land leveling to retain all precipitation on the land.

The second kind of technology, applicable to both irrigated and dryland areas, is to reduce evaporation in relation to transpiration. This can be accomplished by using more intensive cropping systems to eliminate or reduce the long fallow periods often associated with semi-arid agriculture; by adopting improved residue and tillage management practices to maintain mulches on the soil surface that will reduce evaporation and increase soil water storage; and by applying supplemental irrigation at critical plant growth stages using deficit irrigation principles. Use of supplemental irrigation (if available) allows for more intensive cropping, for use of longer season crops, and for increased residue production, thus providing for more efficient use of both precipitation and irrigation water.

The third kind of technology is to use drought resistant or tolerant crops that fit the rainfall pattern. Crop selection is aided by the use of crop calendars to match cropping patterns with the climate.

The optimum use of rainfall should not be restricted to dryland systems. Much of the land that is irrigated occurs in regions where there is substantial rainfall. In such areas, and particularly in those areas where irrigation water supplies are limited, the first priority should be placed on utilizing rainfall. Irrigation water should be considered the secondary source of water for crop production. Limited water supplies, including captured runoff water, can be used in three ways: (1) to supplement the rainfall during the normal crop growing season; (2) to lengthen the rainfall season so that longer season crops can be produced; and (3) to grow crops during dry seasons.

While the application of a single technology may not greatly improve production, the adoption of a combination of technologies along with use of adequate fertility programs and the use of crop cultivars with improved genetic potential will enable producers in semi-arid areas to make a highly significant contribution towards providing for future world food needs.

Introduction

Irrigation played a particularly important role in the rapid increase in food production between 1950 and 1985. While the world's irrigated land in 1950 totalled 94 million ha it increased to 140 million by 1960, to 198 million ha by 1970, and to 271 million ha by 1985. However, the current rate of expansion has slowed to less than 1% per year. The world population continues to increase and agricultural production by the year 2000 will have to be 50 to 60% greater than in 1980 to meet demands. This continued demand for food and fiber, coupled with the sharp decline in the growth rate of irrigation development, means that much of the additional agricultural production in future years must come from cultivated land that is not irrigated.

Agricultural production will be expanded in the arid and semi-arid regions because these regions make up vast areas in developing countries where populations are rapidly rising. Expansion of agriculture in these fragile regions presents a major challenge in crop resource management requiring efficient use of rainfall. Arid and semi-arid regions comprise almost 40% of the world's land area and are inhabited by some 700 million people. Approximately 60% of these drylands are in developing countries. Crop production is also hampered in many subhumid regions because of lack of sufficient water, particularly in years of below average precipitation.

Dryland farming systems lays emphasis on water conservation, sustainable crop yields, limited inputs for soil fertility, and wind and water erosion constraints. The three components of a successful dryland management system are: (1) retaining the precipitation on the land, (2) reducing evaporation, and (3) utilizing drought tolerant crops that fit the rainfall pattern. The use of these principles is required to optimally utilize the rainfall.

The optimal use of rainfall should not be restricted to dryland systems. Much of the land that is irrigated occurs in regions where there is substantial rainfall. In such areas, and particularly in those areas where irrigation water supplies

are limited, the first priority should be placed on utilizing rainfall. Irrigation water should be considered the secondary source of water for crop production.

New technologies are developing that improve the utilization of rainfall in both dryland and irrigated regions. Some of these technologies will be presented and the principles on which they are based will be discussed.

Example Locations

Figure 1 illustrates the precipitation and potential evapotranspiration values for three locations that will be used as examples. The United Nations Conference on Desertification (UNESCO 1977) defined bioclimatic zones based on climatic aridity index: P/ETP , where P = precipitation and ETP = potential evapotranspiration calculated by the method of Penman (Doorenbos and Pruitt 1977). When the aridity index is > 0.20 and < 0.50 , the region is considered as semi-arid. The locations illustrated in Figure 1 vary from Bushland, TX, which has aridity index of 0.25 and is very near the dry end of the semi-arid classification, to Gongxian, People's Republic of China with an index of 0.57, which slightly exceeds the semi-arid classification limit of 0.50 making it a subhumid location. Hyderabad, India, with an index of 0.38, represents a climate somewhat intermediate to the other two locations. It is noteworthy that there is not a single month of the year where the average monthly precipitation at Bushland, TX exceeds even 50% of the average potential evapotranspiration. At Hyderabad, India, average precipitation exceeds or equals average potential evapotranspiration for about 3 months during the monsoon and the precipitation at Gongxian, People's Republic of China, is roughly equal to the average potential evapotranspiration for about four months. Also, the total potential evapotranspiration at Gongxian, People's Republic of China is significantly less than at the other locations. All three locations are water deficient for crop production and optimizing the use of the precipitation is critical. However, different strategies and technologies are required for the locations. A brief summary of some proven production systems for the various locations are presented and discussed.

Hyderabad, India

El-Swaify et al. (1985) reported that the traditional rainy season fallow system on Vertisols utilized only 39% of the rainfall for evapotranspiration during the cropping season. About 28% of the precipitation was lost as runoff, 24% evaporated from the bare fallow, and 9% was lost by percolation. On Alfisols, the traditional system is to grow crops during the rainy season. For this system, they reported that 41% of the rainfall was used for evapotranspiration, 26% was lost as runoff, and 33% percolated below the root zone.

Two major cropping systems were developed by ICRISAT for Vertisols. One was a sequential system of maize followed by chickpea. The second, and preferred system, was intercropping of maize or sorghum with pigeonpea. These systems significantly extended the growing season and utilized much more of the rainfall for evapotranspiration. Pathak et al. (1985) showed that runoff loss from land

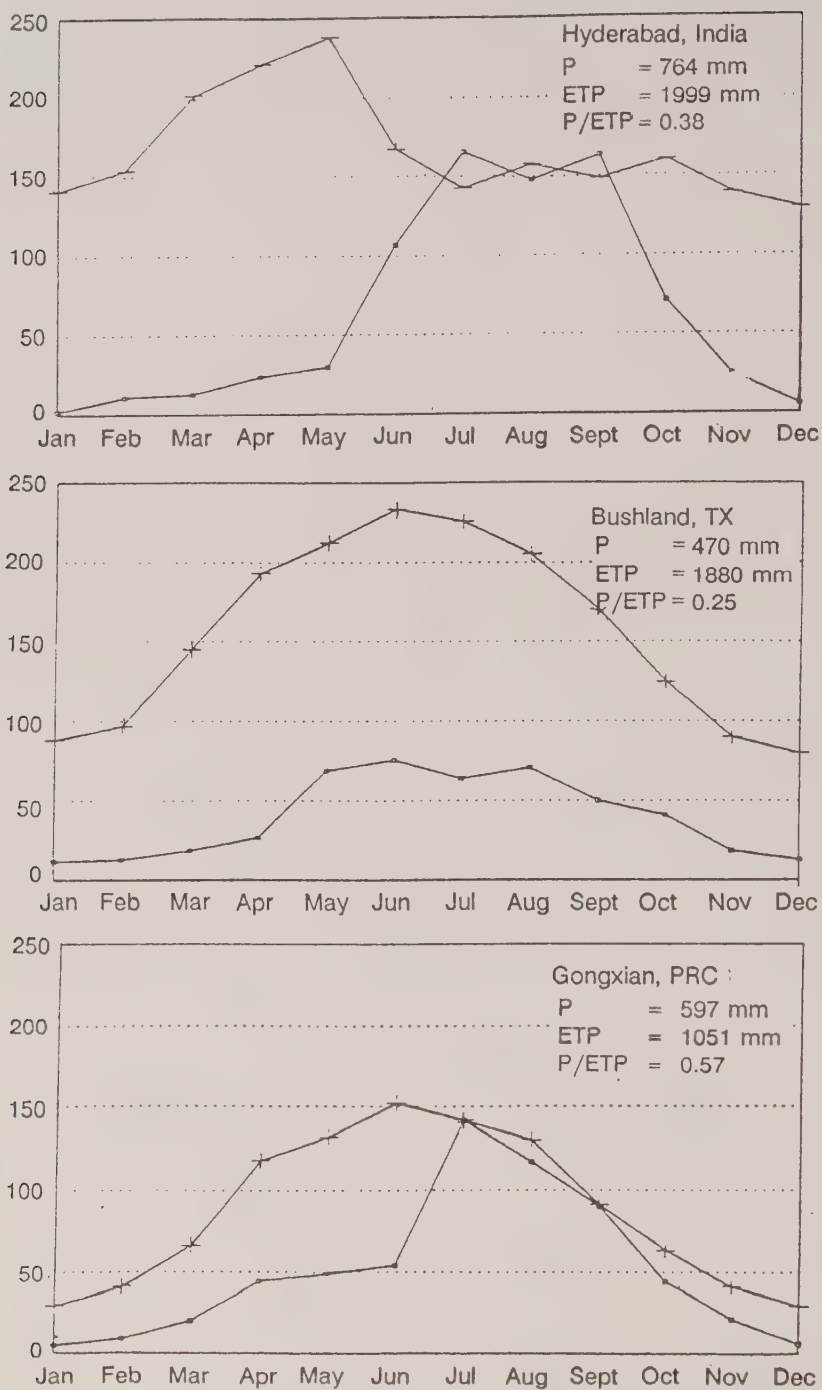


Figure 1. Precipitation and potential evapotranspiration amounts for three representative dryland regions

in the improved systems was only 91 mm as compared to 220 mm from land cropped traditionally.

Bushland, Texas

Retaining Precipitation on the Land

The first priority for utilizing precipitation is to prevent or greatly minimize runoff. Runoff from cropland in the US Southern High Plains can be quite high due to high intensity convective thunderstorms and is highly variable both geographically and seasonally. Other factors, such as topography, soil type, and soil surface conditions are also important. Runoff from cropland on Pullman clay loam (fine, mixed, thermic, Torrertic Paleustoll) at Bushland, where the average precipitation is 470 mm, has averaged about 40 mm annually (Jones et al. 1985). However, runoff occurred in only about one-half of the 26 years studied, so the amount was very significant in some years. Furrow diking, conservation bench terraces, and land leveling have proved very effective. These practices not only result in additional water for crop production but provide an effective means for controlling water erosion. Jones et al. (1985) describe these systems in more detail and summarize the results.

Maintaining all or most of the crop residue on the soil surface has also been shown to significantly increase infiltration at Bushland, thereby reducing runoff (Unger 1978). The residues also suppressed evaporation, thus providing more water for the subsequent crop. Precipitation during the 11-month fallow period averaged 318 mm, and only 72 mm was stored when there was no mulch on the surface. With 2, 4, 8, and 12 Mg ha⁻¹ mulch, water storage increased to 100, 116, 139, and 147 mm, respectively. Cornish and Pratley (1991), working on clay soils in Australia, also found that plant residues on the soil surface caused a major reduction in runoff, principally by protecting soil surfaces that were prone to crusting from raindrop action. Fallow efficiencies in Queensland were increased from about 21% to 29%, almost entirely because of reduced runoff.

Reducing Evaporation

Evaporation from the soil surface during periods when a crop is not growing results in a major loss of water in water-deficient areas. This is illustrated in Table 1, which summarizes long-term data at Bushland. The amount of precipitation lost during the rotation as evaporation during the nongrowing (fallow) season ranges from 36% for the continuous wheat system to 61% for the wheat-fallow system. In the wheat-fallow system, where the fallow period is 15 to 16 months, only about 15% of the precipitation that occurs during the fallow period is stored in soil for later use by a growing crop. Even under the continuous wheat system, where the fallow period is only three to four months, the fallow efficiency is less than 20%. However, in spite of the very low efficiency of water storage during fallow periods, the wheat fallow system is practiced widely because of the importance of sustaining crop yields under dry farming conditions. As illustrated in Figure 1, there is no period during the year when average

Table 1. Water balance for various cropping systems at Bushland, Texas¹

Continuous wheat (one crop annually) ²					
	Wheat	Fallow	Total		
	----- mm -----				
Precipitation	256	202	458		
Evapotranspiration	293		293		
Soil water change	-37	37			
Evaporation (and runoff)		165	165		
Two crops in three years ³					
	Wheat	Fallow	Sorghum	Fallow	Total
	----- mm -----				
Precipitation	256	462	241	416	1375
Evapotranspiration	329		286		615
Runoff	13	25	27	43	108
Soil water change	-86	86	-72	72	
Evaporation		351		301	652
One crop in two years ⁴					
	Wheat	Fallow	Total		
	----- mm -----				
Precipitation	256	660	916		
Evapotranspiration	354		354		
Soil water change	-98	98			
Evaporation (and runoff)		562	562		

1. Source: O.R. Jones (personal communication); Johnson and Davis (1972).

2. Fallow period between crops is three to four months. Runoff was not measured but would be minimal under annual cropping.

3. Fallow periods between crops are about 11 months.

4. Fallow period between crops is 15 to 16 months. Runoff was not measured but was a minor portion of the total.

precipitation is as much as 50% of the potential evapotranspiration. Therefore, without a substantial amount of stored soil water present at seeding, to supplement the growing season precipitation, the chance of a crop failure increases sharply. The annual precipitation in the area ranges from a low of about 50% of average to a high of about 200% of average, and crop yields range from 0 to about

three times the average. Again, referring to the data in Table 1, soil water storage during a four-month fallow is only 37 mm, compared to a 80 mm for an 11-month fallow and almost 100 mm for a 15-month fallow. This additional stored water leads to a significant increase in crop yield. Stewart and Steiner (1990) summarized long-term grain sorghum studies at Bushland and found that there is a threshold of about 110 mm seasonal evapotranspiration required before any grain is produced, and for every mm additional evapotranspiration, 15.5 kg ha⁻¹ of grain is produced. This fact, coupled with the water use data for sorghum shown in Table 1 suggests that grain sorghum yield would be 1.35 Mg ha⁻¹ if only seasonal precipitation was available for evapotranspiration. The 72 mm use of stored soil water would increase the yield by 1.12 Mg ha⁻¹. Therefore, any practice that increases the amount of water stored in the soil at crop seeding time can result in significantly higher yields and improved water use efficiency.

The use of mulches to conserve water and to reduce soil erosion is an age-old practice. The "Dust Bowl" of the 1930s in the US Great Plains led to the development of stubble mulching in the region. Stubble mulching uses V-shaped sweeps or blades that are pulled flat to about 10 cm beneath the soil surface. This under-cutting operation severs plant roots and kills weeds, but does not invert the soil. Therefore, most of the crop residue is left on the surface where it can serve as a mulch to control wind and water erosion, reduce runoff and slow evaporation losses. Only about 15% of the residue is buried by a sweep tillage operation, so that a substantial residue remains on the surface, even after three to four operations which is normally required between the time a crop is harvested and a subsequent crop is seeded. The rodweeder, consisting of a square rod about 2.5 cm thick that turns about 5 to 10 cm beneath the surface as it is pulled, is another tool that is sometimes used to kill weeds without intensively tilling the soil. A rodweeder operation can sometimes bury less than 10% of the residue present on the soil surface. In recent years, to maintain most or all residues on the surface, herbicides have been used to replace tillage partially (reduced tillage) or to completely replace tillage (no-tillage).

Although stubble mulching was developed to address the wind erosion problem, it soon became evident that mulches had beneficial effects on soil water storage. The increase in soil water storage is generally attributed to increased infiltration and reduced evaporation. The data presented in Table 1 and the above discussion illustrate the combined effect of these processes on soil water storage. The degree to which each of these factors contribute varies with specific conditions. It is clear, however, that water storage efficiency values increased sharply with increasing mulch levels.

The most practical way to create a residue mulch is to reduce tillage. Greb et al. (1979) summarized more than 60 years of progress in wheat production in fallow systems in the Central US Great Plains. In the early years, moldboard plowing and harrowing were common practices and only 19% of the precipitation occurring during the 16-month fallow period was stored. Over the years, as the number of tillage operations was decreased, and the intensity of tillage decreased due to the use of stubble mulch plows and some chemicals, storage efficiency

increased to 33%. In recent years, minimum and no-tillage practices have resulted in storing 40% of the precipitation and there has been a marked increase in wheat yields. These positive effects tend to accumulate because higher yields result in more residue and increased residue results in more water storage, which translates into higher yields, creating an upward spiral. Soil physical properties are also improved.

Reduced tillage is also important, particularly in semi-arid regions, as a means of maintaining organic matter. Cultivation increases biological activities in the soil. Cultivation also exposes fresh topsoil to rapid drying and, after each drying, a burst of biological activity occurs for a few days following rewetting. This is because the drying process releases organic compounds, probably from the breakdown of soil aggregates that are bound together by humic materials. Considerable organic nitrogen is mineralized as ammonia and later oxidized in large part to nitrates. Other nutrients are also made available from the decomposition of organic matter. This is particularly true for phosphorus since much of the phosphorus in soils is present in organic forms. The nutrients released as a result of tillage are readily available to growing plants and increased yields are generally obtained. Tillage also increases the infiltration rate of most soils and this reduces runoff and often increases storage of water in the soil profile so it can be used later for plant growth. However, unless the organic matter supply is replenished, the system is not sustainable. This is the situation for many soils of the world in arid and semi-arid regions, and increased attention to the problem is critical. The moldboard plow, and many other intensive tillage implements, were developed in Europe where soil organic matter content of soils is high, and the organic matter level can be maintained at a high level because of favorable precipitation that produces large amounts of biomass and cool temperatures that slow the rate of decomposition. In arid and semi-arid regions, high temperatures accelerate the rate of decomposition and the lack of precipitation severely limits biomass production so organic matter loss can be rapid and severe soil degradation occurs.

Crop Calendars

Traditional cropping patterns have evolved, in part, to match the growing patterns of common crops to average climatic patterns. However, many other factors besides climatic limitations to growth have determined the evolution of commonly used crop calendars, such as labor limitation, conflicting demands for inputs, unavailability of desirable crops or genotypes, lack of markets, and others. If these constraints can be alleviated, then crop calendars can be designed to more efficiently exploit the climatic potential. Objectives of designing an efficient crop calendar might include shifting cropping seasons to cooler, more humid periods of the year to improve the transpiration efficiency, sowing at those times which will avoid probable stress periods during anthesis of the crop, or by manipulating the ratio of early-season to late-season water use.

A simple approach to matching a cropping pattern with the climate is shown for grain sorghum at Bushland in Figure 2. The solid line represents the 10-day precipitation amounts exceeded in 50% of the years, and the dashed line

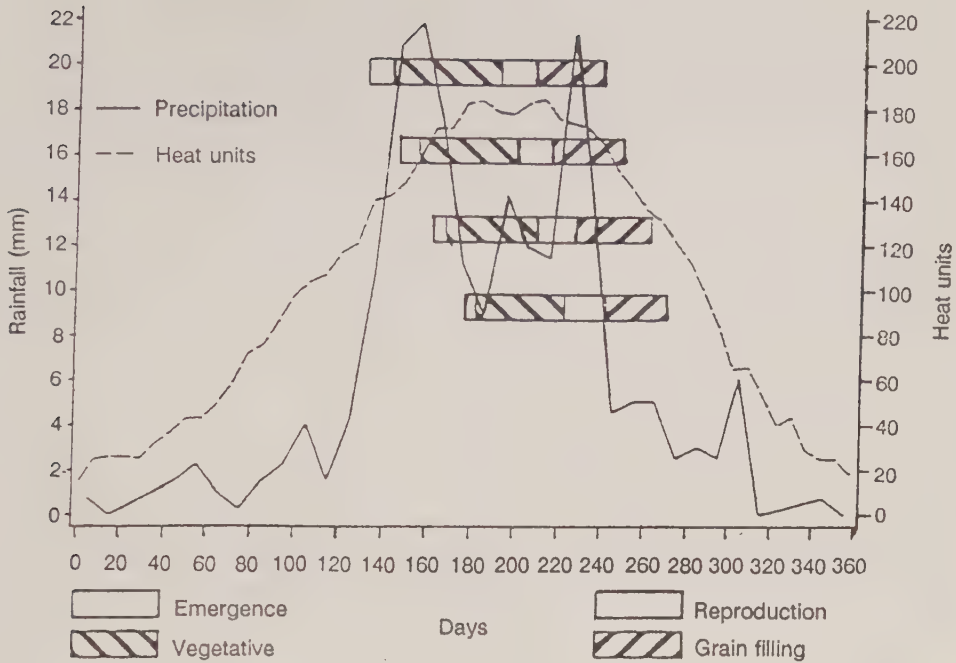


Figure 2. Weekly heat units (above 0°C) exceeded in 50% of the years and 10-day precipitation amounts exceeded in 50% of the years at Bushland, Texas. The boxes represent grain sorghum seeded at four different dates. (Stewart and Steiner, 1990)

represents the number of weekly heat units (degrees C above 0) exceeded in 50% of the years. Constraints for grain sorghum growth include the cool spring and fall temperatures, late spring frosts, early fall frosts, low springtime rainfall, and high temperatures in mid-summer. Climatic characteristics that favor grain sorghum growth are reasonably reliable rains in late May and mid-August. The rectangular boxes represent a crop of grain sorghum planted at four different times. The four divisions within each period represent the emergence, vegetative, reproductive, and grain-filling stages of grain sorghum production.

As indicated in Figure 2, grain sorghum can be seeded in the Bushland area over a fairly wide time period. The data clearly show that growing season rainfall decreases with time after May 24 (day 144). However, there is also a decrease in the seasonal potential evapotranspiration. Field studies at Bushland suggest that the most favorable time to seed grain sorghum is about June 10. Stewart and Steiner (1990) used the SORKAM crop model and also concluded that this was the most optimum seeding date for grain sorghum. There are two apparent reasons why the increase in growing season rainfall with early seeding did not result in higher yields. The first was that the growing season potential evapotranspiration was higher for early seeded grain sorghum. A second reason was that the model simulations showed significant differences in the ratios of transpiration to evapotranspiration for the various seeding dates and soil water

levels at time of seeding. This indicates that a considerably higher percentage of the total evapotranspiration was lost as evaporation for the earlier than for the later seeded grain sorghum. The model also compared two levels of plant available soil water and indicated that there was a higher loss from evaporation when grain sorghum was seeded into a soil with an intermediate soil water storage level than when seeded into a soil with a high soil water storage level. This suggests that plant canopies formed quicker when they were planted later in the season, particularly when seeded into a soil containing a high level of stored soil water. Referring again to Figure 2, it is evident that plant available soil water, particularly in the surface few centimeters, is likely to be high for grain sorghum seeded on June 10 because of the high probability of rainfall in late May and early June.

Gongxian, People's Republic of China

The most efficient use of precipitation occurs when there is a crop growing at all times during the time that precipitation occurs. This is usually not feasible for grain crops except in areas where the precipitation occurs only during a short period of the year. There are areas, however, where multiple cropping can be used to take advantage of precipitation throughout the year. Double cropping is common in some humid regions, and also in areas where irrigation is practiced.

Double cropping of wheat and corn is successful in parts of the People's Republic of China even in regions where the annual precipitation is less than 600 mm. Data from Gongxian are presented in Table 2. Wheat is grown from October to early June, and corn from mid-June to mid-September. Referring to Figure 1, the success of this cropping system depends on proper timing, in taking advantage of the two seasons—a humid season and a semi-arid season. The wheat is harvested only a few days prior to the start of the dominant rainy season. Corn is seeded directly in the standing wheat residue as soon as it is feasible, after the wheat is harvested. At this time, the stored soil water has been depleted by the wheat crop and germination and emergence of the corn does not occur until the rain dominant rainy season begins. During the high rainfall period of July and early August, the emerging corn crop does not use large amounts of water so the soil profile is largely replenished with water. There is also substantial rainfall during the remainder of the corn growing season so the soil water storage at the end of the corn growing season remains high (Table 2). Following the harvest of the corn crop in mid-September, the soil is tilled and manure and other fertilizers are obtained in preparation for seeding wheat. The wheat is grown during the drier part of the year when the average precipitation is substantially less than one-half of the average potential evapotranspiration. Therefore, the wheat crop depends on soil water accumulated during the corn growing season for about one-half of the total amount of water used for evapotranspiration (Table 2), and water stress is common during the latter stages of the wheat growing season.

As already stated, the success of the double-cropping system is largely dependent on timing. Runoff must also be prevented and in the case of the

Table 2. Relationship between yields and evapotranspiration amounts for a double-cropping system in Gongxian, Peoples Republic of China¹

Year (d/mo/yr)	Available water at sowing (mm 1.3 m ⁻¹)	Available water at harvest (mm 1.3 m ⁻¹)	Water consumption (mm)	Rainfall (mm)	Yield (Mg ha ⁻¹)
Wheat					
16/10/83 to 31/5/84	253	18	369	134	6.27
7/10/84 to 30/5/85	262	67	399	204	5.82
11/10/85 to 1/6/86	260	86	381	207	5.01
8/10/86 to 1/6/87	86	11	285	210	4.25
18/10/87 to 1/6/88	222	13	329	120	4.69
Average	217	39	353	175	5.21
Corn					
7/6 to 8/9/84	18	229	271	482	5.13
6/6 to 4/9/85	64	177	290	403	6.36
2/6 to 10/9/86	86	80	175	169	0.64
5/6 to 15/9/98	95	178	305	389	7.09
12/6 to 12/9/88	40	244	275	479	6.30
Average	61	182	263	384	5.10

1. Unpublished data, Zhu Zixi, Institute of Meteorology, Meteorological Bureau of Henan, Zhengzhou, Henan Province, Peoples Republic of China.

study presented in Table 2, this was done by having the land level with the berms around the area. The corn was a short-season cultivar, requiring only about 95 days from the time of seeding to maturity.

The average precipitation values for the 5 years of study was found to be closely parallel to the average values for 27 years of precipitation data at the location. Based on the 27 years of data, average rainfall from October 1 to May 31 is 201 mm, with more than 150 mm occurring in 75% of the years. Precipitation for June 1 to September 30 averaged 399 mm, with a probability of receiving more that 319 mm in 75% of the years. Therefore, the average yields for wheat and corn presented in Table 2 appear representative of what can be expected over a long period. Using the 75% precipitation probability value (319 mm during the corn growing season) as a guideline it could be surmised that adequate water would be available for producing a good corn crop and still partially recharging the soil profile for the subsequent wheat crop. The probability of having poor corn yields such as in 1986 is low because that was the second driest summer recorded in 27 years. Extremely dry summers,

however, affect the subsequent wheat crop as well as the summer corn crop. This is clearly illustrated by the very low amount of plant available soil water stored at the time of wheat seeding in 1986 (Table 1). The 4.25 Mg ha⁻¹ wheat yield that resulted was the lowest of the study, even though the 210 mm precipitation that occurred during the wheat growing season was higher than normal. The probability of producing an average or higher wheat yield will decrease significantly for those years when the available soil water at seeding is below 200 mm in the 1.3 m soil profile.

Supplemental Irrigation

Supplemental irrigation is the use of additional water to stabilize and improve crop yields in areas where crops can be grown by natural rainfall. It contrasts with irrigation which supplies the entire water needs where rainfall is insufficient for plant growth during all, or most, of the growing season. In many semi-arid areas and subhumid regions, supplemental irrigation can alleviate risk, increase and stabilize yields, and make possible the use of inputs such as high yielding cultivars and fertilizers.

Limited water supplies, such as captured runoff water, can be used in three ways: (1) to supplement the rainfall during the normal crop growing season; (2) to lengthen the rainfall season so that longer season crops can be produced; and (3) to grow crops during dry seasons.

Summary

Agricultural production in semi-arid regions will play a major role in providing increased food production to meet world food needs in the face of rapidly increasing population. Technologies are available or are being developed that provide, greatly increased, food and fiber production efficiencies, of both precipitation and irrigation water.

For drylands, increased efficiencies are obtained using three technologies. The first technology is to retain precipitation by minimizing runoff. This can be accomplished by using residue management with reduced or no-tillage systems to increase infiltration rates; by using tillage to control weeds and roughen the soil surface and destroy runoff-inducing soil crusts; and by use of specialized soil management practices such as furrow diking or land leveling to retain all precipitation on the land.

The second technology, applicable to both irrigated and dryland areas, is to reduce evaporation in relation to transpiration. This can be accomplished by using more intensive cropping systems to eliminate or reduce the long fallow periods often associated with semi-arid agriculture; by adopting improved residue and tillage management practices to maintain mulches on the soil surface that will reduce evaporation and increase soil water storage; and by applying supplemental irrigation at critical plant growth stages using deficit irrigation principles. Use of supplemental irrigation (if available) allows for more intensive cropping, longer season crops, and increased residue production, thus providing for more efficient use of both precipitation and irrigation water.

The third technology is to use drought resistant or tolerant crops that fit the rainfall pattern. Crop selection is aided by the use of crop calendars to match cropping patterns with the climate.

While application of a single technology may not greatly improve production, adoption of a combination of the technologies along with use of adequate fertility programs and use of crop cultivars with improved genetic potential will enable producers in semi-arid areas to make a highly significant contribution towards providing for future world food needs.

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Soil Conservation

R. Lal

Abstract

Soil conservation implies judicious and discriminate use of soil and water resources for achieving economic and sustained productivity and high environmental quality. Both soil conservation and sustainability are qualitative and vaguely defined concepts and have subjective values. These concepts are not easily adopted because of difficulties in translating research data into readily usable technology, little if any short-term economic gains, the problem of perception and responsibility, and several socioeconomic and political factors. Furthermore, the on-site economic impact of erosion-induced loss in agronomic productivity is often masked by improved agricultural technology such as supplemental irrigation, chemical fertilizers and soil amendments, or new varieties. There are also several practical limitations of the proposed technology to be adopted by the resource-poor small land-holders.

Soil conservation is a moving target, objectives are never completely realized because achieving one leads to the need to fulfil another. Therefore, the need for conserving soil and water resources will always remain a challenge to agriculturists, ecologists, and environmentalists.

Soil conservation involves more than just erosion control, and embodies all aspects of "good farming." It is the use of poor farming practices over a long period of time that leads to accelerated soil erosion and sets in motion, various soil-degrading processes. The "Law of Marginality," that marginal soils managed with marginal techniques produce marginal yields and lead to marginal living, also applies to soil conservation. Nonetheless, judicious use of scientifically proven technologies can restore soil, substantially improve agronomic productivity even over a short period of time, and reverse the degradative trends.

For objectivity and professional credibility, there is a need for change in perception, strategy, and approach to research and development. It is important to improve the data quality and reliability through innovative approach, originality, and objectivity. The database on magnitude and severity of erosion can be improved by adopting new methods such as Cs¹³⁷ techniques, remote sensing, Geographical Information Systems (GIS), and concept based models. The effectiveness of soil conservation measures can also be assessed in terms of new concepts, such as soil quality, soil resilience, soil life, critical soil depth, and the partial area concept, for adapting remedial measures.

One of the basic research needs is to assess the on-site agronomic impact of accelerated erosion in terms of erosion-induced loss in productivity. The data on runoff, soil erosion, and nutrient loss must be translated into productivity decline through empirical and modeling approaches. There is also a need to quantify the off-site effects of accelerated erosion, and identify

important reasons for the lack of adoption of scientifically proved technologies. Why has there been no widespread adoption of mulch farming, no-tillage, ridge tillage and raised-bed systems, agroforestry and alley cropping techniques, and other promising measures by the farming community? Finally, the scientific community and policy makers should develop a strategy to involve farmers in the decision-making process and adapt indigenous conservation technologies to suit the need of improved farming and cropping systems.

Introduction

Accelerated soil erosion is a serious problem in ecologically sensitive regions, marginal soils, and stressed environments. Most semi-arid regions are severely prone to accelerated erosion, often more than humid regions (Hudson 1987). Soil erosion is a severe problem in the Mediterranean region, where about 40% of the total land area is affected in Morocco, 50% in Turkey, and 67% in Greece (Lowdermide 1975). Accelerated erosion by water and wind respectively is estimated to affect 46 and 38% of vegetated land in Africa, 58 and 30% in Asia, 81 and 16% in Oceania, 74 and 7% in Central America and Mexico, and 51 and 17% in South America (WRI 1993). The problem is extremely severe in India (Yadav 1986; Gurmeh Singh et al. 1992). Out of 328 million ha of land area in India, nearly 175 million are presumably affected by severe erosion. The problem of soil erosion and erosion-induced degradation is aggravating despite tremendous efforts by national and international organizations to curtail it (Chleq and Dupriez 1989). The problem is especially severe in arid and semi-arid regions of sub-Saharan Africa (Milner and Douglas 1989; Mainquet 1986).

Accelerated erosion and land degradation have severe impacts on crop yields and agronomic productivity (Lal 1987; Stocking and Peeke 1986). Past erosion has reportedly caused yield reductions of 10 to 20% in Africa (Dregne 1990; Lal 1991) and Asia (Dregne 1992). Soil erosion is believed to threaten world food production (Pimental et al. 1987) and the world economy (Brown and Wolf 1984). The Ethiopian famine has been largely attributed to accelerated soil erosion (Lamb and Milas 1983; Stahl 1990). It is truly a global problem of the modern times, but it has plagued mankind since the dawn of settled agriculture.

Soil conservation is a complex concept. It is a generic term encompassing a wide range of strategies to control erosion, reduce losses of water from the root zone, enhance soil fertility, and improve and sustain agronomic productivity (Figure 1). It is commonly used as a qualitative, subjective, and broad-based concept generally considered synonymous with "good farming" practices. Good farming practices of soil and water conservation are soil-, crop-, and farmer-specific, because there exists a wide range of conditions of terrain, landscape, soil, climate, sociocultural factors, land tenure systems, farming and cropping systems, etc. Inevitably, therefore, it is difficult to develop a general blueprint of universally applicable conservation-effective technologies.

Agricultural sustainability is also a qualitative and vaguely defined concept. To be meaningful, it should be assessed in terms of productivity per unit input

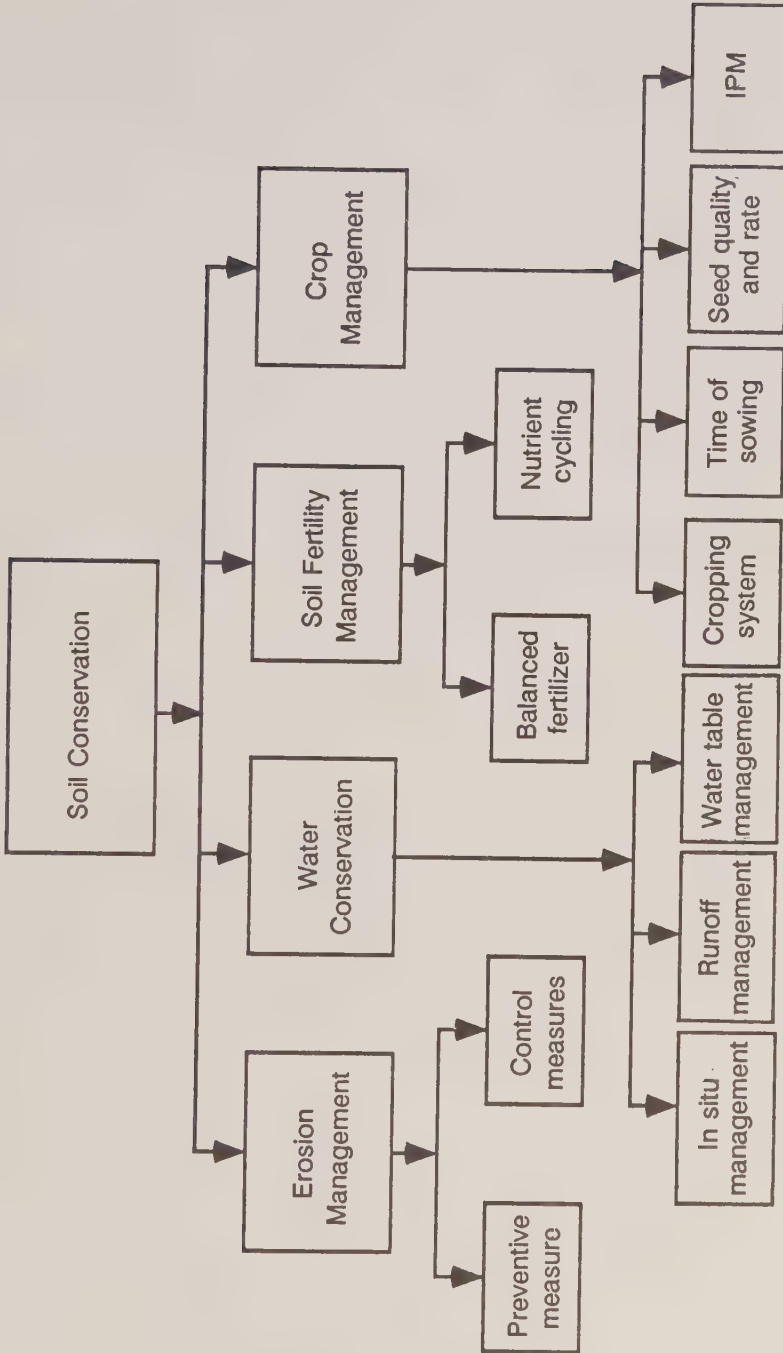


Figure 1. Strategies for soil conservation

of the most limiting or nonrenewable resource(s), such as land area, soil depth, soil organic matter content, energy input, time, and water reserves and quality. Furthermore, it is a dynamic function and changes with time. In the context of "stressed environments," agricultural sustainability refers to an increasing trend in per capita productivity.

For conservation-effective practices, there exists a positive correlation between soil conservation and agricultural sustainability. In fact, conservation effectiveness of different techniques should be assessed in terms of the degree of correlation among these variables. In this regard, analyses of data from relevant long-term experiments may provide some useful information.

Although the dangers of soil erosion and need for soil conservation are widely recognized, little progress has been made in controlling erosion by implementing research information. There exists an opportunity to reduce soil degradation by designing appropriate and economically viable techniques provided that we change our perception, strategies, and research and extension methods.

Perpetuating Crisis in Stressed Environments

The need for soil conservation has been widely recognized since at least the early 1930s. Tremendous progress has been made in: (1) understanding basic processes of soil erosion, (2) developing empirical and conceptual models to predict soil erosion hazards under specified ecological and management conditions, and (3) identifying and adapting cultural practices to integrate soil erosion. Despite these scientific advances, accelerated-soil erosion and erosion-related soil and environmental degradation remain serious economic and ecological problems of modern-day farming. Properly implemented, improved technology can reduce the magnitude and adverse impact of soil erosion. In the US, for example, vast areas of land that were once the "dust bowl" of the south central United States have been transformed into highly productive land by science-based agriculture. Sheet and rill erosion from cropland in the US declined by 11.6% between 1982 and 1987 (Lee 1990). The Conservation Reserve Program authorized in the Food Security Act of 1985 reduced soil erosion by about 0.5 billion Mg in its first five years from 1986 to 1991. The projected reduction for a 10-year period from 1986 to 1991 is estimated at 60% (Brown 1991). This dramatic reduction in soil erosion in the US is not only a major success story, but also an example of how improved technology can control erosion and restore productivity. To date, there are few success stories of soil conservation and land restoration in stressed environments of developing countries. The success rate of most conservation programs initiated in Africa during the 1960s and early 1970s was extremely low (Darkoh 1986). The problem of soil and environmental degradation is being aggravated and perpetuated. Hudson (1989) evaluated several soil conservation projects. He observed that the success rate was often as low as 25%.

One of the principal reasons of failure of conservation programs in developing countries is the lack of clear-cut responsibility. Whose responsibility is soil conservation? Yes, there are several institutions and organizations that have vested

interests and are understandably concerned. There is, however, an obvious conflict of interests. A farmer is interested in avoiding risks, a scientist in basic research, an institution in cost-effective projects, a policy maker in continuity and equity, a government in power and national economy, and an international donor in long-term planning. Regrettably, the land is left to fend for itself with its own "resilience" and built-in capacity to restore itself.

Technological Options and Their Limitations

The literature is replete with a wide range of technologies for erosion preventive and control measures (Table 1) (Roose 1986; Hudson 1987; Sheng 1989; Lal 1992). The scientific community has debated the pros and cons of agronomic techniques of soil and crop management vis-a-vis engineering devices of runoff control and slope modification. Most of these technologies have proven successful on research stations with promising results on soil conservation and increase in crop productivity. Some relevant examples of yield increase due to adoption of soil-conservation measures are outlined in Table 2.

Table 1. Soil conservation technologies

Traditional measures	Improved measures	
	Soil/crop management	Runoff/slope management
Raised beds: ridges, mounds	Tillage: contour plowing, mulch farming, conservation	Vegetative barriers: vetiver
Sunken beds: planting holes	tillage	Engineering devices: diversion channels
Terraces	Cropping systems: multiple cropping, agroforestry, strip cropping, cover crops	Terracing
Square basins		Water reservoirs
Stone lines		Silt traps
Bunds	Fertility management: balanced fertilizer, green manure, compost	
	Pest management: Insecticide, disease and weed control, IPM	
	Crop management: Time of sowing, seed quality and rate, improved variety	

Table 2. Examples of erosion control and productivity increase by conservation measures on research stations and pilot project

Country	Region	Erosion reduction	Crop	Yield reduction	Reference
Brazil	Northeast	drastic	fodder and grain crops	significant	Leprun et al. (1986)
Brazil	Pernambuco	92%	grain crops	—	Margolis et al. (1986)
Brazil	Quixadaceara	15.5 Mg	—	—	Silva and Paiva (1985)
India	Himalayan foothills	drastic reduction	fodder and grain crops	significant	Grewal et al. (1990)
India	Maharashtra	58%	Pearl millet (grain/fodder)	31/18%	Patil and Bangal (1989)
India	Punjab	—	Pearl millet fodder	60%	Hadda and Sur (1987; 1989)
Kenya	Machakos	—	Maize/bean grain yields	400/74 kg ha ⁻¹	Lundgren (1988)
Mexico	Jalisco	90%	grain crops	30%	Maas et al. (1988)
Niger	Sahel	significant	natural vegetation	regrowth	Chase and Boudouresque (1989)
Sudan	Sahel/ Savanna	—	grain crops	significant	Arya et al. (1988)
Tunisia	Siliada dam	—	wheat grain yield	700 kg ha ⁻¹	Mecherqui et al. (1989)

Toward an attempt to improve conservation effectiveness and adoption rate, it is important to recognize limitations or ecological limits of effectiveness of these technologies. There is no single technology or a set of technologies that can be used for diverse situations because there exists a wide range of ecological conditions with diverse soils, terrain, climates, farming systems, land tenure, and socioeconomic factors. For example, Arya et al. (1988) observed that ridge-furrow beds were ineffective on Vertisols in Sudan, whereas these techniques have been found useful in central India (El-Swaify et al. 1987). In northern Africa, Heusch (1986) observed that terraces were inadequate under the conditions of prolonged winter rainfall and predominantly clayey soils. For Oxisols with acidic and nonproductive subsoil in Sumatra, Indonesia, Siebert (1989) found that bench terraces reduced groundnut yield by 50% due to subsoil exposure at the terrace base and 13–32% in the adjacent areas. Contour bunds have been shown to cause yield reduction due to waterlogging on Vertisols in central India (Patnaik et al. 1987). Alley farming is not as effective in semi-arid conditions as it is in subhumid and humid environments.

In addition to biophysical constraints, application of these technologies should be reviewed in a politicoeconomic framework. Millington et al. (1989) suggested the following factors: (1) land considerations, such as land availability and tenure, and farm size, (2) capital and labor constraints, and (3) access to and functioning of institutions.

Hudson (1989) suggested that conservation technology should: (1) be appropriate and tested locally, (2) offer short-term, on-site benefits, and large obvious benefits of 50–100%, (3) require affordable inputs, especially labor, (4) not include forgone benefits, e.g., giving up land, (5) not include any increased risk, and (6) be in tune with existing social factors.

Effectiveness of soil conservation measures depend on the “Law of Marginality.” The law states that marginal soils cultivated with marginal inputs produce marginal yields and support marginal living. An important conservation strategy is to intensively cultivate prime agricultural land with science-based inputs, and relieve the pressure on marginal land and fragile ecosystems. Dependence on resource-based low-input and marginal technologies on marginal and fragile soils in ecologically sensitive ecoregions is an integral part of a vicious cycle that must be broken to free the victims of poverty, malnutrition, and soil degradation.

New Concepts in Soil Conservation

The concept of soil conservation should be quantitative, precise, and objective. It should be closely linked to agricultural productivity and sustainability. Consequently, there is an urgent need for change in perception, strategy, and methodologies.

Perception

Soil conservation. Being a complex concept, it cannot be measured as an entity. It comprises, however, a number of factors, each of which is measurable.

Quantitatively, soil conservation may be defined by an index (I_c) involving relevant factors outlined as follows:

$$I_c = \int_{t_i}^{t_f} \int_{r_i}^{r_f} (\theta_a + N_r) dr dt \quad (1)$$

Where I_c is an index of soil conservation, r is rooting depth, θ_a is available water-holding capacity, N_r is plant-available nutrient reserve, and t is time. Variables and N are functions of several other parameters, e.g., soil structure, pore size distribution, soil organic matter content, cation exchange capacity, parent material, and stage of weathering. There are also other factors that can be included in the equation. Because of different parameters involved, all factors need to be converted into dimensionless variables. To be relevant, the term conservation (I_c) should also be related to agronomic productivity. The latter, however, is not an inherent property of the soil and is an integrated response to all factors of production, such as soil, climate, and management.

Agricultural sustainability. Agricultural sustainability should also be defined by a function similar to that shown in equation (2):

$$A_s = d(P_i * S_p * W_r * C_f)/dt \quad (2)$$

Where A_s is agricultural sustainability, P_i is the productivity per unit input of the limiting or non-renewable resource, S_p is a measure of critical soil property (e.g., rooting depth, soil organic matter content, cation exchange capacity), W_r is plant-available water reserve and quality, C_f is a climatic factor with reference to evapotranspiration, soil temperature, flux of radiatively active gases into the atmosphere, etc. Once again, all variables should be made dimensionless.

Strategy

For conservation strategy to be effective, it must be linked to new concepts. Some important new concepts include the following:

Minimum soil depth. It is important to determine the minimum (critical) soil depth required to produce desired goods and services and sustain productivity.

Soil life. Biot et al. (1989) defined the concept of soil life or residual stability of land on the basis of the minimum allowable crop production and socioeconomic factors. They also proposed the term "production half-life" as a relative measure of the soil sustainability.

Partial area concept. Some parts of a watershed are more susceptible to erosion and degradation than others. Identification of these areas can be a cost-effective strategy. In India, Dhruvanarayana and Sastry (1988) observed that treating 25% of the watershed areas resulted in sediment reduction of 50%.

Soil resilience. Soil resilience refers to the soil's ability to restore its life-support processes and respond to science-based inputs. Lal (1992) defined soil resilience as per equation (3):

$$S_r = S_a + \int_{t_0}^t (S_n - D_d + I_m) dt \quad (3)$$

Where S_r is soil resilience, S_a is antecedent soil condition, S_n is soil renewal rate, S_d is soil degradation rate, I_m is input, and t is time.

Soil quality. Soil quality refers to the soil's ability to produce economic goods and services and maintain acceptable standard of environment quality and functions within an ecosystem's potential and constraints. Soil quality is defined as per equation (4):

$$S_q = f(P_i * S_c * R_d * f * e_d * N_c * B_d)_t \quad (4)$$

Where S_q is an index of soil quality, P_i is productivity, S_c is structural characteristics, R_d is rooting depth, N_c is nutrient capacity and intensity factor, B_d is biodiversity, and t is time.

Methodology

There are several new techniques and methods available to quantify the degree and extent of soil erosion, fill data gaps, and predict soil erosion hazard and its impact on productivity (Table 3). Where applicable, remote sensing and GIS can be cost-effective methods of assessing erosion on a large scale (Griffiths and Richards 1989). In fact, the geographical approach and remote sensing techniques to assess the impact of environment on land degradation has been used in Haryana, India. New concept-based models have been developed to predict erosion risks by water (Lafren et al. 1991) and wind (Hagen 1991). Considerable progress has also been made in developing methods for assessing impact of soil

Table 3. Modern research techniques and methodologies

Objective	Methodology/technique	References
1. Degree of soil erosion	C_s^{137} technique	Walling and Quine (1990)
2. Extent of soil erosion	Remote sensing:	Hassenpflug and Vetter (1991)
	(i) Landsat MSS	Ritchie and Cooper (1991)
	(ii) GIS	Brown (1990)
3. Filling data gaps	Informed opinion	Dregne (1989)
4. Predicting water erosion risks	WEPP	Elliot et al. (1991)
5. Predicting wind erosion risks	WERM/WEPS	Hagen (1991)
6. Assessing erosion productivity impact	PI	Biot (1990) and Pierce (1991)

erosion on productivity (Pierce 1991; Biot 1990). Accelerated erosion affects productivity mostly through reduction in available plant water capacity. The water-holding capacity of soil, function of soil properties, and rooting depth are reduced by erosion. Because there is a close relationship between actual transpiration and yield, crop yields can be predicted as a function of available soil water and air temperature. A model relating water budget to crop yield was proposed by Timlin et al. (1986).

Research and Development Needs

A high priority should be the identification of the reasons for the nonacceptability of research information by the farming community. Several innovative concepts are apparently technically sound. However, their economic feasibility and social acceptability need to be assessed for different sociocultural environments of the resource-poor small farmers. Research data must be translated into a simple and practical technology.

There is a strong need to improve data quality and reliability by adopting original and innovative approaches. It is important to know what is being done by colleagues in other regions of the world, duplication of effort can be costly and counterproductive.

To be comprehensive, the data on soil erosion rates must be translated in terms of agronomic productivity. Economic consequences of accelerated erosion and conservation measures must be assessed. Unless the relationship between erosion, conservation, and productivity is developed, it is difficult to plan development strategies and choose conservation methods.

Emphasis should also be given to indigenous conservation technologies. Some traditional methods of soil conservation may turn out to be the best techniques under local conditions.

With a high population pressure in stressed environments, special emphasis must be given to developing and identifying economic land-uses for marginal soils of low agricultural potential. These soils should be used for nonagricultural uses.

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VI. Technology for Mitigating Stresses

Systems Modeling for Evaluating Sustainability

G. Uehara

Abstract

Sustainability of agroecosystems is defined in terms of their biophysical productivity, stability and resiliency, and socioeconomic equitability. These four properties of agroecosystems are measurable and are the indices by which sustainability is evaluated. Since sustainability often entails tradeoffs among agroecosystems' properties, the aim of systems modeling should be to enable producers and policy makers to evaluate practices and policies that can increase productivity without sacrificing stability, resiliency or equitability for future generations. The traditional method of conducting experiments on the system to evaluate sustainability is too slow and costly and will have to be supplemented by some form of ex ante analysis. Systems modeling for ex ante analysis of sustainability is developing rapidly, but will require international coordination for standardization and economy of effort. Model development should also be tied to specification of the minimum data set needed to operate the models. A serious problem with system modeling is that model development is progressing faster than the time needed by producers and policy makers for the compilation of local soil, weather, crop and socioeconomic data, to evaluate sustainability. This imbalance between model development and compilation of local minimum data sets, needs to be corrected immediately.

Introduction

It would be useful at the outset, to define the three key words, systems, models and sustainability, that appear in the title of this chapter. A system is a set of interdependent parts that work together to determine the behavior and performances of the system as a whole. Since a system is affected by changes occurring in the environment outside the system, it is useful to define the boundary of the system and its environment.

A model is any representation of a system that includes only those attributes relevant to the purpose of developing the model. An old truism of modeling is that it is not necessary to know everything about a system to model it.

There is less agreement on what is meant by sustainability, but a definition can be chosen from many that have been proposed. Productivity, stability, sustainability and equitability are the key properties of agroecosystems. Productivity is defined in terms of yield or profit derived from inputs of land, labor

and capital; stability as the constancy of yield or income overtime, sustainability as the capacity of an agroecosystem to recover from stresses or disturbances; and equitability as the equal sharing of benefits derived from the system.

Most would find Conway's definition of sustainability too narrow, call it resiliency, and redefine sustainability to include productivity, stability, resiliency and equitability. Henceforth, in this chapter, sustainability will be used in the latter form.

There are two advantages of defining sustainability in terms of all four properties of agroecosystems. First by doing so, sustainability becomes the product of tradeoffs among four, competing properties of systems. For example, productivity and stability can be increased by irrigation, but often at the risk of lowering resiliency through salinization and waterlogging. The second advantage of separating sustainability into four distinct components is that, the components themselves can be quantified and measured.

Systems Modeling

In agriculture it is customary to study a system by experimenting on the system itself. We learn by observing how a system responds to natural disturbances and human interventions, and manage it in accordance with the experience gained from these observations. This trial-and-error approach to learning from experiments which Nix (1980) disparagingly calls "white peg agronomy," is now on the brink of collapse. This approach is no longer able to keep pace with the demand for information that farmers and policy makers require to accommodate rapid changes that take unexpected directions.

An alternative to "white peg agronomy" is systems modeling. This approach is premised on the assumption that it is more convenient to study a system using models than to experiment with the system itself. Models are especially useful for complex systems which involve interactions among other processes. In such processes, control measures based on human intuition often produce unexpected results and also unwanted side effects. A model provides the framework for specifying, organizing, and integrating knowledge about complex phenomena in a precise and concise form (Spain 1982), and serves as a tool to help humans whenever the complexity of a situation transcends assessment by intuition and experience.

Choice of Models

Mathematical models can be categorized as being either statistical or process-based, deterministic or stochastic, and static or dynamic. Although the choice depends on the purpose, a model for evaluating the sustainability of an agroecosystem should be process-based, deterministic or stochastic and dynamic. Unlike a statistical model which has a narrow extrapolation range, a process-based model can simulate a systems behavior over wide ranges of locations and a variety of seasons. Most models today are deterministic and use fixed values for model parameters and generate the same results given the same input variables. These process-based, deterministic models, however, can accept

stochastic input data such as rainfall data and account for their stochastic effects on systems behavior and performance. Since agroecosystems undergo constant temporal changes, the model must necessarily be dynamic. Most models today operate on a daily time step, i.e., changes in the system (e.g., biomass, soil, water content, nutrient concentration in soil layer of plant organ) are computed on 24-hour increments.

Finally, models can differ in purpose and therefore in scope, detail and data requirements. Models differ because they are developed to: (1) study and understand how systems operate or (2) predict outcomes for improving practices and policies. They are sometimes called research models and management models, respectively.

Research models tend to focus on subsystems with only a few components, be more detailed and require more input data to operate. An example of a research model is the Richards model for predicting water movement in soils. To use the model, one must have hydraulic conductivity versus soil water content data and water content versus soil water pressure data. Such models can be used to recommend new practices or policies, but only in limited circumstances.

Management models are better suited to evaluate sustainability, and by necessity encompass more parts of the agroecosystem including soil, water, atmosphere, animals, plants and people (SWAAPP). Management models must not only integrate the many parts into a coherent system, but must also treat the parts in a balanced way because a model can only be as good as its weakest part. Figure 1 (Godwin and Vlek 1984) illustrates how the parts of a management-type model are linked to produce results governed by many interactions. Although people are not included in the chart, people decide what crops to grow, where, and when, and how much, how often and what type of fertilizer to apply. If straw or grain is used to feed animals, the manager can alter the practice to achieve that particular objective.

Why Use Models

Models are used for the following reasons to understand and manage agroecosystems:

- to reduce site-specific, long-term field experiments;
- to interpret climatological records in terms of production potential and limitation;
- to evaluate expected returns of soil- and crop-management practices;
- to evaluate risk associated with management practices;
- to communicate research results between locations;
- to enhance understanding of biological and physical systems and their interactions; and
- to conceptualize multidisciplinary activities.

Implicit in Steiner's list is the fact that the performance of an agroecosystem is not only governed by human intervention, but by factors outside human control. In risky and stressed environments, the performance of an agroecosystem depends as much, or sometimes even more on uncontrolled, random variables such as the weather than on human factors. Agronomic experiments are rarely conducted to understand effects of uncontrolled factors on a system performance. In virtually

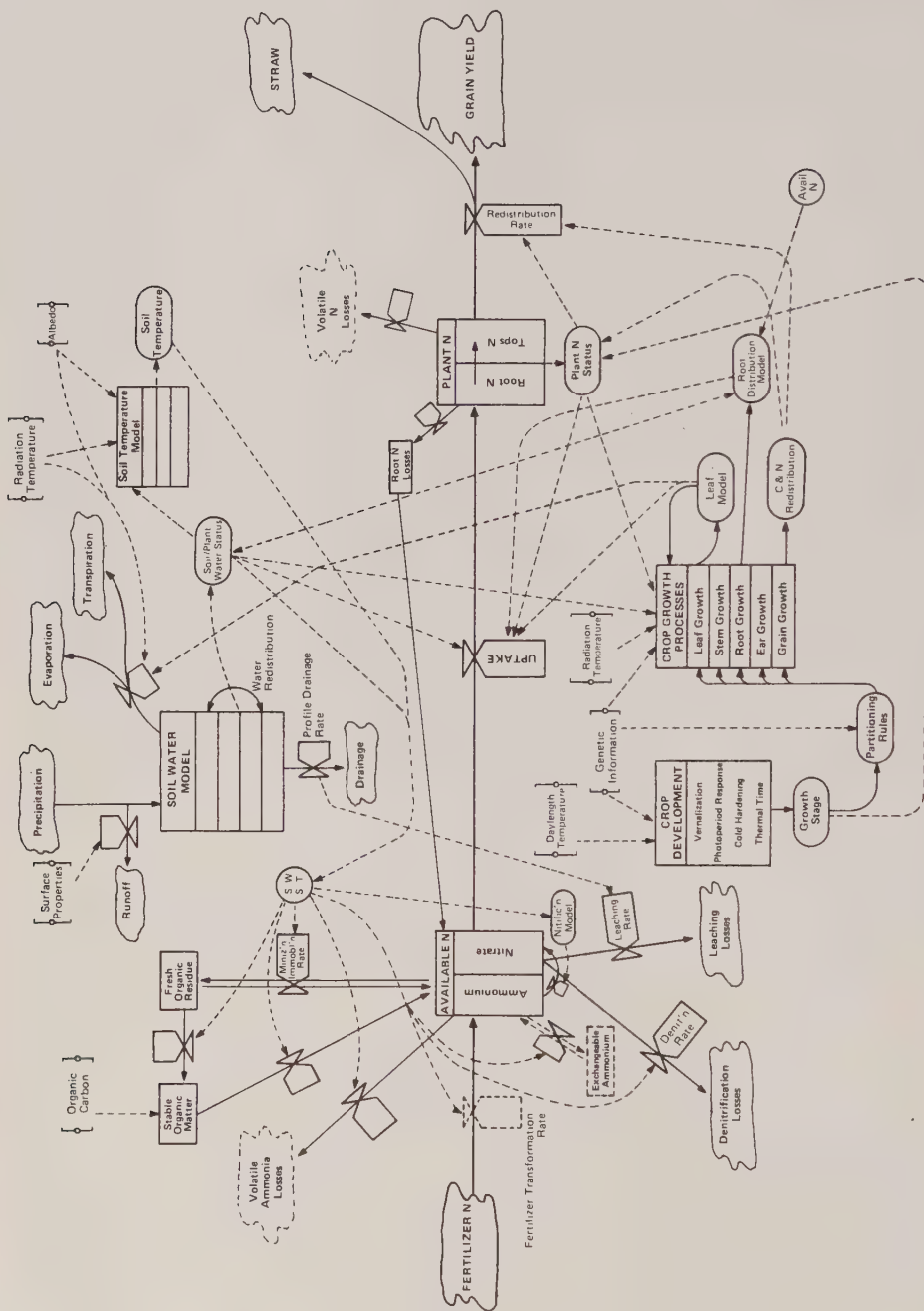


Figure 1. Interacting factors illustrating the complexity of the production system

all experiments, uncontrolled variables such as the weather, are treated as constants over treatments, even though the outcome of the experiment may be more influenced by the uncontrolled variable.

To measure and assess agricultural sustainability, it is necessary to know how all factors, both controlled and uncontrolled affect the performance of the system. Since a variable such as weather varies with time and location, it becomes necessary to repeat experiments over many locations and years. An ongoing example is the variety trials conducted to assess effects of genotype by environment interactions on varietal performance.

To understand why we need models, consider a simple experiment to compare the efficiency of organic and inorganic nitrogen sources to increase productivity of three crops in six stressed environments. Consider also, the same experiment conducted in the field by an agronomist, and again on computer by the same agronomist using a systems model.

In the field the agronomist would install experiments in six locations, using three crops fertilized with three rates of inorganic and organic nitrogen sources. The treatments would be replicated three times and the entire experiment repeated the following year to assess weather effects. If the agronomist had in fact conducted this study, a total of 648 experiments would have been installed, monitored and harvested. In reality, the cost and effort would have been so great that the study would have been drastically reduced or not conducted at all.

Had the same study been conducted using a computer, the agronomist could have broadened the scope of the experiment to consider many more factors, and still have completed the study and displayed the analyzed results in a matter of a few hours. In addition to the six locations, three crops, two nitrogen sources, three nitrogen rates and repetition of the experiment on the following year, the simulated study could, for example, have examined the effect of six sowing dates, three sowing densities, two timings and three frequencies of nitrogen applications and repeated the experiments for 25 consecutive years. A study that would have been impossible in the field is made simple by specifying, organizing and integrating existing knowledge about agroecosystems in a model.

It should be evident from this example that it is impossible to evaluate agricultural sustainability by field experiments. Field experiments must be reserved for a more important purpose, namely to understand processes so that they can be used to improve models.

Who Should Use Models?

Models are still used primarily by researchers. To make a substantial difference, however, many users outside the scientific community will need to apply models, to evaluate and adopt practices and policies that lead to sustainable development.

There are many reasons for the small number of model users outside the scientific community. First of all, the models themselves have not been developed with any user group in mind other than researchers, and secondly, individuals who might benefit from modeling are not aware of their existence. A third factor is the difficulty of using models without some familiarity with models and

computers. This, however, is rapidly becoming a nonproblem. Fourthly, there is still a considerable amount of skepticism about the ability of models to simulate conditions in the real world. Part of this skepticism stems from the infinite nature of the problem domain in agriculture.

Take for example the words "stressed environments." How many kinds of stresses are there? Let me name a few. There are 17 essential plant nutrients, any one of which can cause stress. There is drought stress, heat or cold stress, oxygen stress and stresses imposed by countless insects, diseases, and pests. A soil stress could be caused by mechanical compaction and accumulation of pesticides or toxic metals. Whole irrigated areas are at risk due to salinization and waterlogging. Wind and water erosion diminish the value of lands, and acid rains alter the chemistry of aquatic and terrestrial systems. The list is endless. This leads to the obvious fact that there are many more factors which models do not take into account than they actually do. While users may not want models that will do everything for everyone, they might want one that can diagnose and solve critical problems for a particular customer. Models have a long way to go before they reach the latter stage in their development.

But of all the factors that now prevent even the most enthusiastic user from applying models, the most critical is accessibility to local, site-specific data required by the user to run the models. Models available today have been designed to operate globally and locally, which is to say that they operate anywhere in the world on a site-specific basis. Models can operate globally because they are process-based; but to operate locally, a model must be provided with a minimum set of site-specific soil, weather, landscape, and socioeconomic data. Although much still remains to be accomplished, model development is far more advanced than the task of organizing and storing local data for easy retrieval by users (Uehara and Yost 1986; Uehara 1989).

Minimum Data Set for Systems Modeling

It was just a decade ago that an international conference was held here at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT 1984) to specify the minimum amount of environmental, crop and management data a user would need to validate and use crop models. The participants were asked to focus on system analysis and crop simulation models as the primary means to match crop requirement land characteristics. The aim was to develop a solid foundation for dealing with the soil-water-plant-atmosphere continuum so that strong links between the biophysical and socioeconomic aspects of agricultural systems could later be forged. The scope of work was limited to ten food crops including four cereals (pearl millet, rice, sorghum, and wheat), three grain legumes (dry bean, groundnut, and soybean), and three root crops (taro, cassava, and potato). The first approximation of the minimum data set needed to drive crop models was produced (IBSNAT 1984). This initial report was revised in 1986 (IBSNAT 1986) and again two years later (IBSNAT 1988).

Reaching an agreement on the minimum data set was a major achievement for the Conference. Fortunately, the state of crop models existing at that time enabled the participants to focus on data required by the models. Most models

of that period were operating on a daily time step, and considerable convergence in their data requirement had already occurred. Thus the minimum data set was largely predetermined by the models themselves. In the beginning what was important was not so much the number and the kind of variables that were included in the minimum data set, but the simple fact that a data set, imperfect as it was, existed. The minimum data set specified then, and now, is still imperfect because the knowledge of the processes researchers are trying to model is imperfect.

In the final analysis it was the practical goal of the participants that determined the size and nature of the minimum data set. It was reasoned that a large and complex data set would merely add to the burden of data acquisition in developing countries. There was full agreement that the participants would not develop models, however powerful they might be, which would be rejected by the very clients they were meant for, simply because the input data to use them was unavailable or too costly and difficult to obtain.

The lessons learnt over the past decade tell us that model development and specification of the minimum data set, must go hand in hand. Past experience also tells us that models and minimum data sets should be standardized for maximum use and therefore should be constantly reexamined by an international committee of users and scientists.

Conclusions

Within the next 40 years, the world must learn to produce twice as much food on less land than it now cultivates. The task of doubling production on more land would have been difficult enough, but now producers everywhere are being asked to produce more on less land and to do so without compromising the sustainability of production. To complicate matters further, the future is now blurred by the specter of climate change and the risk and uncertainty it adds to the planning process.

The traditional approaches to studying agricultural system will no longer be adequate. Systems modeling with all its shortcomings provides an alternative way to address the complex ways in which humans interact with the environment, and to ensure that these interactions can continue on a sustainable basis indefinitely.

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Technology for Mitigating Stresses: Alternative Land Uses

J.C. Katyal, S.K. Das, G.R. Korwar and M. Osman

Abstract

Rainfall and soil are the key resources of dryland agriculture or rainfed farming which is typical to seasonally arid environments. The amount of precipitation and its distribution determine the type of crops/cropping systems that a rainfed region can support. Generally rainfall is limited to a period during which its availability is highly undependable. Suboptimal moisture availability is common to vast majority of dryland regions. Span and degree of low moisture availability set the limits for categorizing dryland regions. The length of moisture deficiency period is conditioned further by the quantitative ability of a soil to hold water. Within a soil series, soil depth dominantly controls moisture storage. Nearly half of the rainfed soils in India suffer from depth limitations.

Because of undulating physiography, soils of varying depth occur more or less on a toposequence in a watershed—the common denominator of rainfed agriculture development. The bottom lands are deep and are capable of being used permanently for cultivation. Contrarily, depth-induced moisture restrictions make top lands less suitable for regular cropping. In addition, sparse vegetative cover leaves them exposed to severe land degradation during the greater part of the year. Long-term productivity for stable rainfed agriculture, therefore, demands implementation of land capability biased, alternative cropping and management strategies.

Review of the information generated in the semi-arid tropical environments has established that annuals cultivated on land capability of class IV and above are exposed to risk and are poorly responsive to input use. Soils falling in these capability classes can successfully support self-propagating or self-generating grass and legume forages and perennial woody plants.

Research on resource use optimization has led to the development of a number of land-use options. These include tree or pasture based cropping in harmony with agriculture on a catchment basis. Agroforestry, agrihorticulture and silvipasture are typical examples of alternative land-use systems. The emphasis in this chapter is more on multivalued crops that generate food and ensure uninterrupted supply of fuel and fodder and are ecofriendly. Role of alternative land-use options besides the stabilizing of biological productivity has been explained from the point of moderating the impact of climate-induced drought.

Rainfed or dryland agriculture is the principal form of land-use in seasonally arid environments. Worldwide, 6150 million ha of land is under dryland agriculture of which 21% is dry subhumid, 37% semi-arid, 26% arid and 26% hyper-arid (Down to Earth 1992). Drylands spread from Australia to Asia and from Africa to Latin America. Among the Asian countries, agriculture in India is extensively rainfed where crops in 70% of the cropped land depend on rainwater for their survival. Rainfed agriculture supports more than 60% of the 488 million cattle heads in India. Around 40% of India's population (Randhawa, and Venkateswarlu 1980) [total 840 million (1991 census)] live in the drylands. Forty four percent of foodgrains comprising more than 90% of the coarse cereals and pulses produced in India, originates in the drylands (Katyal et al. 1991). Nearly 70% cotton, 55% rice and 22% wheat (India: Ministry of Agriculture 1992) are located in the rain-dependent regions.

During the last two decades, though productivity of dryland crops has risen steadily the growth rate has been marginal. Overall yields of dryland crops continue to be dismally poor and highly unstable. A serious question that needs immediate consideration is, how to improve the economic conditions of the rainfed farmers with arable farming. If the resource use is planned efficiently by matching the capability of the land with its land use then the productivity and profitability from drylands can be enhanced. This chapter attempts an introspection on the possible alternative uses of rainfed regions. In the final analysis, the objective is to outline strategies that increase and stabilize agricultural output by maintaining the sustainability of an agricultural system. The main focus of this presentation is that the poor crop in India is not so much due to the expanse in dryland area, as due to the wide array of climatic domains and diversity in soils. In fact, India can be aptly described as a dryland gallery.

Dryland Resources

Climate

Climate and soil are the key resources that influence the choice of farming systems in dryland regions. Of the three climatic variables—rainfall, temperature and solar radiation—rainfall is the biggest constraint to the success of a dryland farming enterprise. It is most undependable because of the high variability and relative unpredictability in its nature between and within seasons. The coefficient of variation (CV) in its occurrence, increases with a fall in annual precipitation (Table 1). In dryland regions (annual rainfall restricted to less than 1000 mm) CV generally varies between 25% and 30%, while values higher than 50% are not uncommon.

The southwest monsoon contributes the maximum (74%) of the 400 mm equivalent of precipitation (Table 2) received in India (FAI 1993). Only 3% of the total annual rain is due to the northeast monsoon. The remaining 23% is received either during the pre/or postmonsoon season. Obviously, the fate of the rainfed agriculture swings with the oscillations in the southwest monsoon.

Table 1. Effect of mean annual rainfall on coefficient of variation (CV) and probability of occurrence of deficit rainfall¹

Station	Mean annual rainfall (mm)	Annual rainfall CV (%)	Probability (%) of occurrence of deficit rainfall (< 75% of normal)
Jodhpur	369	55	51
Anantapur	568	30	38
Hyderabad	767	29	31
Varanasi	1026	25	25
Ranchi	1434	21	20
Shillong	2415	15	7

1. Source: B.V. Ramana Rao, Central Research Institute for Dryland Agriculture, Santoshnagar, Saidabad P.O., Hyderabad 500 659, Andhra Pradesh, India (personal communication).

Table 2. Seasonal distribution of annual rainfall in India¹

Source	Duration	Seasonal distribution (%)
Pre-monsoon	March–May	10.4
Southwest monsoon	June–September	73.7
Post-monsoon	October–December	13.3
Northeast monsoon	January–February	2.6

1. Source: FAI 1993.

Long-term studies on the behavior of rainfall distribution show that the availability of rain is confined to a "period" marked by a "beginning and end." A small departure from the norm is enough to trigger droughtlike conditions. During the last 120 years (1870–1990) drought in 29 out of 35 agrometeorological divisions of India has occurred 425 times. On 70 occasions, its intensity was severe. On an overall basis, 39% of the arable land faces drought perennially [(Kaushalya Ramachandran, Scientist, CRIDA, Hyderabad) (personal communication)].

Since rainwater availability is limited to a "period," droughts cause suboptimal moisture availability which adversely affects crop growth and yield. Span and degree of low moisture availability therefore sets the limits for categorizing dryland regions. Apart from the influence of spatial and temporal distribution of rainfall, the duration of moisture deficiency is conditioned by the quantitative ability of soil to hold water. Most dry farming regions of India are either monocropped or intercropped (Figure 1). The area under double cropping is very limited.

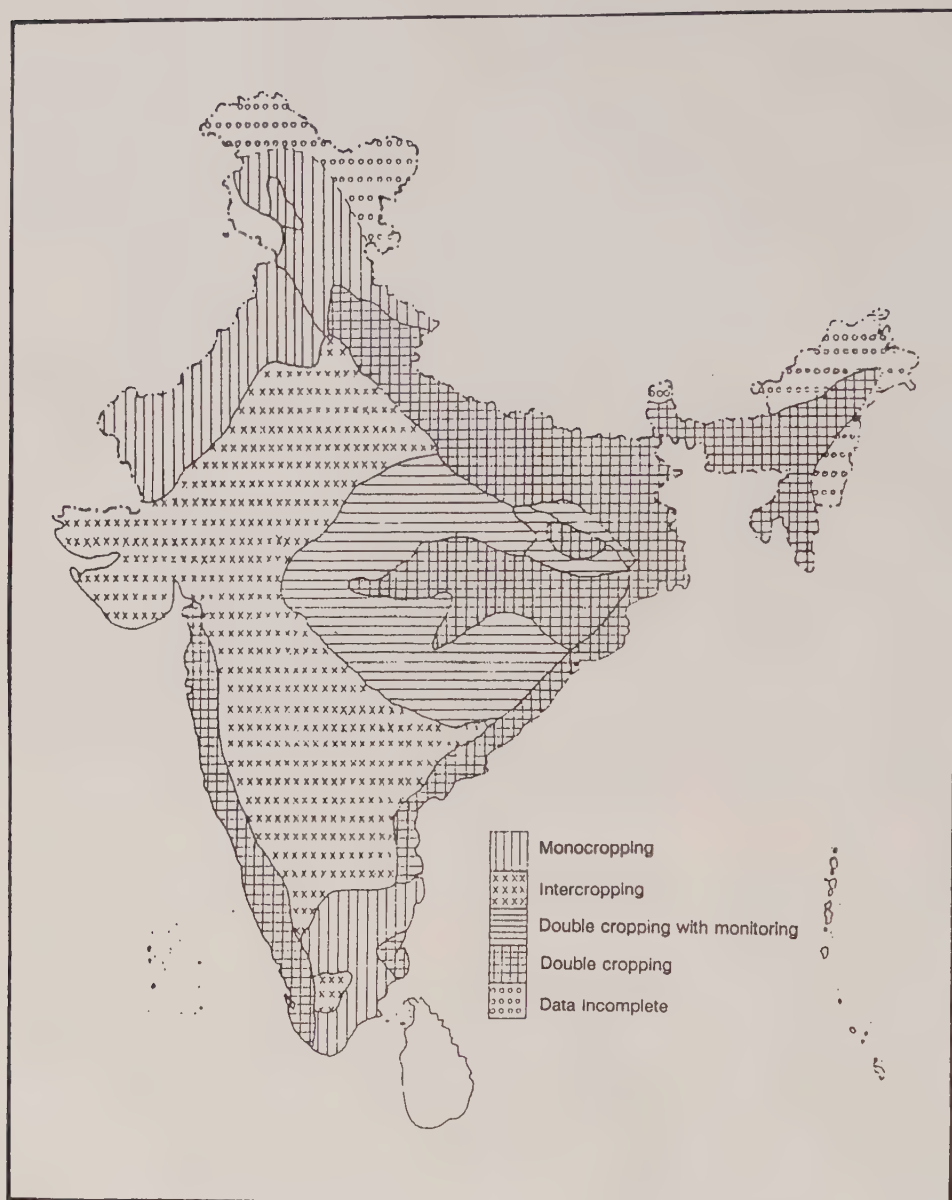


Figure 1. Potential cropping patterns in India

Soils

Soils of the semi-arid tropical (SAT) regions are poor in fertility, structurally degraded, undulating in physiography and shallow in depth. Land degradation is a familiar feature of drylands because of sparse vegetative cover. In India,

167 million hectares, constituting half of its total geographical area suffer from degradation of one or the other kind (Katyal et al. 1992). The world as a whole loses up to 42 billion US dollars annually due to land degradation (Down to Earth 1992).

Since land resources vary spatially, all rainfed lands are not suitable for arable farming. Soils belonging to land capability class IV (LCC IV) and above are not very suitable to arable farming because of certain inherent constraints. Data shown in Table 3 support this contention. Compared to LCC II soils, the relative fall in yield of sorghum, pigeonpea and cotton was far more striking when grown on LCC IV soils and LCC III soils. Among the three crops, pigeonpea followed by cotton was more sensitive to worsening land capability class than sorghum. On account of poor growth leading to sparse vegetative cover, LCC IV soils suffer severely from wind and water erosion when annual crops are grown on them. This explains why water and wind erosion are the most potent degradative processes operating in dryland regions of India. Erosion vulnerability of rainfed soils can be effectively arrested if they are set apart for perennial pastures, trees or their combinations (Das et al. 1993).

Table 3. Reduction (%) in yield of sorghum, cotton and pigeonpea on different lands with varying capability¹ (mean of 3 years)²

Land capability class	Reduction (%) from that obtained with class-II land		
	Sorghum grain	Seed cotton	Pigeonpea grain
III	18	33	67
IV	35	46	86

1. Rainfall: 840 mm; Soil: Vertisol and associated soils.

2. Source: Annual Reports of AICRPDA Center at Akola.

Land capability classification of 47 model watersheds (Table 4) showed that 41% of the soils could be categorized under LCC IV to LCC VIII (Dhruva Narayana et al. 1987). Because of undulating physiography, soils of varying depth occur in a toposequence in a watershed. Bottom lands are deep with a flat plane.

Table 4. Land capability classes of the 47 ICAR model watersheds¹

Land capability class	Area (%)
II	16
III	43
IV	19
VI & VII	15
VIII	7

1. Source: Dhruva Narayana et al. (1987).

These are suited to arable farming. Soil depth generally decreases towards a hill top. Depth related moisture storage restrictions render toplands unsuitable for shallow rooted annuals. The top lands can be successfully utilized for perennial arboreal plants. Sustainable rainfed agriculture demands land capability biased alternative land-use technologies and management strategies. The adoption of alternative land uses based on resource potentials will help solve a variety of land-use problems that currently do not sustain rainfed agriculture.

Alternative Land Uses

A pattern of land use that is different from the existing or the conventional can be described as an "alternative land-use system." With the primary focus on sustainable agriculture, an alternative land-use system must foster the development and adoption of agricultural practices that are ecofriendly, economically advantageous, and socially supportable. An alternative land use is aimed:

- at optimizing resource use by enhancing biological productivity and profitability;
- at conserving, and enhancing, the quality of resource base;
- at integrating crops (including arboreal and pastoral) and livestock;
- at making agriculture less dependent on off-farm inputs;
- at expanding employment potential; and
- at improving the overall quality of farm life.

In total, the purpose of alternate land use is to maximize the output and to prevent land degradation via capability biased resource use (Figure 2). Commonly known alternative land uses are listed below:

- | | | |
|----------------|---|---|
| Agroforestry | : | A system of land use integrating woody perennials with pastoral or arable crops. Agroforestry can be further classified in to agrisilviculture, alley cropping, silvipasture, and agrihorticulture. |
| Socialforestry | : | Forestry to meet social objectives |
| Tree farming | : | Growing trees on lands not suitable for arable cropping. |
| Ley farming | : | Rotating arable crops with forages, particularly legume forages. |

An agroforestry system is more acceptable than tree farming alone since intercropped annuals regulate income when the trees are too young to yield beneficial produce. On the other hand, mature trees bring about more stability in the system because of their innate ability to withstand destructive aberrations in rainfall. Their perennial character helps make use of the nonseasonal rains which constitute nearly one-fourth of the total precipitation received in India (Table 2). Furthermore, an agroforestry system provides for varied needs of farmer for food, fuel and fodder. Some agroforestry systems (i.e., agrihorticulture system) enhance employment opportunities by spreading labor needs which otherwise are concentrated in the cropping season.

Competition for water and nutrients between tree and under-tree crops is typical of an agroforestry system. Because of sheer range in root distribution, it is the under-tree crop which is at a disadvantage in this competition. Tree

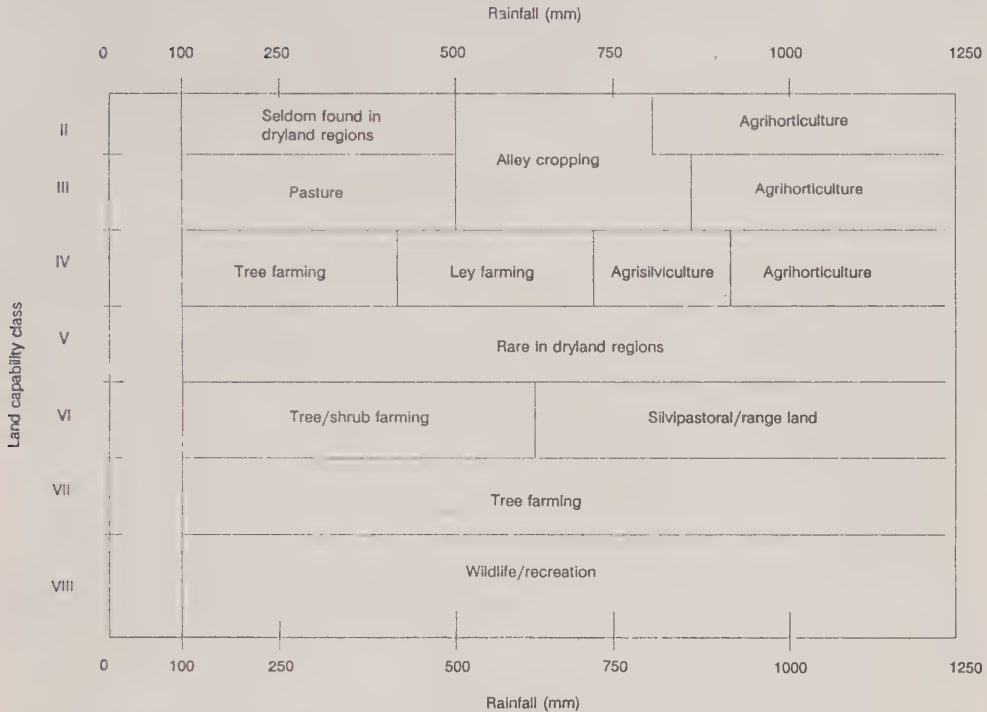


Figure 2. Possible alternate land uses as influenced by resource (LCC and mean annual rainfall) capability

canopy induced light deprivation misplaces further the under-tree crop. Maximization of output from an agroforestry system requires a careful blend of synergistic influences tree-crop components. Some agroforestry systems are analyzed from the point of compatibility between perennial and annual species in that the competition is moderated. Some of the important systems are discussed here.

Agrisilviculture

This alternate land-use system combines perennial arboreals with annual arable crops. The tree component yields fodder, fuel or timber. It is also intended to produce green leaf manure so that dependence on purchased inputs is lessened. This system is well suited to LCC IV soils occurring in rainfed suited regions with annual rainfall around 750 mm (Figure 2).

In a study involving four N-fixing tree (NFTs) species (Table 5) intercropped with sorghum or castor in rotation revealed that growth and yield of perennial and annuals varied significantly. Among the tree species, *Leucaena leucocephala* grew fastest, yielding maximum N for the under-tree crop and brought about more improvement in soil quality (measured by build up in soil organic carbon)

Table 5. Growth parameters and leaf N-content of 4-year old NFTs planted in 4 m × 4 m geometry and relative yield of understorey sorghum and castor¹

Species	Growth		Leaf-N (%)	Soil carbon % 1.0	Relative yield	
	DBH (mm)	Height (m)			Sorghum	Castor
<i>Faidherbia albida</i>	60	4.12	4.0	0.73	114	110
<i>Albizia lebbbeck</i>	77	4.41	3.0	0.61	90	76
<i>Acacia ferruginea</i> ²	45	3.24	ND	0.67	103	106
<i>Leucaena leucocephala</i>	97	7.77	2.2	1.27	14	0
Control (no tree)				0.732	100	100

1. Source: M. Osman (unpublished data).

2. Sowing delayed by one year.

due to larger leaf fall and contributions through pod shedding. However, the fast-growing habit of *Leucaena* proved disastrous for the intercropped sorghum or castor, since they yielded lowest in its company. In comparison, the relative yield of sorghum and castor was slightly higher in the presence of *Faidherbia albida* and *Acacia ferruginea*. Earlier (Poschen 1986) *Faidherbia albida* has held promise in the African Sahel cropping system.

Keeping in view the minimal competition offered by *F. albida* to understorey crop, research was expanded to evaluate the sustainability of the system by altering the population of trees as they grew older. At the tree age of seven years the performance of intercropped sorghum or groundnut was assessed. Since older trees shade the under-crop extensively and also require more water and nutrients the relative decrease in yield of sorghum or groundnut was far less when the tree population was reduced from 625 to 156 trees ha⁻¹ (Tables 6 and 7). In contrast, the change in population of sorghum or groundnut was to no avail in modifying the competition put up by *F. albida*. Rather, maintenance of their admissible numbers was necessary for optimum productivity.

Perennial pigeonpea having qualities to improve soil fertility and to yield high value pulse in humid tropics of Africa was tested for its ability to accommodate quick growing intercrops on Alfisols of semi-arid tropics (rainfall: 750 mm). Except for the first year when the land equivalent ratio (LER) rose up to 1.66, perennial pigeonpea was a failure due to excessive mortality caused either by wilt, moisture deficiency and/or both. More research is necessary to find out the treatments needed to ensure maintenance of perennial pigeonpea population.

Silvipasture

This system is primarily meant to augment the scarce fodder supply. When located in marginal soils (LCC VI and higher), this system promotes sustainability via resource conservation and its efficient use, improvement in soil quality and by linking agriculture with cattle. Saharan et al. (1989) studied a silvipasture system

Table 6. Yield (kg ha⁻¹) of sorghum and groundnut under two densities of 7-year old *Faidherbia albida*¹

Tree density ha ⁻¹	Sorghum grain	Groundnut pods
625	1415	463
156	2588	677
0 (sole crop)	2986	561

1. Source: M. Osman (unpublished data).

Table 7. Effect of plant population on yields of sorghum and groundnut grown in association with *F. albida* (156 trees ha⁻¹)¹

Sorghum		Groundnut	
Plant population ha ⁻¹	Grain yield (kg ha ⁻¹)	Plant population ha ⁻¹	Pod yield (kg ha ⁻¹)
90000	1852	170000	524
180000	2042	333000	582
270000	2112	500000	606

1. Source: M. Osman (unpublished data).

involving *Leucaena* intercropped either with *Cenchrus ciliaris* (a grass) or with *Stylosanthes hamata* (a legume). The productivity of forages fell with the increasing growth of *Leucaena* due to resultant shade. Extensive root system of grown up trees deprived further the understorey crop of water and nutrients. Compared to *S. hamata*—a legume, *C. ciliaris*—a grass was able to tolerate competition from the tree better and longer. In a parallel study, when the understorey forage species were rotated following a four-year stand and the gaps thus created were attempted to be filled up with fresh seeding/vegetative cuttings, *S. hamata* failed to grow under *Leucaena* trees, while *C. ciliaris* established well.

Results suggest that:

- Grass forages suits silvipasture systems on marginal lands better than legumes.
- Grass forages can be established successfully even under grown up trees.
- It is advantageous to sustain the original silvipastoral system rather than placing the understorey forage crops.

Alley Cropping

Alley cropping represents a system of farming suited to LCC II and LCC III areas situated in 500–750 mm rainfall zone (Figure 2). Alley cropping embodies growing of crops in the space between the rows of trees or shrubs (hedge rows) established generally on contours. In such a set up, the hedge rows act as live bunds and

help prevent runoff. In order to minimize the competition, hedge rows are maintained to a suitable height through regular pruning. Clippings are returned to the alleys to serve as nutrient source and as mulch. These can also be an important fodder source. As fodder, their value is far greater during drought years when they are able to effectively provide some minimal fodder for cattle. Results depicted in Figure 3 illustrate the changes in the productivity of alley cropped groundnut and *Leucaena* over the years due to varying rainfall. During deficit rainfall years, while the groundnut crop almost perished, *Leucaena* was only slightly affected and it continued to yield significant green biomass.

Compared to the favorable environs of humid tropics, hedge rows of an alley cropping system in SAT conditions have to struggle for survival along with alley crops. The two component crops particularly compete for moisture. Results obtained thus far show that by manipulating the height, the water needs of hedge rows can be substantially reduced to the benefit of the alley crop. Findings

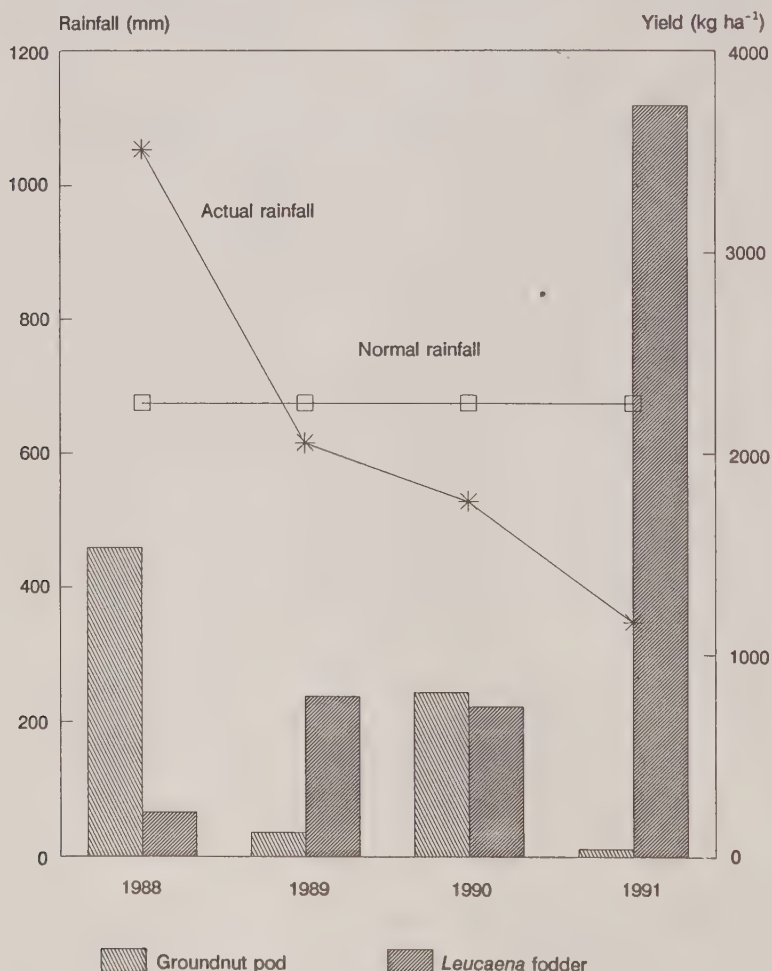


Figure 3. Productivity of alley cropping system on a degraded Vertisol at Rajkot. (Source: Annual Reports of AICRPDA center at Rajkot)

reported in Figure 4 support this contention since the yield of sorghum increased by maintaining hedge row height to a minimum of 15 cm from the ground or arresting the growth.

Despite management of hedge row height, some crops still perform poorly in alley cropping system. This happens when the crop duration stretches beyond the end of the rainy season. The competition for stored soil moisture is intense. Because of its more extensive root system, the hedge row has an advantage. Poor performance of long duration (> 150 days) crops like castor or pigeonpea compared to relatively short duration (< 110 days) sorghum or pearl millet in alley cropping system at Hyderabad (Rainy season of 100 days; Soil: Alfisol with depth < 50 cm) is due to its lack of ability to utilize stored moisture. Competition from hedge rows can be regulated further by widening the alleys or by trimming the roots extending towards alleys.

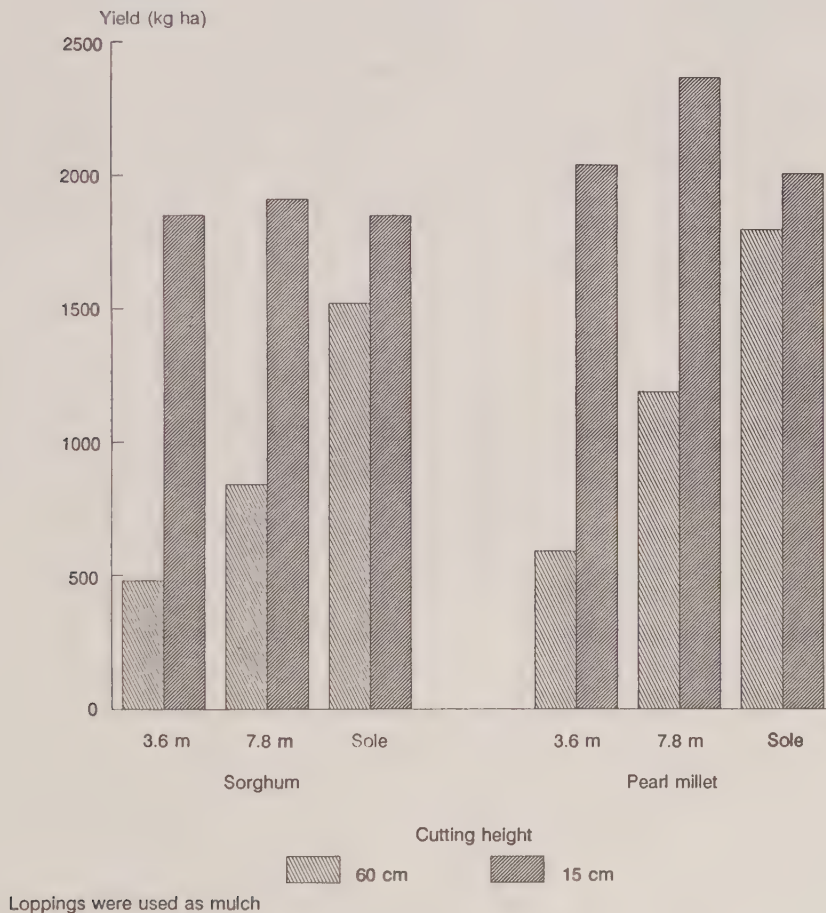


Figure 4. Effect of cutting height of *Leucaena* hedge rows on yield of sorghum and pearl millet (Source: Korwar, 1992b)

Agrihorticulture

As the name suggests this alternative land use combines production of arable crops with horticultural plants. Since success with fruit trees hinges on an ample supply of moisture when young or in reproductive phases, agrihorticulture are suited to regions endowed with possibilities of supplemental irrigation. Such rainfed ecozones generally should receive more than 750 mm annual rainfall and LCC II to LCC IV soils (Figure 2).

Since irrigation of the horticultural component is crucial during the dry months, water resource augmentation should aim at maximum rainwater harvesting. Special land treatments that increase the infiltration opportunity time and lead to maximum in situ water soaking are fundamental to the success of an agrihorticultural system. Microsite improvement in conjunction with setting up of tiny catchments where trees are planted is the initial step in tree establishment and survival. Ground water recharge by erecting masonry barricades in the natural water courses or via runoff hoarding in dug out wells ensures water availability during critical periods. Judicious use of water by employing efficient means of irrigation is of utmost significance to maintain the balance between ground water recharge and its over-exploitation. Apart from prudent use of soil moisture reserves, the water needs of fruit trees can be effectively modulated by selecting species that respond to pruning treatment. Agrihorticultural system involving Ber (*Zizyphus mauritiana*)—a species amenable to pruning, with two to three irrigations has produced highest returns (Table 8) on deep black soil (Vertisol) occurring in a drought prone zone receiving 650 mm annual rainfall. This alternative land use produced a five-fold income compared to the traditional intercropping system of chickpea and safflower. In other studies also, a high, benefit to cost ratio (5.53) was obtained with agrihorticultural system (Reddy and Korwar 1985; Reddy, 1989 and Reddy et al. 1992) (Table 9). In fact, this alternative land use appears to be most sustainable when supported by irrigation at critical periods of growth.

Ley Farming

This system involves rotation of legume forages with cereals. Inclusion of legume in the cropping system improves soil fertility. In a four-year study conducted under SAT environments (annual rainfall = 750 mm) on a shallow Alfisol (depth < 45 cm) inclusion of *Stylosanthes hamata* (a legume fodder) in rotation improved soil quality, (build up of organic C, total and available N) and led to an increase in yield of sorghum crop (Table 10). Compared to featuring *Stylosanthes* in rotation, fallowing, an age-old practice to rejuvenate soil health, was of no avail. Rather, it deteriorated soil health and the result was a significant loss in yield due to unhindered soil and water loss. Ley farming is a valuable system from the point of generating fodder for the cattle which forms an important component of rainfed farming.

In order to make ley farming practically feasible in areas where currently castor-sorghum rotation is the practice, we suggest that one divides a farm holding into four segments. A segment each can be allocated to sorghum or castor, and the remaining two to *S. hamata* (or any other leguminous forage crop). With this

Table 8. Performance of alternative land uses on a deep (90 cm) soil (mean of 3 years)¹

Land use	Gross income (Rs ha ⁻¹)
<i>Zizyphus mauritiana</i> (Ber)	24440
<i>Morus alba</i> (Mulberry)	21570
<i>Leucaena leucocephala</i> + Napier grass	6032
<i>Murraya koenigii</i> (curry leaf)	14466
Chickpea + safflower	4937

1. Source: Annual Reports of AICRPDA center at Bijapur.

Table 9. Benefit to cost ratio of alternative land-use systems¹

Farming System	Period (year)	Benefit cost ratio
Arable farming	Annual	1.34
Agroforestry (with sorghum/pigeonpea intercrops)	10	1.65
Agrihorticulture	30	5.53
Agrisilviculture (with castor intercrop)	10	1.99
Silvipasture	10	2.45

1. Source: Reddy (1989).

Table 10. Sorghum yield and soil fertility as influenced by duration of *Stylosanthes* ley on LCC-IV Alfisol (Rainfall: 651 mm)¹

System ²				Before year 4 sorghum		Grain yield of year 4 sorghum (kg ha ⁻¹)
Year 1	Year 2	Year 3	Year 4	OC (%)	Available N (kg ha ⁻¹)	
C	S	C	S	0.22	110	1802
C	S	SH	S	0.31	113	2549
S	SH	SH	S	0.35	141	3481
SH	SH	SH	S	0.56	145	3912
C	F	F	S	0.15	88	1032
CD (0.05)						789

1. Source: Korwar (1992a).

2. C = Castor; S = Sorghum; SH = *Stylosanthes hamata*; F = Fallow.

arrangement, *S. hamata* will occupy a segment continuously for two years and could be followed either by sorghum or castor. This set up is essential because, *S. hamata* requires one year for establishment.

Conclusions

Sustainability of rainfed farming is seriously affected by weather aberrations in the Indian subcontinent. The studies at the Central Research Institute for Dryland Agriculture (CRIDA) have shown that diversification of agriculture with alternative land uses can help maintenance of both biological productivity and profitability. Since stressed marginal ecosystems (low rainfall, LCC IV and worse soils) abound in dryland regions, introduction of alternative land uses is important to sustain and enhance their quality of the resource base. It has been recognized that the tree based farming systems require more research and training to promote skills on integrated tree-crop management. Sowing techniques on microsite improvement, plant density and geometry and microcatchment treatment for increasing in situ moisture conservation are yet to be perfected. Canopy manipulation for harmonizing improved tree species within different land-use systems and efficient use of limited water through agronomic interventions and methods of its application need major emphasis in the future programs.

Land apportioning based upon its capability class, remains the foremost in a scheme of alternative land-use systems. In our assessment, an alternative land-use system should yield substantial profits to the farmers, link animals to agriculture and on an overall basis focus on enhancing the quality of environment.

Although the emphasis of alternative land uses is founded on the resource capability biased planning, the unit of development needs to be a watershed. This approach alone can usher in the creation of a permanent water resource. Efficient use of stored water will, however, be imperative in assuring success with alternate land uses. Since a watershed is owned by several individual farmers, a community action is basic in organizing a just sharing of the harvested rainwater and in maintaining and sustaining the perennial tree species. Institutional efforts are vital and necessary to develop a land-use policy since the degraded lands are largely owned by the State.

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Efficient Plant Types

K.S. Gill

Abstract

A substantial improvement in crop productivity per unit time is essential in view of the rapid increase in human population and decrease in arable land area. Along with the increase in potential yield, an equally important objective is the sustainability of yield, i.e., maintenance of potential yield under varying environmental conditions over a long period of time without any adverse effect on the environment.

Suitable plant types need to be developed that utilize the resources more efficiently and convert these into economic plant products. Efficiency is defined as the amount of product produced per unit of resource used. The crop yields can be enhanced by increased net photosynthesis, improved translocation and larger sink capacity. The plant breeders have strived hard and made significant strides in improving crop yields. This has been achieved mainly through increased photosynthetic area per unit land area. However, significant increase in efficiency of photosynthesis has not yet been achieved in spite of its accepted prime importance. This has probably been due to difficulty in conducting large-scale selection for this trait in plant breeding programs. Efforts are being continued to transfer the more efficient C_4 system into C_3 plants. The duration of photosynthetic activity is positively correlated with grain yield. The nutrient use efficiency of the plant, depending upon uptake efficiency and utilization efficiency, has been improved in chickpea. The plants with crassulacean acid metabolism (CAM) pathway exhibit the C_3 plants. The efficiency of translocation of photosynthesis depends upon distance between source and sink, rate of transport and rate of sink growth. More assimilates should be translocated and stored in the economic plant part that can be achieved by enlarging the sink capacity in favor of the economic plant part.

Efforts have been made to design an ideal and efficient plant type based on several morphological traits capable of high yield potential under ideal conditions. However, breeders should have a moving target, i.e., plant type should be defined according to the environment for which it is to be developed. Erect leaf orientation is the most important component of an efficient plant type as it allows better light penetration even under dense planting. However, deeply curved leaves with steep ascent and descent are even more efficient than erect leaves. A larger flag leaf area results in higher grain yield. Furthermore, maintenance of leaf area for a longer duration would result in increased production of photosynthates. A prolonged grain filling period would allow the deposition of assimilates in the sink for a longer period, thereby increasing grain yield. Prolonged grain filling period and quicker rate of grain filling have helped in enhancing the yield potential of maize hybrids. The awned varieties in some cereals have higher

photosynthetic activity than awnless varieties. Harvest index is highly and positively correlated with grain yield and selection based on harvest index is more effective. The increases in harvest index of a number of grain and fruit crops may be considered as one of the major breakthroughs achieved in plant breeding.

During crop production, several factors influence grain yield and most of them are not under human control. To breed for sustainable high yields, cultivars should be able to tolerate the environmental fluctuations. The crop plants adapt to drought through several mechanisms that can be broadly classified as drought escape, maintenance of water uptake and reduction in water loss. Breeding for drought tolerance involves breeding for high yields under drought or incorporating one or more characters conferring drought resistance. Cold stress can be categorized as freezing stresses and chilling stress. Further, genotypic differences for cold tolerance have been reported. Similar differences exist for salt tolerance. Indigenous germplasm from salt affected areas has shown salt tolerance and is being used as donors. Contrary to the general belief, hybrids possessing high yield potential under stresses can also be developed as evidenced by the performance of pearl millet and sorghum hybrids.

Disease epidemics can lead to complete crop failures. Extensive research has been done on genetic control of disease resistance and host-pathogen interaction. Breeding for disease resistance involves deployment of genes over time or over space, and development of multiline or multigene or hybrid varieties. Resistance to insects can be due to nonpreference, antibiosis or tolerance.

Plant breeder is faced with an extremely tedious task while developing a cultivar with the most efficient plant type. He has to combine desirable physiological and morphological features contributing to efficient utilization of resources and production of high and sustainable grain yields even under biotic and abiotic stresses.

Introduction

Plant breeding in general strives to enhance the genetic yield potential of crop plants. The necessity to act quickly is dictated by the needs of the enormously growing human population and the constant reduction in agricultural land. Loomis and Williams (1963) estimated that the potential net production of dry matter of a crop under favorable conditions may be $67 \text{ g m}^{-1} \text{ day}^{-1}$ or $245 \text{ t ha}^{-1} \text{ year}^{-1}$. The record yields of dry matter achieved under controlled conditions are reported to be $55 \text{ g m}^{-2} \text{ day}^{-1}$ for rice, $52 \text{ g m}^{-2} \text{ day}^{-1}$ for maize, $51 \text{ g m}^{-2} \text{ day}^{-1}$ for Sudan grass, $30 \text{ g m}^{-2} \text{ day}^{-1}$ for wheat and $27 \text{ g m}^{-2} \text{ day}^{-1}$ for soybean. Therefore, more efficient plant types need to be developed that can favorably compare with the potential production.

The maximum potentially possible yield of grain could be $370 \text{ kg ha}^{-1} \text{ day}^{-1}$ or $137 \text{ t ha}^{-1} \text{ year}^{-1}$. The record yields reported in the last decade throughout the world are 23.9 t ha^{-1} of maize, 21.5 t ha^{-1} of grain sorghum, 14.4 t ha^{-1} of rice, 14.1 t ha^{-1} of wheat and 7.4 t ha^{-1} of soybean. These record yields exceed the average ones for the same year and country by two to seven times.

Considering the theoretically possible yield, the record yields hardly reach a half of it or less than a half. In commercial production, the level of genetic potentials could not be achieved because it is not possible to exercise full control over soil, water, temperature, light, carbon dioxide, and pathogens. The largest yield losses, i.e., differences between record and average yields are due to drought, floods, cold, hail and wind. Diseases and pests cause in general only 7–10% of total reduction. Therefore, the genetic yield potential of the existing cultivars are not fully exploited and the yields are not sustainable. More efforts should be made to reduce the fluctuation in yield due to stresses, both biotic and abiotic, in order to sustain the present yield levels at least, or even to sustain the rate of increase in yield if possible. The development of an efficient plant type is a basic prerequisite for sustainable agriculture.

Efficient Plant Type—Physiological Basis

The production of adequate food, feed, and fibre depends upon the conversion of the sun's energy into useful plant products. Increasing world population and decreasing natural resources demand that these fundamental life-sustaining processes be both effective and efficient.

The major challenge facing agricultural scientists is to increase the efficiency of conversion of energy and then its partitioning to useful plant products. Adequate information concerning basic plant processes and desired plant type of various crops is needed by breeders so that they can more efficiently identify and combine physiological and morphological traits into cultivars with improved yield and quality.

Partitioning of photosynthates, the differential distribution and deposition of assimilates among the organs, tissues and cells of plants must be made more efficient. Efficacy is defined as the amount of product produced per unit of resources used. In cropping systems, this is the ratio of the amount of food, feed or fiber energy produced per unit of radiant energy absorbed. Production efficiency of the plant is determined by the genotype and the environment. Cultural practices affect growth rate and total seasonal biomass accumulation. Stand, or plant density, plays a major role in determining the efficiency of solar energy conversion to plant product per unit of land area.

Efficiency cannot be considered only in terms of quantity of food crops. Quality must also be considered. Thus, efficiency is expressed as the amount of usable product per unit of resource.

Source and Sink

Synthesis, translocation, partitioning, and accumulation of the photosynthetic products within the plant are controlled genetically and influenced by the environment. Leaves and other green tissues and organs of plants that produce photosynthate are called sources. Organs or tissues which receive products, temporarily store them, and later release the products to other sites are also called sinks. All sites within the plant which utilize the photosynthetically derived products, either in situ or after receiving the products are called sinks.

The crop yields can be increased by increased net photosynthesis, improved translocation and larger sink capacity. Deficiencies in water and mineral nutrients results in a smaller source, lower photosynthetic rates, and altered partitioning. Sources and sinks, their relative sizes and physiological activities, and the distances between the source and the sink also influence the rate and amount of substrate movement (Synder and Carlson 1984).

Photosynthetic Efficiency

Of the many processes having a major effect on yield potential photosynthesis would seem to be a prime candidate for improvement. It generates most of the substrate for crop yield, and the enhancement of photosynthetic rate by higher irradiance or CO_2 levels frequently leads to substantial increases in yield. Moreover, there is substantial variation in the rate of photosynthesis per unit leaf area among cultivars of many crops.

Although it has not been selected for directly by plant breeders in the past, one might have expected some indirect selection to have taken place, given the central role of the photosynthetic process (Evans 1983). Although it seems logical to accept that the selection for greater photosynthetic rates in crop plants could be a direct route to greater yield potential, there is no evidence to support it. Varieties with higher yield potential have not been found to have higher light saturation rates of CO_2 exchange per unit of leaf area.

The success in breeding achieved so far is attributable to the increase in photosynthetic area rather than to any increase in the efficiency of photosynthesis (Borojevic 1990). The modern high yielding cultivars have not been found to have photosynthetic rates higher than either older cultivars or wild progenitors in wheat, maize, sorghum, pearl millet, sugarcane, cotton or cowpea. In fact, the highest rates for four of these crops are found among the wild relatives. Similarly, in rice there appears to have been no increase in photosynthetic rate in the course of evolution and improvement. The two crops in which higher photosynthetic rates may be associated with higher yield potential are beans and soybeans.

The potential production rate differs in the so-called C_3 and C_4 plants (the name refers to the length of the C-skeleton of the first product of assimilation.) In plants with C_4 dicarboxylic acid pathway of photosynthesis (maize, sorghum, sugarcane, tropical grasses), it varies up to $350 \text{ kg dry matter ha}^{-1} \text{ day}^{-1}$. For plants with C_3 —calvin pathway of photosynthesis (temperate grasses, rice and many dicotyledonous crops) the potential growth rate appears to be about $200 \text{ kg dry matter ha}^{-1} \text{ day}^{-1}$. The main carboxylating enzyme in C_4 plants has an affinity to CO_2 which is about twice as great as that of the carboxylating enzyme in C_3 plants. Moreover, in C_3 plants a respiratory process occurs during photosynthesis, which results in the dependence of assimilation on the oxygen concentration in the air. This photorespiratory process is absent in C_4 plants. At high light intensities, the net assimilation of C_4 plants is twice that of C_3 plants. Up to now, selection for C_3 species with C_4 traits has had little success although efforts are being continued to transfer C_4 character into C_3 plants by hybridization.

It remains to focus attention on indirect ways to increased photosynthetic productivity. Some of these are: changes in canopy structure, duration of photosynthetic activity, stay green (maintenance of crop health), and prolongation of grain filling period (Borojevic 1990).

Duration of Photosynthetic Activity

Duration of photosynthetic activity has been reported to have a positive effect on grain yield (Austin et al. 1982; Duveck 1983). There exist genetic differences between cultivars in duration of photosynthetic activity although this parameter is also affected by environmental factors at the time of its development as well as by disease attack (Borojevic 1990).

A long leaf area duration is highly positively correlated with leaf area index. Since, an excessive leaf area index may have negative direct effects on yield, leaf area duration should be harmonized with the length of vegetative period and the environment in order to preclude their negative effect on grain development.

Duration of photosynthesis before flowering should not be increased to avoid excessive vegetative growth. However, duration of photosynthesis after flowering should be increased to provide higher amount of assimilates to the developing grains. Duration of photosynthetic activity is certainly a parameter to be taken into consideration, together with the changed harvest index and increased sink capacity, when breeding for higher genetic yield potential.

Wild diploid wheats have the highest photosynthetic rates but it decreases rapidly, with the result that modern wheats display the highest rates several weeks after anthesis. Similarly, in cowpeas and soybeans, rankings for photosynthetic rate during flowering were not related to yield, whereas those during pod filling were related to yield rankings. Thus, correlations between photosynthetic rate and yield probably reflect differences in the duration rather than the maximum rate of photosynthesis.

Nutrient Use Efficiency

Mineral nutrition accounts for about 8% of the total dry matter formed by plants. Although it may seem small when compared with the 90% of dry matter made in the process of photosynthesis, that process cannot proceed without mineral nutrients and water. Nitrogen uptake depends solely on the density of the root system whereas the utilization of nitrogen taken up by plants may be increased only at the expense of protein content.

Cultivars with larger above-ground parts (tall stems and many tillers) have a better developed root system than do semi-dwarf and dwarf cultivars. It indicates that when shortening the stem, to increase harvest index, strict attention should be paid to two things; on the one hand, to avoid a reduction in the root system and on the other, to breed for increased and more efficient root system, for they also contribute to increased genetic potential for yield as well as sustainability of yield.

As mineral nutrients, especially nitrogen, take the largest portion of costs of plant production, attention has started being paid in plant breeding to the nitrogen harvest index (Austin et al. 1980) or the nutrient harvest index (Fisher 1981).

The efficiency of nitrogen use is a product of nitrogen uptake per unit of supply (uptake efficiency) and grain yield per unit of uptake (utilization efficiency). The new wheat cultivars with short stems have a higher nitrogen harvest index than do the tall varieties (Austin et al. 1980). The grain legumes have a low nitrogen harvest on account of low harvest index of grains. Improvement in nitrogen harvest index has been reported in chickpea (Sinha and Swaminathan 1984). The increase in nitrogen use efficiency at higher levels of nitrogen input with the shorter higher yielding cultivars has resulted less from increased nutrient uptake but more from increased efficiency of utilization (Fisher 1981).

Water Use Efficiency

Water use efficiency is the total dry matter or economic yield per unit of water used. For higher water use efficiency, plant breeders need to reconcile two vital but opposing requirements for crop growth. On the one hand, the plant requires a rapid gas exchange with the atmosphere for the assimilation of CO_2 and the production of dry matter. On the other hand, to reduce water loss, the plant requires minimal gas exchange with the atmosphere.

The internal method of utilizing carbon can have a marked influence on water use efficiency of plants. Plants exhibiting crassulacean acid metabolism (CAM) show singular stomatal behavior when growing under water stress. Under these circumstances, the stomata open at night and fix CO_2 in malic acid. The stomata close during the day and the CO_2 absorbed at night is then assimilated by the pathway in almost complete absence of transpiration.

Plants exhibiting C_4 metabolism have high light-saturated photosynthetic rates because the internal resistance is one-half or less of those in plants exhibiting C_3 metabolism. As a consequence, the transpiration efficiency of C_4 plants is about twice that of C_3 plants.

Photorespiration

Until recently, the substantial loss of CO_2 by photorespiration seemed wasteful, with no apparent function, and was therefore an attractive target for elimination by plant breeding. Despite a wide search among many crop plants with C_3 photosynthesis, nonphotorespiring forms have not been found. Furthermore, a close positive correlation between photorespiration and gross photosynthesis was observed in sunflower. The fact that photorespiration has not been eliminated by natural selection suggests that photorespiration has an adaptive value, at least in many environments.

Selection for dark respiration, which seemed theoretically undesirable, now appears to have provided an effective route to greater yield. The slow respiring lines are more productive in closed canopies.

Efficient Translocation of Photosynthates

The photosynthates produced in the source must be rapidly and efficiently translocated to the sites where they are to be utilized. The efficiency of translocation depends upon the closeness and directness of the connection by vascular bundles. Grain growth often proceeds linearly in spite of substantial variation in crop irradiance, suggesting that it is also limited by factors other than the supply of photosynthetic assimilates. The high yielding varieties of wheat and maize have higher rates of assimilate transport and faster grain growth.

Efficient Utilization of Photosynthates

A major portion of the photosynthates should be utilized in the development of economic product. However, a certain amount of minimum requirement of other organs must be met that directly or indirectly affect yield of economic product. Improvement in harvest index in grain crops involve reductions in stems, leaves, roots and reserves. In semi-dwarf wheat varieties, the assimilate saved during the stem elongation phase has been invested in greater grain growth. Some could be used directly to promote greater inflorescence development, some could be temporarily stored until grain growth begins several weeks later, and some could promote the development of more ear bearing tillers.

In tropical maize population selected for reduced height, the reduction in stem weight of $1\text{--}2\text{ t ha}^{-1}$ has been associated with an increase in ear weight of only 0.1 t ha^{-1} at flowering, but of more than 3 t ha^{-1} at maturity. Clearly, although only a small part of the assimilate released by reducing stem growth was immediately invested in greater inflorescence growth, its ultimate impact on grain yield was greatly enhanced.

However, the reduction of stem height and leaf size is practicable only if weeds are controlled. Root system can be reduced only if irrigation and fertilizers are adequately supplied. Reserves can be reduced only when environmental stresses and biotic stresses are controlled. Water and nitrogen insufficiencies usually increase the proportion of root to total biomass. Water stress leads to decrease in shoot: root ratio and less partitioning of dry matter to the grain.

Efficient Storage of Photosynthates

Stem height reduction, especially in grasses, was accomplished by shortening the length of the internodes while the number of internodes remained constant. Consequently, the number of leaves stayed more or less the same and so did the photosynthetic area. It is, therefore, logical that the old tall cultivars and the new dwarf cultivars do not differ much in the size of the photosynthetic area per plant or their source capacity. As a result of changed partitioning within shoots, the assimilates saved by stem reduction are translocated to ear development resulting in heavier ears than the tall varieties. However, further improvement can be brought about by inducing genetic changes in the sink capacity itself, in accordance with the changes made or being made in source capacity. Therefore, sink capacity increases offers prospects for further plant

improvements, especially if it is taken into account that green parts of these organs also play an important role in photosynthetic activity.

Genes which reduce the growth of competing organs such as stem may allow more assimilate to be partitioned into the storage organs, but several characteristics of the latter may also augment their share. Cook and Evans (1978) determined the effects of relative size and distance of competing sinks on partitioning of dry matter in wheat. Grain in the larger sink received more than their pro rata share of assimilate from the flag leaf and the bias increased with increase in its relative size. In addition, proximity of sink to the source conferred a marked advantage in accumulation. The greater the relative size of a sink, or the closer it is to the source of assimilates, the greater is its share of current assimilates. Thus the position, potential size and geometry of the storage organ may all influence the partitioning of assimilate and therefore the harvest index.

The semi-dwarf cultivars of wheat partitioned proportionately more assimilates to the ear than did the tall cultivars. More than 90% of ^{14}C provided to the flag or second leaf 25 days after anthesis went into the mature ear (Makunga et al. 1978). Thus, as the grain matured, its sink strength or ability to accumulate photosynthate increased as compared to other competing sinks. According to Evans (1981), one key to increased yield potential lies in the greater ability of the differentiating ear to compete with other organs for assimilates. Such competition is influenced by the relative size of the competing organs, by their relative distance from the photosynthate, and by the relative directness of vascular connections to it.

Water stress tends to alter the partitioning of photosynthate resulting in a decrease in the share of grains. The effect of water stress on dry matter accumulation by the cereal grains depends upon the time and intensity of stress during grain development (Donald and Hamblin 1976).

Greater Remobilization of Reserves

The remobilization of reserves into the harvested organs varies among crops and cultivars. Fifty years ago, with much lower levels of fertilizer application, photosynthesis during grain growth was restricted and the uplift of remobilized reserves contributed substantially to grain growth. With more nitrogenous fertilizer, and faster and more prolonged leaf photosynthesis, current assimilates are more important than earlier reserves. On the other hand, the greater sink capacity of higher yielding cultivars may lead to greater remobilization of reserves. But such reserves may also play a valuable role in adaptation to water stress and in resistance to lodging and diseases as in maize and sorghum.

Prolongation of Grain Filling

A prolongation in the vegetative period may bring an increased production of total biomass and a prolongation of the grain filling period or fruit development may increase the production of grains. Longer vegetative period is not always positively correlated with grain yield whereas a longer period of grain filling most frequently results in yield increase. Genetic variability for this trait is

available in germplasm. Genotypes with earlier spring growth would facilitate earlier spike initiation and allow a longer period of spike development. The prolongation of grain filling period is of particular importance for the increase of grain dry matter production. For many environments, this will be achieved if flowering starts earlier and the time taken to reach maturity remains the same.

The duration of vegetative phases and of grain filling phase must be in harmony with the agroecological conditions for which a cultivar is created. The occurrence of diseases and environmental stress would determine the duration of these phases. In conditions where grain filling is restricted due to terminal drought conditions, storage of assimilates in the grain should start immediately after anthesis and proceed at a very rapid rate during a short grain filling period so that by the time the stress becomes severe, sufficient quantity of photosynthates would have been stored in the grains.

Improvement in grain yield of maize by breeding resulted in earlier silk emergence, decreased pollen-silk interval, longer time to black layer (in grain) from silk emergence or duration of grain filling, and improved plant health (stay green at 54 days after silking) in addition to ear and grain characters (Russell 1984). Duration of grain fill or days to black layer increased significantly but rate of grain fill remained constant from old to new varieties (Russell 1985). He also reported a highly significant correlation of grain yield with rate of grain fill ($r = 0.77$), with days to black layer ($r = 0.71$) and with stay green ($r = -0.65$). Whereas, production of total dry matter increased from old to new maize hybrids during three phases of development from planting to maturity, the increase was greatest during the period 3 weeks past silking to maturity (Tollenaar 1991).

High Harvest Index

Harvest index is the ratio of the yield of economic product to the total biomass produced. Harvest index of mature grain crops is the ratio of economic product, i.e., grain to the total biomass at harvest. Since the weight of underground parts, i.e., roots is difficult to record, an estimate is worked out on the basis of partitioning ratio of 5:3:2 for grain:stem (including leaves):root. Alternatively, it can be expressed as the ratio of weight of grain to the weight of above ground biomass at harvest. It estimates partitioning of the dry matter between the grains and the stems and leaves. Donald and Hamblin (1976) have reviewed the development of the concept of harvest index and presented detailed discussion of the advantages and limitations in the use of harvest index in the selection of increased grain yield in cereals. Harvest index is closely and positively correlated with grain yield and has high heritability. Selection based on harvest index is more effective than for yield *per se*. However, when harvest index is used as a sole parameter for selection, it may fail to indicate accurately the comparative yield of grain per unit of land for an array of cultivars.

In the obsolete types, vegetative growth was favored at the expense of grain because of the competition for light and nutrients. Consequently, the total biomass of these types exceeded the yield of grain by two or three times. If the vegetative parts are not the main products, then more energy is spent on byproducts than

the main product, i.e., grain. Consequently, plant breeding was directed to reduce vegetative parts to about 50% of total biomass.

The increase in the harvest index of a number of grain and fruit crops, e.g., rice, wheat, maize, sunflower, pea, etc. may be considered a major breakthrough in plant breeding achieved in recent decades. With the old wheat cultivars, 20–30% of the total biomass was the grain yield. The semi-dwarf and dwarf cultivars have a harvest index over 40%. Since the optimum partitioning has not been attained yet with a large number of cultivars and even crops, breeding for a harvest index of 50% or more should be set as a target.

It is possible to increase the harvest index of wheat from the present level of 50% to about 60% without a change in the above ground biomass, achieving a genetic gain in yield of some 25%. The yield of total biomass should be kept in mind when breeding for increased harvest index. In wheat, for example, some dwarf lines have a higher harvest index than do semi-dwarf cultivars, but their grain yields are lower which make them commercially unimportant. The progress made so far resulted from dry matter partitioning which did increase harvest index but retained the total biomass of the new varieties on the level of old ones. Therefore, another possibility is to keep the harvest index at 50% but increase the total biomass which would bring about a corresponding increase in grain yield.

In upland cotton, the harvest index increased from 15 to 20% of LSS variety to about 50% of LH 900 variety. This has resulted from a change in the plant frame, i.e., from predominantly monopodial (vegetative) branching in LSS to an exclusively sympodial (fruiting) branching in LH 900. Munro (1987) reported that seed cotton yield obtained from the first node of sympods is larger than the yield from all other nodes combined. Jenkins et al. (1990) observed that the first three nodes of the sympods almost approximately accounted for the bulk of seed cotton harvested. Therefore, the development of further internodes would be a wastage of photosynthates. Hence, the plant type of cotton with high harvest index is characterized by a dwarf plant with short internodes, lower position of the first sympod, absence of monopods, and large number of sympods with few nodes. Russell (1985) reported that grain yield was highly positively correlated with harvest index ($r = 0.83$). Tollenaar (1989) reported that approximately 15% of the genetic gain in total grain yield in maize could be attributed to increased harvest index.

Efficient Plant Type—Morphological Basis

In developed countries, plant breeding has reached a point at which the chances of a major breakthrough are more and more difficult. Thus in order to develop cultivars superior to the ones used at present (which is possible because the genetic limit has not been reached in any crop), efforts should be made to design a detailed breeding program resulting in the development of an ideal and efficient plant type (ideotype). The theoretical basis for the development of a model cereal cultivar relating to specified environment has been worked out by the Swedish scientist Mac Key (1966). Searching for efficient criteria for breeding for yield, Mac Key started with photosynthesis as the first factor which determines the

yield of grain. Since, currently used methods do not allow for the practical application of physiological parameters in breeding, Mac Key pointed out that morphologically distinctive traits which may be relevant for yield realization in different environments should be taken into consideration when designing an efficient plant type. The cereals possess several yield components which develop successively such as tillering, number of spikes, and number and weight of grains per spike.

Donald (1968) presented a model of a dwarf wheat plant type with erect leaves, long awned spike and a monocolm stem. This plant type was proposed for high planting density in a pure stand with isocompetition among plants and with no insufficiency of water and nutrients.

Breeding for the most efficient plant type was criticized by Finlay (1968) because such a procedure will reduce sustainability of yield although it will achieve high yield potential under ideal conditions. He maintained that a high and stable yield may be achieved by development of cultivars with a wide genetic variability. Blixt and Vose (1984) suggest that breeders should give preference to the concept of adaptability rather than to the concept of ideotype for sustainable high yields. They proposed that the definition of plant type should not be static but the breeders should have a moving target i.e., the plant type should be defined according to the environment for which it is to be developed. The various morphological traits that can be used as components of an efficient plant type are hereby discussed.

Leaf Architecture

Based on photosynthetic activity studies, the portion of leaves or the leaf angle has been identified as an important contributor to yield. When grasses were grown in a thick stand, erect leaves were superior to horizontal ones (Duncan 1969). Erect leaves have been the most important component of the ideal plant types described for rice (Jennings 1964), wheat (Donald 1968), maize (Mock and Pearce 1975) and several other crops.

Pendleton et al. (1968) reported that when compared single cross maize hybrids with erect leaves produced 40% more grain than its counterpart with normal (horizontal) leaf type, in narrow spacings. Winter and Ohlrogge (1973), Pepper et al. (1977) and Lambert and Johnson (1978) reported that upright leaves in maize tended to increase grain yield only at high leaf area index. Mock and Pearce (1975) suggested a plant type of maize with stiff, vertically oriented leaves above the ear whereas leaves below the ear should be horizontally oriented. Mason and Zuber (1976) reported that erectness of leaf angle was positively correlated with grain yield in maize.

In case of wheat and rice, the ear is borne terminally on the stem and major source of photosynthate is the flag leaf. Therefore, an erect orientation of all the leaves of the plant would allow better light penetration even under very high planting density. However, in case of maize, the ear is borne in the axis of a leaf at an intermediate position up the main stem. The major source of assimilate is the leaf in whose axis the ear is borne. Therefore, erect leaf orientation and fewer number of leaves above the ear would result in better

light penetration to the ear leaf. Furthermore, a horizontal orientation of leaf bearing the ear would lead to better interception of solar radiation. At the level of crop canopy, the erect leaf position shows an advantage in the interception of solar radiation by the canopy (Loomis and Williams 1969; Duncan 1969). In recent years, attention started to be paid to genotypes with erect leaves, especially in case of semi-dwarf or dwarf cultivars. Rice cultivars and maize hybrids with erect leaves rank among the highest yielding in their maturity groups, indicating that leaf position does contribute to increased yield potential. During the past 60 years of genetic improvement in maize, the leaf orientation value above the ear (LOVA) showed a change towards more erect leaves. Leaf orientation value below the ear (LOVB) increased slightly over the ears. The values of 1930 hybrids were 27.3 for LOVA and 30.2 for LOVB compared to the corresponding values of 1970 hybrids of 43.0 for LOVA and 32.3 for LOVB (Tapper 1983).

However, Borojevic (1990) proposed that leaves with the curved position and angle of about 30 degrees between the stem and the ascending part of the leaf, and between the ascending and the descending part of the leaf are more efficient than erect leaves. This statement is supported by the fact that the curved leaf position is the most stable throughout the stages of development as well as in a dense canopy, while the majority of genotypes with erect leaves lose that position soon after the heading stage, even to become pendulous in the milk stage. Moreover, in genotypes with erect leaves, tip firing is pronounced starting from the heading stage, which is seldom the case with the curved leaf genotypes. Among the 1400 entries of wheat screened from 36 countries, about 70% of the entries showed curved position of the flag leaf and the second leaf, about 15% were horizontal and about 15% were of erect leaf position (Borojevic 1990). This indicated that the very process of selection favored the curved type of leaves, because conscious human selection for leaf architecture has begun only recently.

Optimum Canopy Structure

To achieve maximum yield, it is necessary to secure an optimum canopy structure. As many crops are grown in pure stands and dense populations, stems and leaves should not be regarded on an individual plant basis but rather as elements of the canopy structure. For such crops, Donald (1981) proposed the term "communal plants" which may give low yield per plant but when grown in a pure stand and at proper density, they are able to give high yields.

The number of stems per unit area serves as an axis on which the parameters of source and sink capacity develop and function. Therefore, the number of stems per square meter represent the first yield component developed by the plants and it is essential to secure an optimum density of stems m^{-2} for each genotype and environment. With regard to cereals which have the capacity of tillering, the optimum density may be reached by low seeding rates under favorable conditions due to better tillering, and by medium to high seeding rates under stress conditions due to poor tillering. In a thin population, the leaves should

be large in size and horizontal, whereas in a dense population the leaves should be small in size and erect in architecture.

Leaf Area Index

Leaf area index (LAI) is the ratio of leaf area to the area of soil surface. LAI is positively correlated with dry matter production and grain yield. At low planting density, the crop canopy is open and LAI is low. Under such conditions leaf size should be large. However, when the crop canopy is closed, the LAI is high, then small leaves are desirable. A larger area of flag leaf (wheat, rice etc.) or ear leaf (maize) would result in higher grain yield. In case of pulses, the trifoliate leaf (as source) and the pod in its axis (as sink) constitute one unit. Here the area of trifoliate leaf would determine the yield of pod borne in its axis. In a comparison of old and new maize hybrids, final leaf number and leaf area index increased from old to new hybrids (Tollenaar 1989).

Maintenance of Crop Canopy

Maintenance of crop canopy involves securing the optimum crop stand and the leaf area. Breeding for drought resistance, lodging resistance, and pest resistance would help maintain the number of plants per unit area. Further the photosynthetic process would be effectively continued until well after the grain filling period.

Leaf Area Duration

Leaf area duration has been found to have the highest positive correlation with grain yield. Nevertheless, the actual measurement of leaf area duration, limited even to flag leaf is totally impractical requiring more work than measuring the yield itself. However, selection should be practiced for longest leaf area duration since such plants are characterized by a long activity of the flag leaf and the top internode, lasting after the spike has turned yellow. This parameter is closely related to resistance to foliar diseases although genotypes with the same levels of disease resistance also show differences in leaf area duration (Duvick 1983).

Tassel Size

Duncan et al. (1967) reported that shading of underlying leaves by maize tassels probably reduces photosynthetic rates and hence the grain yield. The shading effect is small at low plant densities but increases with plant density. Hunter et al. (1969) reported that a large portion of the yield response from detasselling resulted from the elimination of tassel light interception. Simulated small tassel size produced by tassel side branch removal resulted in increasing grain yields. Geraldini et al. (1985) reported that selection for decreased tassel branch number would increase yield as it is negatively correlated with yield.

Awns

The awns of small grained cereal plants are another morphological criterion that might be related to increased photosynthetic activity. Studies on isogenic lines

have shown that awned wheat and barley lines have a higher photosynthetic activity than awnless ones as well as the fact that awns may contribute to increasing yield by up to 10%. The presence of bristles in ears in pearl millet are desirable to protect the grains from bird attack.

Tolerance to Drought

The ability of a crop to grow satisfactorily in areas subjected to water deficits has been termed as drought tolerance. The modification in structure and function that increases the probability that a crop will survive and reproduce in a particular environment is termed as adaptation. The adaptive mechanisms in relation to drought tolerance are:

- Drought escape
- Maintenance of water uptake
- Reduction in water loss

Turner (1982) considered the influence of the adaptive mechanism on crop productivity and concluded that only those mechanisms that aided in drought escape and maintenance of water uptake did not reduce photosynthesis, crop growth and yield. Maintenance of water uptake by the development of deep roots into a wet profile will maintain the assimilation rate of leaves, but the diversion of carbon from new leaves to new roots and the maintenance of a deep root system will ultimately reduce the above ground productive capacity of the plant compared to the one with an adequate supply of water (Passioura 1983). Conversely, the development of water deficits in an indeterminate plant such as cotton may trigger reproductive development at the expense of vegetative development and hence improve yields when water or length of season are limiting (Turner 1986).

Drought Escape

Drought escape is the ability of a plant to complete its life cycle before serious soil and plant water deficits develop. Since sowing is delayed until there is sufficient soil moisture for establishment, one characteristic that enables crop plants to yield satisfactorily is the matching of phenological development with soil moisture supply. In regions with a characteristic terminal drought, short season cultivars enable the crop to escape severe soil water deficits. In an experiment on wheat, barley and triticale cultivars, it was observed that each day of earliness conferred a yield advantage of almost 30 kg ha⁻¹ (Fisher and Maurer 1978). Earliness, however, also reduces the potential yield of the crop by reducing the dry matter at anthesis and the sink size. Fereres et al. (1986) reported that late sown cultivars of sunflower extracted soil water to 270 cm compared to only 180 cm in the short season cultivars. Hence, when roots are not restricted and water availability is deep, drought escape by earliness may restrict yield potential. Development of short season varieties has provided benefits where early season soil moisture is predictable. Under conditions where soil moisture store is less predictable, an extended period of flowering and reproductive development appears to be important.

Maintenance of Water Uptake

Maintenance of water uptake requires the development of roots into water-containing soil and their continued extraction of water in the absence of rain. The growth of roots into deeper soil layers is a function of both genotype and environment. Deeper rooting, i.e., a greater frequency and greater depth of roots, is likely to increase yields by at least 20 to 50% (Jordan et al. 1983). Passioura (1983) suggested that the frequencies of sorghum roots in the deeper profile should be sufficient to extract the available water.

Reduction in Water Loss

Several mechanisms for reducing water loss have been identified.

Reduction in leaf area. Leaf area is more sensitive to water deficit than leaf photosynthesis (Turner 1986; Turner et al. 1986). The sensitivity of leaf expansion to water deficits is a mechanism for reducing water loss since below a leaf area index of about 3, crop transpiration is reduced linearly with leaf area.

Stomatal closure. Stomatal closure provides another mechanism for reducing water loss. In the past decade, the sensitivity of stomata to atmospheric humidity has been widely recognized (Turner 1986). The sensitivity of stomata to vapor pressure deficit may provide an important mechanism for restricting water loss in the middle of the day when atmospheric humidities are low, while maintaining some photosynthetic activity at the times of day when humidities are higher. A singular stomatal behavior is exhibited by plants with crassulacean acid metabolism (CAM) of photosynthesis when grown under water stress. The stomata open during the night and close during the day leading to almost complete exclusion of transpiration.

The role of abscisic acid in stomatal conductance is well recognized. The high or low ABA lines of wheat differed in stomatal conductance, in that the ones with high endogenous levels of ABA had the lower stomatal conductance (Quarrie 1983).

Leaf rolling. The rolling of leaves in graminaceous plants reduce transpiration. The leaf rolling which develops as leaf water deficits develop, postpones dehydration and development of leaf water deficits. In rice cultivars, a greater sensitivity of leaf rolling to leaf water deficits did delay the development of water deficits by 1–3 days, but this was insufficient to have any detectable effect on dry matter production (Turner 1986).

Leaf movement. Alfalfa, cowpeas and beans reduce their water losses by leaf movements which avoid direct solar radiation.

Increased reflection. The development of lines of wheat isogenic for leaf glaucousness has enabled the evaluation of this trait in water use and yield under water limited conditions. Johnson et al. (1983) showed that the glaucous lines reflected more radiation and that this was associated with higher yields under

drought conditions. The presence of reflective waxes on the leaf, leaf sheaths, and heads reduces transpiration, increases water use efficiency, decreases leaf death and increases yield when soil water supply is limited (Richards 1984; Richards et al. 1986).

Breeding for Drought Tolerance

Four basic approaches to breeding for drought resistance are being followed :

Breeding for yield potential. This approach involves breeding for high yields under optimal conditions and then assuming that this will provide a yield advantage under stress environment. Fisher and Maurer (1978) working on bread wheat, durum wheat, triticale and barley found that a high yield potential gave improved yields when the crop was stressed under drought.

Breeding for maximum yield in stress environments. This approach suffers from the problem that water-limited environments are notably variable from year to year, and as a consequence the environmental selection indices and pressures on breeder's populations change drastically from generation to generation resulting in slow breeding progress (Turner and Begg 1981).

Selection for physiological and morphological mechanisms. In the traditional breeding program for high yield in optimal environment, selection should be practiced for several physiological and morphological characters conferring drought resistance (Blum et al. 1983).

Breeding for single character influencing drought tolerance. This approach does not utilize multiple physiological selection criteria, but aims to establish that a single drought resistance character will benefit yield under water limited conditions and then incorporate the character into an existing yield breeding program. Selection for lines of wheat with high endogenous levels of ABA have increased yields by 16 and 10% at two sites, with yields being improved more at the drier site (Quarrie 1985).

Cold Tolerance

Cold stress can be categorized into discrete classes.

Freezing Stress

Results into chlorosis which has adverse influence on maize grain yield (Sharma et al. 1987).

Purpling of Leaves

Leaves become purple in color in some genotypes. However, the purpling did not reduce grain yield except in some instances of extreme purpling (Khehra et al. 1981).

The presence of genetic variability for both freezing as well as chilling tolerance has been reported in maize (Dhillon et al. 1988), tomato (Patterson and Payne, 1983), rice (Kwak et al. 1984) and a number of other crops.

The sources of cold tolerance are available in material from temperate and high altitude regions. Cultivated varieties resistant to frost have been found in wheat, barley (Graffius 1981), Oats (Marshall 1982) and Chickpea (Singh et al. 1990).

Salt Tolerance

Accumulation of excessive soluble salts in the root zone of soils result in partial or complete loss of soil productivity. Soil salinity is a serious problem in areas where ground water of high salt content is the only source of water available for irrigation. Salt affected soils occupy nearly seven percent of the world's land area.

The resistance to salt stress denotes a plant's ability to prevent, reduce or overcome the possible injurious effects caused directly or indirectly by the presence of excessive soluble salts in its root zone.

Response of crop plants to increasing salinity levels reveals about 8-fold differences among species regarding tolerance to salinity stress. Barley, cotton and *Agropyron* species are tolerant to saline conditions as compared to beans.

The allopolyploid species are more tolerant to alkaline and saline soils as compared to their diploid progenitors (Rana 1986). Hexaploid bread wheats were found to be far more tolerant compared to the tetraploid durum and diploid einkorn wheats. Similarly, allotetraploid *Brassica napus* was found to be superior in salt tolerance compared to its diploid progenitors *B. campestris* and *B. nigra*. Allopolyploid species of *Medicago sativa*, *Sesbania grandiflora*, *Chrysanthemum indicum* were also characterized by a high level of salinity/alkalinity stress tolerance. However, in *Gossypium*, there was a reverse trend as the diploid Asiatic species *G. arboreum* and *G. herbaceum* were more tolerant compared to tetraploid species *G. hirsutum* and *G. barbadense*.

Convincing evidences have accumulated over years showing considerable exploitable intraspecific variability regarding tolerance to salinity/alkalinity (Singh and Rana 1984; Noble et al. 1984; Norlyn and Epstein 1984).

The highest level of salt tolerance was found in indigenous cultivars of salt affected areas. Salt tolerant wheat material comprised of selections made from locally adapted Kharchia wheats of Rajasthan. Two lines KR 375 and KR 387 have been extensively used in hybridization programs designed to combine superior salt tolerance with high grain yield potential. The salt tolerance is largely due to the superior ability of genotypes for potassium uptake under competition with sodium.

The maximum tolerance to salinity stress among rice genotypes was found among tall, photosensitive, long duration and coarse-grained cultivars. Efforts to combine this level of tolerance in dwarf and photoinensitive forms through recombination breeding have not succeeded as yet. The breeders are reluctant to use highly salt tolerant traditional cultivars (low yielding genotypes) as donors

because of the likelihood of undesirable linkages and possible disruption of favorable gene combinations. Therefore, it is necessary to undertake prebreeding programs with the objective of obtaining the desired genes for salt tolerance in superior genetic backgrounds and readily acceptable forms.

Disease Resistance

The pathogens causing plant diseases have coevolved with the host plants. During natural selection, susceptible plants were eliminated by the pathogen with the result that only resistant plants were maintained. Then this situation exerted selection pressure on the pathogen so that only the virulent races could survive. Therefore, this process of coevolution has continued since long.

The incidence of diseases cause about 7–10% of the total loss of grain yield. However, sometimes, the pathogen multiplies and attacks the crop plants in an epidemic form resulting in nearly complete crop failures. The most important examples of crop failures due to diseases are those of late blight of potato in Ireland and leaf blight of corn in USA.

Several approaches are being utilized to minimize the losses due to diseases. However, when disease resistant varieties become available, these are preferred to other measures of disease control. The pioneering work on disease resistance was done by Farrer in Australia, Biffen in England and Orton in USA.

The most important achievement in breeding for disease resistance was the elucidation of relationship between pathogen and host by Flor (1956). The Flor's hypothesis, also called gene for gene relationship, states that for every resistance gene in the host there is a corresponding gene for virulence in the pathogen.

Genetic control of disease resistance has been studied for almost all the major diseases. Further, the genetic resistance to diseases is available in several cultivated and wild species from where the plant breeders transfer these to cultivated high yielding varieties.

Reduction in yield losses due to diseases can be brought about by:

Avoidance

This mechanisms reduces the chances of contact between the prospective host tissue and the parasite. The resistance of barley cultivars with closed flowering to loose smut (*Ustilago nuda*) is due to avoidance. Early maturing potato cultivars avoid the attack by late blight pathogen.

Tolerance

Tolerance is the ability of a plant to perform well even though it exhibits the symptoms of a susceptible host. A tolerant plant lacks the ability to prevent the establishment of a pathogen or to retard its development after establishment. On the basis of visual assessment of symptoms, a tolerant plant would be rated as susceptible. Despite the exhibition of disease symptoms, however, the performance of a tolerant plant would be similar to that observed in plants without infection.

Resistance

It is the failure of the pathogen to establish itself successfully in a plant. Several types of resistance reaction have been described (Nelson 1984; Vanderplank 1984).

Resistance to infection. It is also referred to by such terms as hypersensitivity, race specific resistance, vertical resistance, nonuniform resistance, major gene resistance etc. It is the ability of the host to prevent any multiplication of the parasite. The resistant plant uses the toxins to prevent the parasite from invading the plant and thriving on it. The resistant genes operate in a gene for gene relationship with the virulence genes in the parasite (Day 1974).

Resistance to spread. It is characterized by partial resistance, slow rusting field resistance, durable resistance, horizontal resistance, uniform resistance or minor gene resistance. This type is expressed as a reduction in the rate of epidemic build up, occurring in spite of a susceptible reaction to infection. It is rate reducing in nature—it affects the rate of disease increase and thus the terminal amount of disease.

Breeding for Drought Tolerance

Several breeding methodologies have been suggested and are practiced to incorporate disease resistance genes. These are:

Deployment of genes over time. Several cultivars are developed incorporating different genes for resistance to different races. These varieties are then rotated over time. The concept is similar to crop rotation. This will help reduce the soil-borne inoculum of pathogen. However, practically, at any given time very few varieties are at their prime leading to almost an entire area under a single cultivar.

Deployment of genes over space. In countries where a particular crop is under cultivation throughout the area and the inoculum spread along the length and breadth of the country, the resistant genes are deployed over space. The cultivars possessing different genes are cultivated in belts alternated with each other at the same time. This method has been successfully used to control stem rust disease of wheat in USA. In India, the rust resistant varieties of wheat are grown in the foothills to check the spread of inoculum from hills to the plains.

Multiline varieties. The concept of the multiline variety has been developed and put in practice for oats and wheat. Multiline is a mixture of isogenic lines that carry resistance to different races of pathogen. A pathogenic race capable of infecting a certain plant is not capable of causing an epidemic if the neighboring plants are resistant. This is a way of maintaining a stable field resistance of a crop without large negative effects on yield. As the array of races continuously change in prevalence and composition, corresponding changes must be introduced in lines constituting a multiline variety. This has turned out to be a tedious

choice to breeders and seed producers. This method was applied to control crown rust of oats and rusts of wheat.

Pyramiding genes. For the pyramid strategy, the major genes that would be put into individual lines for a multiline are incorporated into a single cultivar. More major genes may be used than are necessary to give adequate resistance to prevalent races of the pest. The diversity of major genes is expected to provide protection against new races that may develop in the pest population. However, a multigene variety is difficult to develop. Secondly, it will encourage evolution of new virulent races of the pest.

Insect Resistance

The increasing complexities of insect pest control in recent years, and the growing awareness of such problems as pest resistance to insecticides, rising costs of insecticides application, destruction of useful insects, accumulation of undesirable residues, environmental pollution, etc., all associated with the large scale use of a broad spectrum of insecticides, have emphasized the critical need for effective control measures which are relatively free of adverse side effects. The use of insect-pest tolerant crop varieties offers one promising possibility.

Crop varieties that are resistant have the unique advantage of providing an inherent control which involves no expense or environmental pollution problems and is generally compatible with other methods of insect control. Resistance to insects can be classified into three categories:

Nonpreference. The plant is unattractive to the insect pest for feeding, oviposition or shelter.

Antibiosis. The host plant has adverse effects on the growth and survival of the insect and its progeny.

Tolerance. The plant can withstand a heavy insect attack and still produce a good crop.

Nonpreference

In field plantings, nonpreferred crop variety frequently escapes infestation and even when insects are caged or nonpreferred hosts, they lay fewer eggs and produce smaller populations than on susceptible hosts.

In cotton, the red color of foliage, combined with hairiness and absence of stem glands, is involved in resistance to cotton boll weevil. Hairiness of foliage increases resistance to cotton jassid and aphid. Hairiness of flower buds was found to impede the feeding of boll weevil and obstruct the movement of pink bollworm larvae (Smith et al. 1975). Conversely, smooth leaved cotton has shown promise for bollworm resistance by reducing sites for oviposition. The frego bract character reduces oviposition by the cotton boll weevil and allows better application of insecticides on flower buds.

Resistance to corn earworm has been attributed in certain varieties to tight kernel husks which help confine the larvae longer in the husks. The solid stems of Rescue variety of wheat result in sawfly eggs being mechanically damaged and desiccated and restrict the movement of newly emerged larvae. The resistance of wheat to cereal leaf beetle depends very much on the size and density of leaf hairs (pubescence). The yield loss on non hairy leaf lines ranged up to 25.6% (Webster et al. 1982).

Elden et al. (1986) found a negative correlation between clones of lucerne with pubescent stems and degree of damage by larvae of potato leaf hopper.

Some wild species of potato contain granular trichomes on their foliage which convey resistance to potato leaf hopper (Tingey and Laubengayer 1986). Such trichomes were also found with some wild species of *Lycopersicon* and play an important role in the resistance to both tobacco hornworm and Colorado potato beetle (Kennedy et al. 1987).

Antibiosis

Antibiosis is considered the most important mechanism which influences or even disrupts one or more of the various stages of an insect's establishment on a plant.

The resistance of lucerne to its pests is attributed to antibiosis caused by higher saponin content, particularly medicagenic acid which is predominant in some resistant varieties. Cotton with a high gossypol content in the flower buds inhibited larval growth and suppressed population of *Heliothis*. The antibiosis against *Heliothis* larvae shown by flower buds of a few wild races of *Gossypium hirsutum* could be explained by the presence of at least three chemicals, called heliocides (Maxwell 1977). Condensed tannin from flower buds of certain *G. hirsutum* lines has been reported to have a strong antibiotic activity against *Heliothis* (Chan et al. 1978). Physiological inhibitors responsible for borer resistance in maize have been identified as DIMBOA (2,4-dihydroxy-7-methoxy-1, 4-benzoxazin-3-one) (Russell et al. 1975). Resistance to Hessian fly in wheat is mainly due to antibiosis as larvae feeding on resistant plants generally die. Hemicellulose and silica content appear to be implicated (Gallun 1978).

Tolerance

Tolerance is attributable to plant vigor and is more or less independent of effects on the insect. Tolerant varieties do not inhibit insect populations and under certain conditions may even be responsible for the build up of larger population than is found on susceptible varieties, which are killed when a certain level of infestation is reached. However, the ability of tolerant plants to survive infestations for a longer period permits a longer exposure of the insects to their natural enemies. Tolerance is frequently valuable in integrated pest management.

Conclusions

An overview of the achievements made till date would indicate that the genotypes cultivated prior to 1960s had less efficient plant types characterized by excessive

vegetative growth with low harvest index resulting in poor grain yields. The late sixties witnessed a quantum jump in yield levels with the development of semi-dwarf cultivars of wheat and rice and of hybrid varieties of sorghum and pearl millet. The semi-dwarf cultivars possessed a relatively more efficient plant type with erect leaves and short stems. These morphological characters coupled with fertilizer responsiveness resulted in significant increase in harvest index and total grain yield. To obtain further increase in yield level we have to analyze our past achievements to identify the areas where progress has been made and also to identify the means through which further progress is possible. The three parameters that can be improved to increase grain yield are production of photosynthates, their translocation and storage. The translocation of photosynthates has been improved in semi-dwarf cultivars by reducing the distance between source and sink and by strong, thick culms. The storage of photosynthates has been improved by improving the sink capacity of the plant, especially of the economic plant part. The increase in production of photosynthates was achieved by increasing photosynthetic area and by maintaining the optimum leaf area index for longer duration by stabilizing LAI against fluctuations caused by biotic and abiotic stresses.

Development of hybrid varieties have resulted in increased yield potential. Hybrid breeding is a common breeding method employed in cross pollinated crops like maize where artificial hybridization is easy. In crops like pearl millet and sorghum where emasculation is difficult, hybrid varieties have been developed by exploiting cytoplasmic genetic male sterility. The first hybrid variety of pearl millet in India, HB 1, was developed at Punjab Agricultural University, Ludhiana. Such a system of pollination control was also utilized in sunflower. Genetic male sterility is available in often cross pollinated crops like cotton and pigeonpea. The first hybrid cotton variety in the world, H4, was developed in India by hand emasculation and pollination. A large number of hybrids in maize, sorghum, pearl millet, cotton and sunflower are being cultivated. In rice, a highly self-pollinated crop, heterosis has been commercially exploited in China utilizing cytoplasmic genetic male sterility. Similar attempts have been made in other self-pollinated crops.

Hence, the total crop production per unit area per unit time can be increased by sustaining the existing yield potential through resistance to biotic and abiotic stresses. The yield potential can be improved by further advancements in the above mentioned areas where some improvement has already been made. Exploitation of hybrid vigor in self-pollinated crops is another alternative approach to break the yield plateau. However, major emphasis needs to be given to the improvement in physiological efficiency of plant, the area that remained neglected in plant breeding in spite of its prime importance. Although indirect selections have been practiced on the basis of morphological characters, but significant progress in physiological efficiency of plants could not be made. Photosynthetically more efficient C_4 system can be exploited. Similarly, water and nutrient use efficiency of plants can be improved.

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Sustainable Land Management Systems for Mitigating Stresses

J.K. Syers and M. Latham

Abstract

The working group on the establishment of a framework for evaluating sustainable land management has defined sustainable land management as "A set of technologies, policies, and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously:

- maintain or enhance production/services;*
- reduce the level of production risks;*
- achieve environmental stability;*
- be economically viable and socially acceptable."*

First of all, we must note that the concept of sustainable land management is broader than that of sustainable agriculture. It "Encompasses agriculture within a framework of environmental resource optimization and land-use planning." Sustainable agriculture is generally viewed as dealing with on-site constraints—at the field level—whereas sustainable land management deals with off-site constraints as well and therefore deals with wider areas at the watershed level.

Management techniques for mitigating stresses need to take into account, the following: (1) proper land-use planning needs to have a sustainable aim in mind; (2) problems of stresses can result from off-site effects as well as from on-site effects; and (3) technologies designed to mitigate stresses need to be adapted to the diversity of the environment and to the socioeconomic constraints of its population.

In terms of research and development, this means that land-use planning needs to: (1) be taken much more seriously than is done at present by research and policy makers/developers; (2) address a whole regional management system with the interaction between the management of each individual systems; (3) offer acceptable and attractive options to farmers and not offer only a single recommendation; and (4) to develop a system of incentives and regulations to enforce sustainable land management.

Introduction

The need to make a more effective and efficient use of land resources is now widely recognized. It is particularly significant that Chapter 10 of Agenda 21 adopted at Rio de Janeiro in June 1992 is concerned specifically with an integrated approach to the planning and management of land resources. Although it is primarily concerned with the concept of environmental sustainability, Agenda

21 is also an important statement on sustainable land management. This is particularly the case for sustainable agriculture, which has emerged as a global issue aimed at securing enhanced productivity and performance, of land resources consistent with minimizing adverse effects on the environment. To achieve this, there is an urgent need to develop and implement appropriate techniques and policies for effective land management, which are sustainable over time.

The Concise Oxford Dictionary (Fifth edition) defines "stress" as a "constraining or impelling force 'and cites' under stress of weather and of poverty," as examples. From the standpoint of sustainable land management, stresses may be viewed as externally-induced constraints which constitute one of the major challenges in establishing sustainable land management systems. As a consequence, there is a need to develop systems which will mitigate stress. At the outset, it is important to establish and identify the cause of the stress if mitigation is to be effective.

Types of Stress

Three modes of stress are singled out for brief comment, namely weeds, soil acidity, and moisture deficit.

Weeds are a major stress in some production systems. In parts of Indonesia along-alang infestation is a very serious problem and in Luang Prabang Province, Laos, a farmer spends some 300 days of each year weeding, placing a major constraint on the area of land which can be cultivated. Sanchez and Benites (1987) concluded that difficulty in weed-control was the single most important factor for the instability of the low-input cropping system at Yurimaguas, Peru in the 3rd year. Clearly, weed control is a priority issue in developing new and improved land management systems and the challenge is to establish an acceptable level of weeds, in a given situation.

Of the soil-related stresses, soil acidity is one of the most important. Soil acidification is a pervasive and insidious process which is present in all countries and agricultural systems. For example, the area of acid soils is increasing in Thailand (Parkpian et al. 1991) and it has been claimed (Ridley et al. 1990) that soil acidification has the potential to decrease the long-term productivity of prime agricultural land in Australia.

Soil acidity has been studied extensively over the years and it is commonly believed that the technology for managing acid tropical soils is reasonably well understood. Regrettably, farmers have yet to adopt this new technology to any meaningful extent and acid-tropical soils, as a result, are very often underutilized for food crop production. Although the development of new aluminum-tolerant cultivars of crop and pasture species should make for more economical agricultural production on acid, infertile soils (Howeler 1991), the fact remains that where serious aluminum and manganese toxicities occur, the use of lime is still the key to increased crop production. Reduced availability to plants, of phosphorus in acid soil, commonly results in phosphorus deficiency, usually resulting in substantial yield reductions. The amelioration of the effects of soil acidity must be given high priority in the development of sustainable land management systems.

Drought stress, particularly moisture deficit, is a major limitation to crop production in many countries of the world. This necessitates farming under conditions of climatic risk. Farmers have often proved to be adept at managing the recurrent risk of drought using a range of techniques, such as opportunity cropping in semi-arid Australia. The techniques include multicropping, which aims to balance the risks depending on the crops or varieties sown, sowing robust varieties and water harvesting from one year to the next, using simple, low-cost schemes, as in southern Africa. In most cases the farmers' strategy is oriented more towards managing risk than towards maximizing crop productivity.

Recent advances in computer modeling of crop growth now make it possible to simulate the effect of climate to the extent that the economic impact of a change in management practice can be predicted with a reasonable degree of reliability. The Proceedings of an International Symposium on "Climate Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics" held in Brisbane, Australia, in 1990 (Muchow and Bellamy 1991) indicate the considerable advances that have been made in this area. Nevertheless, climatic risk is still a "pervasive fact of life that surely exerts a significant if not an overwhelming influence in the determination of the survival of both crops and the humans who depend upon them" (Anderson 1991).

Sustainable Land Management

An international working group on Sustainable Land Management has developed the following definition:

"Sustainable land management combines technologies, policies and activities aimed at integrating socioeconomic principles with environmental concerns so as to simultaneously:

- maintain or enhance production/services;
- reduce the level of production risk;
- achieve environmental stability;
- be economically viable and socially acceptable."

The above four objectives of sustainable land management, which can be summarized as productivity, stability, equitability, and viability, respectively, are the foundations and basic pillars of a Framework for the Evaluation for Sustainable Land Management (FESLM), which is being developed and is briefly discussed below.

In the conceptualization of sustainable land management it is important to emphasize that sustainable agriculture represents only one component, albeit an important component, of sustainable land management.

According to Dumanski et al. (1992) sustainable land management "encompasses agriculture within a framework of environmental resource optimization and land-use." In this regard, off-site effects are particularly important, whether they be effects on adjacent land-use, hydrology, water quality, the atmosphere, or the loss of biodiversity.

The on-site/off-site land management challenge is a very real one which will come under increasing scrutiny as a consequence of Agenda 21. Whereas farmers

and most agronomists think essentially in terms of the field or the plot where the production takes place, most production systems are interactive and the management of one tract of land often has consequences on neighboring tracts of land. It is clear that the off-site effects of production systems cannot be tackled by individual farmers; there is a need for community involvement using appropriate incentives, laws, and regulations.

Coping with Diversity

In establishing sustainable land management systems for mitigating stresses it is important to find systems which are adapted to the physical and socioeconomic constraints of each agroenvironment. In situations where the diversity of land is high, particularly in the tropics subtropics, there is no single recipe which can cope with all of the constraints. What is required is a range of solutions from which the farmer can choose the best option.

Small farmers often cope well with diversity by varying the crops grown in both space and time, as shown by Conway and his Thai co-workers in the Chiang Mai Valley (Chiang Mai University 1980). Unfortunately, diversity is often seen as a constraint. Either it tends to be overlooked, often resulting in major problems for development schemes, or is compensated for by farmers by varying fertilizer, tillage, and irrigation inputs.

In high-input agriculture in the temperate zone, the comparatively low cost of producing food with inexpensive inputs has often resulted in land degradation and pollution problems. In recent years, the environmental costs of such production systems in terms of water pollution, the production of greenhouse gases (such as CH_4 , N_2O , etc.), and of increased flood risks due to the removal of natural buffers have placed increasing pressures on farmers to use technologies which are more environmentally friendly. Consequently land management systems must be adapted to land diversity by tailoring the systems themselves and the inputs involved to be in tune with land characteristics and to mitigate the potential environmental risks.

Need for Land-use Planning

Recognition of the different stresses which must be accommodated and the complexity of issues involved in sustainable land management, particularly the off-site effects and the need to cope with diversity, point to the vital importance of developing a land-use plan which is based on reliable information on land form, soil, climate, vegetation, and socioeconomic constraints. A proper land-use plan should provide different options at various levels of stress and production, giving a desirable measure of flexibility. Such an approach requires the development of quantitative indices which enable evaluation of interactions between the different production systems proposed. A proper land-use plan should consider not only production aspects, but also issues of sustainability, such as equity for users, environmental considerations and provision for future needs. To implement the land-use plan it will be necessary to create incentives and to introduce appropriate laws and regulations to achieve success. While the

challenges and difficulties in bringing this about should not be underestimated, the need at present is great and the potential rewards substantial.

Evaluation for Sustainability of Land-use Management

Having developed a land-use plan, and specifically in the present context, involving land management systems for mitigating stresses, it is necessary to evaluate the effectiveness of such a plan and in particular, the probability of achieving sustainability.

An important outgrowth of the International Workshop on "Evaluation of Sustainable Land Management in the Developing World" held at Chiang Rai, Thailand, in September, 1991, was the formation of an international working group dedicated to developing a Framework for Evaluation for Sustainable Land Management. A framework approach offers the potential for evaluating the sustainability of land management (Dumanski et al. 1992). The Framework is being developed and evaluated by the International Board for Soil Research and Management (IBSRAM), in cooperation with Agriculture Canada, Food and Agriculture Organization, International Fertilizer Development Center, International Society of Soil Science, and Trop Soils CRSP. Of late, the group has been expanded to include the International Center for Research in Agroforestry and Tropical Soil Biology and Fertility Programme.

The Framework is being designed to function as a logical pathway for the analysis of sustainability or the probability of sustainability being achieved. It aims to link and use the economic, social, and environmental conditions which determine sustainability. As presently conceived, the Framework aims to provide a scientifically sound, logical, and stepwise procedure, not only from an assessment angle but would also allow for the identification of important controls on, and constraints to, sustainability, thus offering the potential for manipulation of the system. Diagnostic criteria, and indicators and thresholds which identify the status or condition of the diagnostic criteria, facilitate assessment of the extent to which a system can be judged to be unsustainable.

The Framework is currently being subjected to a detailed evaluation by IBSRAM and its collaborators using case studies in different agroecological and social environments. As new information and experience become available, the Framework will inevitably require modification and fine tuning. There are indications that it can assist in identifying how new technologies of land management, including the application of biotechnology, can best be deployed to develop innovative strategies and policies for agriculture, consistent with maintaining environmental quality, and which are in support of sustainable land management.

Concluding Thoughts and Research Needs

Sustainable land management is not just an issue for developing countries where degradation of the land is accelerated by nil or inadequate inputs, particularly of nutrients, although it is recognized that stresses are often more accentuated in these countries. In contrast, in developed countries degradation can arise from

excessive inputs which may also have adverse effects on the environment. Although a reduction in inputs is an option for developed countries, this is not the case for many countries in the Third World where only low or zero inputs are used for crop production. In developing technological options for sustainable land management and alleviating stresses, a clear distinction must be made between those required for developing countries as compared to those required for developed countries (Lal and Pierce 1991).

The need for more research on land management systems is repeatedly emphasized. What is really required is appropriate research, which pays adequate attention to the needs of all users and particularly takes into account the attitude and aspirations of farmers. Fujisaka (1992) listed inappropriate innovation and incorrect identification of the adoption domain as two of the several reasons for nonadoption of new techniques by farmers in upland agriculture in Asia.

Significantly, the World Commission on Environment and Development (1987) in its report "Our Common Future," pointed to the need to include farmers in applied agricultural research, if practical recommendations are to be adopted. As emphasized by Bentley (1991) "it is pointless to continue to develop research outputs, with potentials to increase agricultural production, if those potentials are not going to be realized more adequately than they are currently, because of soil degradation or because of a lack of effective programs for on-farm validations and to promote their adoption by farmers." This message has never been more relevant than it is today.

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Managing Water Resources to Improve the Sustainability of Dryland Farming Systems

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Abstract

Approximately 40% of the world's land area consists of arid and semiarid regions that are inhabited by more than 700 million people, many of whom are subsistence-type farmers. These regions produce most of the world's food grains, although yields are often very low. In some countries of the near east, sub-Saharan Africa and South Asia foodgrain production per capita had declined dramatically during the last decade. Much of this decline can be attributed to the continuing degradation of often fragile and marginal lands from soil erosion and nutrient depletion, and the concomitant loss of soil productivity in these dry environments. Crop residues provide the most practical and effective means of controlling soil erosion by wind and water, and of enhancing infiltration and storage of rainfall in the soil profile. Conservation tillage or reduced tillage helps to maintain crop residues at the soil surface which reduced runoff, evaporation, energy use, and mechanical disturbance of the soil. This helps to promote effective soil and water conservation practices which, in turn, offset soil degradative processes and maintain soil productivity at an acceptable level. Many strategies are discussed for managing on-farm water resources to improve the sustainability of dryland farming systems.

Introduction

About 40% of the world's land area is comprised of arid and semiarid regions that are inhabited by more than 700 million people. Approximately 60% of these drylands are in developing countries that produce most of the world's food grains including sorghum, wheat, barley, pearl millet, chickpea, pigeonpea, cowpea, and groundnut. Crop yields, however, are very low compared with those obtained in the higher rainfall zones. In some countries of the sub-Saharan Region of Africa and the near east, foodgrain production per capita has declined markedly during the past decade. While a part of this decline can be attributed to large increases in population, severe drought, and unfavorable agricultural production and marketing policies of national governments, improper and exploitive farming practices are also responsible, largely, for the decline in food production. Such practices have accelerated the degradation of agricultural lands by both wind

and water erosion, and depletion of organic matter and nutrients which, in turn, have resulted in a concomitant loss of soil productivity (FAO 1986; Dregne 1989; Parr et al. 1990a; Unger et al. 1991). In the United States today, and indeed worldwide, soil erosion by wind and water, and the resultant loss of soil productivity and impaired soil quality, continues to be one of our most serious agricultural and environmental problems (Larson et al. 1990).

Many of the soils in dryland areas are used only marginally for crop production. They are often coarse-textured, sandy, and inherently low in fertility, organic matter, and water-holding capacity. They are also often poorly managed with little or no utilization of soil and water conservation practices. Such soils are highly susceptible to degradation by wind and water erosion. In India, some 45% of the total crop production now comes from drylands. By the year 2000, this will have to be increased to 60% if India is to provide adequate food and fiber for a projected population of one billion people. The same situation exists in the West Asia/North Africa Region where, by the year 2000 AD, more than 70% of the food and feed deficit must come from increased yields on existing croplands because there is no other land available for agricultural development (Steiner et al. 1988; Singh 1989; Parr et al. 1990a).

This chapter discusses the dynamics of soil productivity, the relationship of soil quality with alternative and sustainable agriculture, the value of crop residues in conserving soil and water resources, and considers some strategies for improving the sustainability of dryland farming systems.

The Dynamics of Soil Productivity

Soil productivity has been defined as:

"The capability of soil for producing a specified plant or sequence of plants under a defined set of management practices. It is measured in terms of outputs or harvests in relation to the inputs of production factors for a specific kind of soil under a physically defined system of management" (USDA 1957).

Figure 1 illustrates an important relationship that is often overlooked, i.e., for most agricultural soils, degradative processes such as soil erosion, nutrient runoff losses, and organic matter depletion are going on simultaneously with the beneficial effects of conservation practices such as crop rotations, conservation tillage, and recycling of animal manures and crop residues (Hornick and Parr 1987). As soil degradative processes proceed and intensify, soil productivity decreases concomitantly. Conversely, soil conservation practices tend to slow these degradative processes and increase soil productivity. Thus, the potential productivity of a particular soil at any point in time is the result of ongoing degradative processes and applied conservation practices. Generally, in arid and semiarid environments the most serious degradative processes are soil erosion and associated depletion of plant nutrients and organic matter.

On the best of agricultural soils—that is soils which are gently sloping, medium-textured, well-structured, and with a deep, well-drained profile—a high level of productivity can be maintained by relatively few, but essential

conservation practices that readily offset most degradative processes. However, on marginal soils of limited capability, such as steeply sloping, coarse-textured, poorly-structured soils depleted of nutrients, and with a shallow, poorly-drained profile, soil conservation practices must be maximized to counteract further degradation. Thus, a truly sustainable farming system is one in which the beneficial effects of various conservation practices are equal to or exceed the adverse effects of degradative processes. Organic wastes and residues offer the best possible means of restoring the productivity of severely eroded agricultural soils or of reclaiming marginal soils (Hornick and Parr 1987; Parr and Hornick 1992).

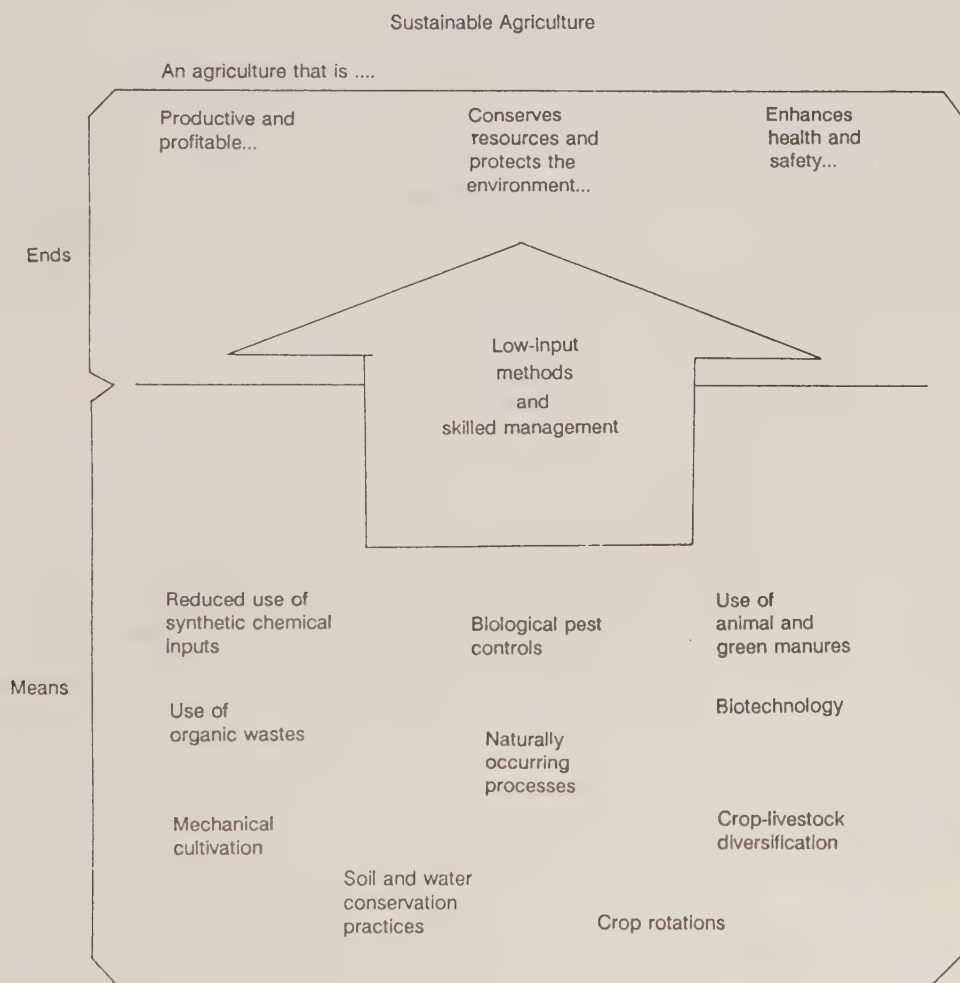


Figure 1. A current concept of sustainable agriculture in the USA showing the ends or objectives and the means of achieving them through low-input methods and skilled management

The Concepts of Agricultural Sustainability and Alternative Agriculture

Sustainable agriculture is increasingly being viewed as a long-term goal that seeks to overcome problems and constraints that confront the economic viability, environmental soundness, and social acceptance of agricultural production systems both in the US and worldwide. While there are many definitions of sustainable agriculture, most of them include the same elements of productivity, profitability, conservation, health, safety, and the environment, differing only in the degree of emphasis. Furthermore, "sustainable" implies a time dimension and the capacity of a farming system to evolve and endure indefinitely (Lockeretz 1988).

The Agricultural Research Service (USDA) defines sustainable agriculture as: "Agriculture that for the foreseeable future will be productive, competitive and profitable, conserve natural resources, protect the environment, and enhance public health, food quality, and safety."

The US Congress (1990) in drafting the 1990 Farm Bill defined sustainable agriculture as:

"An integrated system of plant and animal production practices having site-specific application that will, over the long-term:

- Satisfy human food and fiber needs
- Enhance environmental quality and the natural resource base
- Make efficient use of nonrenewable resources
- Utilize natural biological cycles and controls
- Improve the economic viability of farming systems
- Enhance the quality of life for farmers and society as a whole."

The relationship between sustainable agriculture and alternative agriculture is illustrated in Figure 1. The ultimate goal or ends of sustainable agriculture is to develop farming systems that are productive and profitable, conserve the natural resource base, protect the environment, and enhance health and safety. Alternative agricultural practices provide the best means of achieving this goal. The National Research Council (1989) defined alternative agriculture as a system of food and fiber production that applies management skills and information to reduce input costs, improve efficiency, and maintain production levels through such practices and principles as:

- Crop rotations in lieu of monoculture
- Integrated crop/livestock systems
- Nitrogen fixing legumes
- Integrated pest management
- Conservation tillage
- Integrated nutrient management
- Recycling of on-farm wastes as soil conditioners and biofertilizers.

A US House of Representatives Report (1988) considered low-input or alternative agricultural practices as promising strategies for preventing groundwater

pollution and lowering the farmers' production costs. The report implied that these goals could be achieved by reducing, or largely excluding, the use of chemical fertilizers and pesticides. Thus, alternative agriculture seeks to optimize the use of internal production inputs (i.e., on-farm resources) and skilled management in ways that provide acceptable levels of sustainable crop yields and livestock production, and result in economically profitable net returns (Parr et al. 1990c; Reganold et al. 1990). This approach emphasizes such cultural and management practices as crop rotations, use of animal and green manures, and conservation tillage to control soil erosion and nutrient losses. The authors emphasize here that the single most important component of a sustainable agricultural system is skilled management.

In the United States, "sustainable agriculture" has become the ultimate goal. How we achieve this goal will depend on creative and innovative conservation and production practices that provide farmers with economically-viable and environmentally-sound alternatives or options in their farming systems. While low-input/sustainable farming systems may be feasible in developed countries, it is likely that inputs in many developing countries will have to be increased substantially to raise the production potential above the subsistence level before meaningful agricultural sustainability can be achieved.

The Concept of Soil Quality

Various physical, chemical, and biological properties of a soil interact in complex ways to determine its potential fitness or capability for sustained production of healthy, nutritious crops. The integration of growth-enhancing factors that make a soil productive has often been referred to as "soil quality." The Soil Science Society of America (SSSA 1984) defines soil quality as an inherent attribute of a soil which is inferred from soil characteristics or indirect observations (e.g., compactability, erodibility, and fertility). Thus, soil quality has traditionally focused on, and has been equated with, soil productivity. More recently, the concept of soil quality has been broadened to include attributes of food safety and quality, human and animal health, and environmental quality (Parr et al. 1992). In view of this, soil quality might be defined as:

"The capacity or capability of a soil to produce safe and nutritious crops in a sustained manner over a long-term, and to enhance human and animal health, without impairing the natural resource base or adversely affecting the environment."

Although not well understood, soil quality may also play a major role in plant health and in the nutritional quality of the food that is produced. Thus, if properly characterized, soil quality should serve as a measure or indicator of changes in (a) the soil's capacity to produce optimum levels of safe and nutritious food, and (b) its structural and biological integrity, which can relate to the status of the certain degradative processes, as well as environmental and biological plant stresses.

Soil quality can decline through all of the degradative processes that are cited in Figure 2. Thus, soil quality is directly related to the state of soil degradation which can also be defined as the time rate of change in soil quality (Parr et al. 1992). The maintenance or restoration of soil quality is highly dependent on organic matter and an array of beneficial macroorganisms and microorganisms that it supports. The proper and regular addition of organic amendments such as animal manures and crop residues can effectively offset many of these degradative processes. It is also the best and most expedient means of developing a biologically-active soil that requires little energy for producing crops; increases the resistance of plants to pests and diseases; and enhances the decomposition of toxic substances such as residual pesticides (Sampson 1931; Hornick and Parr 1987; Parr et al. 1992).

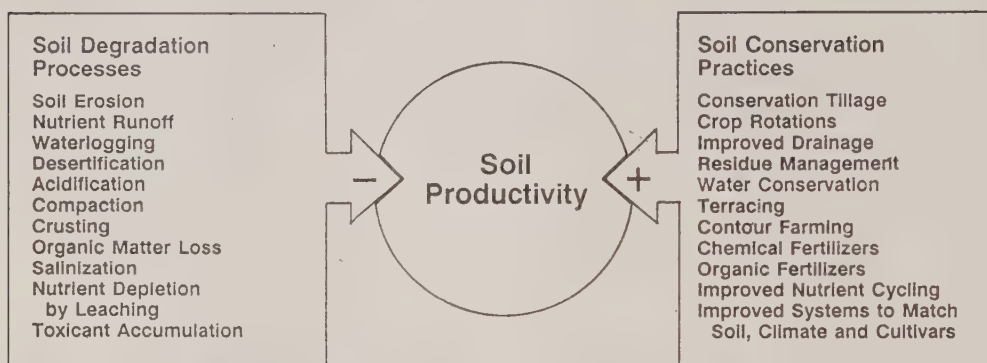


Figure 2. Relationship of soil degradative processes and soil conservation practices (Hornick and Parr, 1987)

Soil Quality: The Linkage between Alternative Agriculture and Sustainable Agriculture

It has been mentioned earlier that soil quality is now considered by many in a broader context than just soil productivity; i.e., the concept of soil quality should include the attributes of food safety and quality, human and animal health, and environmental quality. It follows then, that the best means of improving and maintaining soil quality are alternative agricultural practices such as crop rotations, recycling of crop residues and animal manures, reduced input of chemical fertilizers and pesticides, and increased use of cover crops and green manure crops, including nitrogen fixing legumes. All of these help to maintain a high level of soil organic matter which enhances soil tilth, fertility, and productivity, while protecting the soil from erosion and nutrient runoff. Effective implementation of these alternative agricultural practices using a holistic or systems approach requires skilled management and innovativeness by the farmer.

A conceptual diagram of how the attributes of soil quality provide a vital link between the strategy of alternative agriculture and the ultimate goal of sustainable agriculture is shown in Figure 3. Soil quality occupies a pivotal position in this concept. Indeed, many would agree that soil quality is the "key" to agricultural sustainability.

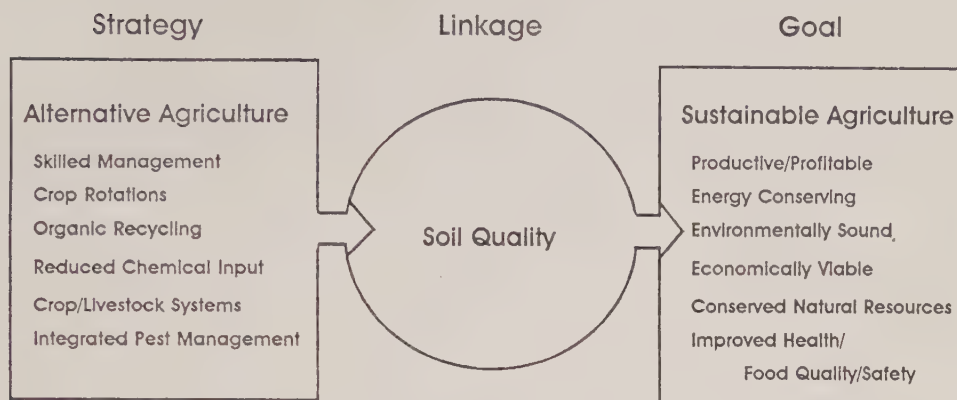


Figure 3. A conceptual diagram that illustrates how the attributes of soil quality provide a link between the strategy of alternative agriculture and ultimate goal of sustainable agriculture

Conservation Tillage: Perspectives and Practices

In recent years there has been considerable research conducted to develop and adapt conservation tillage systems for erosion control and water conservation. Conservation tillage systems mainly reduce mechanical disturbance of the soil and maintain crop residues on the surface to reduce runoff and evaporation, wind and water erosion, and energy use. According to the Conservation Technology Information Center (CTIC) in West Lafayette, Indiana, USA, conservation tillage is defined as:

"Any tillage and sowing system that maintains at least 30% of the soil surface covered by residue after sowing to reduce erosion by water, or where soil erosion by wind is the primary concern. This maintains at least 1000 pounds of flat, small grain residue equivalent per acre (1120 kg ha⁻¹) on the surface during the critical erosion period."

Management practices used range from several tillage operations for weed control and seedbed preparation, to one-pass no-till sowing. Conservation tillage mainly excludes conventional clean tillage operations that invert the soil and bury crop residues.

According to estimates by the CTIC, the average reduction in soil erosion for conservation tillage systems is about 50% of that for most conventional tillage practices (Brosten 1988). However, the range may vary from 30 to 90% depending on the particular type of conservation practice, and factors such as the soil type and previous tillage system. For example, no-till with a substantial residue cover may reduce erosion by 90% or more, whereas stubble mulching may be considerably less effective (e.g., only 30 to 40%) compared with clean cultivation.

Potential Value of Crop Residues for Water Conservation

Water conservation is the single most important practice in dryland or rainfed

cropping systems. The value of surface mulches for water conservation is well documented and depends on a number of factors. First, relatively small amounts of residues are effective in enhancing infiltration by slowing runoff and minimizing surface crusting, but greater amounts are necessary to significantly reduce evaporation. Second, surface residues are most effective in slowing evaporation during the rainy season and have much less effect on evaporative loss after the soil surface layer dries, unless unusually heavy amounts of residues are present. Surface retention of stubble may also improve the structure of soil in the shallow layers which can markedly improve infiltration. Other factors affecting the ability of residues to conserve water include residue color, surface configuration (standing vs. flat, etc.), stubble height, and rate of decomposition (Papendick and Parr 1989).

Greb (1983) summarized the results of long-term field experiments conducted at several locations in the Great Plains USA, on soil water gains during fallow for different mulch rates of small grain residues. At most locations the cropping system was alternate wheat-fallow. Results at North Platte, Nebraska USA (Table 1) showed that increases in soil water from the mulches were significantly proportional to the amounts of surface residues over the range of 2.2 to 6.6 t ha⁻¹. During the period from 1936 to 1977, the average wheat yields in the central Great Plains USA increased from 750 kg ha⁻¹ to 1800 kg ha⁻¹. According to Greb (1979), improved water conservation practices and technology accounted for 45% of the increase. Other production inputs and their estimated contribution to this yield increase were improved wheat varieties (30%), harvesting equipment (12%), sowing equipment (8%), and fertilizer practices (5%).

Table 1. Increase in soil water storage from straw mulch during a one-year fallow period and expected increase in grain and straw yield of wheat at North Platte, Nebraska, USA¹

Mulch rate (t ha ⁻¹)	Water gain (mm)	Yield increase	
		Grain (%)	Straw (%)
2.2	28	0.4	0.6
4.4	51	0.7	1.0
6.6	69	0.9	1.4

1. Source: Greb (1983).

The gain in stored water from surface mulches results in significant increases in crop yields. In the Pacific northwest USA, which has a winter precipitation climate, each mm of stored water above a threshold level of 100 mm (amount required to get the crop to grain production stage) will produce an average of 16 kg ha⁻¹ of grain and 24 kg ha⁻¹ of straw (Leggett 1959). Water use efficiencies are somewhat lower in the Great Plains USA, where most of the precipitation occurs during the summer months. Table 1 shows the amount of water conserved

with straw mulch during fallow at a central Great Plains location (500 mm average annual precipitation). The expected increase in grain and straw yields from each additional mm of stored water was 13 kg ha⁻¹ of grain and 20 kg ha⁻¹ of straw. A mulch rate of about 3 t ha⁻¹, which would be produced by a wheat crop yielding approximately 2 t ha⁻¹ of grain, would increase the grain and straw yields of the following wheat crop by about 0.5 and 0.75 t ha⁻¹, respectively. However, this does not include the long-term benefits to the soil such as improved tilth and increased crop yields from repeated additions of residues.

In studies in the USA, it has been found that, the benefit of residue mulch for water conservation is more from evaporation suppression and is less from runoff control. There are many situations, for example, in West Africa where runoff losses, especially from the first rains after a long dry season, may reach up to 70% of the total rainfall (Roose and Piot 1984). There are many farmers well aware of the benefits of small quantities of surface residues in enhancing infiltration and markedly reducing these large runoff losses. One reason for this is that residues enhance termite activity. These soil insects bore stable channels to the surface to access the litter for food which, in turn, allows water to readily percolate into the subsoil layers.

Potential Value of Crop Residues for Erosion Control

One of the basic principles in controlling wind and water erosion is to keep the soil protected with surface residues. Flattened or nonstanding residues are more effective in dissipating raindrop impact and slowing runoff than vertical cover, and hence more effective for water erosion control. Nevertheless, soil loss caused by either wind or water is directly related to percent surface cover. The relationship between the soil loss ratio (i.e., the ratio of soil loss from residue-covered soil to that of bare soil) and percent surface cover is quite similar for both wind and water erosion as shown in Figure 4. These data show that small quantities of residues are highly effective in the control of both wind and water erosion. For example, approximately 1 t ha⁻¹ of wheat straw uniformly distributed on the surface would provide about 50% surface cover. According to Figure 4, this amount would reduce both wind and water erosion to about 20% from that of bare soil. The data indicate that when surface cover is less than 30%, residues are more effective in controlling water erosion than wind erosion. The reverse is true when the residue cover exceeds 40%.

Crop Residue Management for Sustainable Crop/Livestock Production

Scientists generally agree that the return of crop residues or other organic materials on a regular basis is essential to maintain the long-term productivity of most agricultural soils. Residue management along with good weed control can markedly influence water conservation and crop yields. For example, wheat yields in the drylands of western Nebraska USA, doubled from 0.7 to 1.5 t ha⁻¹ during the late 1930s when stubble grazing was eliminated, and mulch tillage and improved weed control were introduced in the wheat-fallow cropping system

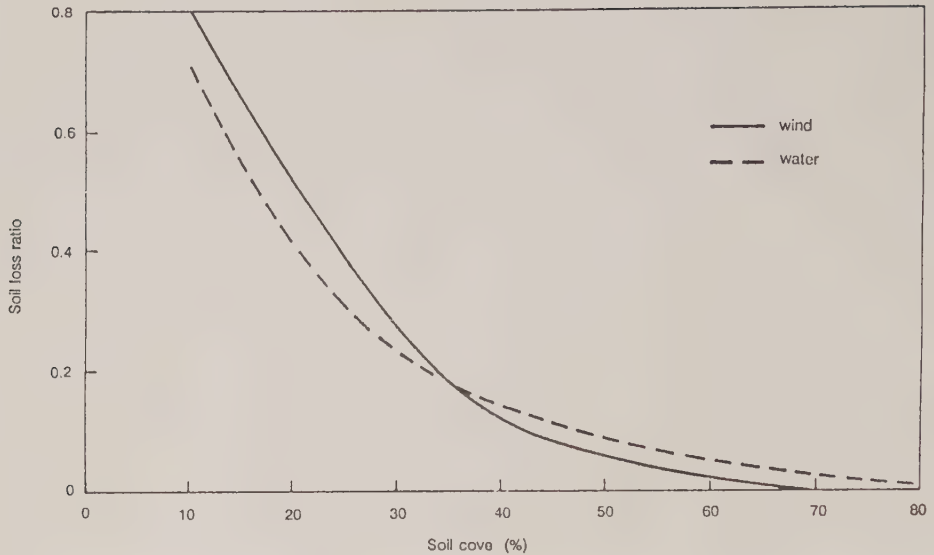


Figure 4. Relationship between Soil Loss Ratio (SLR) and Percent Surface Cover. The SLR is the ratio of soil loss from residue-covered soil to that of bare soil. Adapted from Laflen et al. (1981) for water erosion and Fryrear (1985) for wind erosion

(Fenster 1989). Fertilizer usage was an important but secondary factor contributing to this yield increase. The removal of animals from cropland resulted in more surface cover and, coupled with good weed control, substantially increased the infiltration and storage of water. This, in turn, produced higher yields and more crop residues for additional water conservation. The practice of excluding livestock from land devoted to cereal grains production is common throughout most of the drylands in USA today.

Although the benefits of crop residues for soil and water conservation are widely recognized, the scarcity of this material in many developing countries has made it virtually impossible to apply mulch farming on a practical basis. In most dryland regions, crop residues are utilized almost entirely for forage by ruminant animals, building materials, or for fuel. Little or none is returned to the land to maintain or enhance soil productivity. The intensive grazing with animal traffic leaves the soil bare and compacted between crops, and highly vulnerable to wind and water erosion. The removal of crop residues is also costly in terms of water loss through increased runoff and evaporation when precipitation occurs (Parr et al. 1990b). Retention of surface stubble reduces wind and water erosion which in turn helps to sustain long-term soil productivity.

Where animals are an integral part of the farming system, as in most dryland regions, research is needed to determine the agronomic and economic value of crop residues for soil and water conservation and for animal feed. We need to know what trade-offs are possible to optimize the production of both crops and livestock while at the same time sustaining the soil resource base (Papendick and Parr 1989; Parr et al. 1989; Papendick et al. 1993).

Conclusions

The single most important consideration in achieving a more sustainable dryland or rainfed agriculture is skilled management to ensure that all components are integrated into a holistic system, and that decisions are made with regard to timeliness and precision. Future research needs to focus on the integration of management practices to restore and protect the soil resource base, and at the same time enhance farm productivity and profitability. Other goals of sustainable agriculture include energy conservation, safeguarding human and animal health, ensuring food safety and quality, and improving the economic and social well-being of rural communities. Research is needed to develop methodologies for determining indicators, by which agricultural sustainability can be reliably quantified. Other research needs include identifying barriers or constraints that limit the development and adoption of sustainable agricultural systems; defining scientifically-based criteria for designing sustainable systems; and developing methods and procedures for integrating modern scientific technologies into productive, profitable, and sustainable crop and livestock enterprises.

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Tillage and Land Management as a Means to Mitigate Stresses Constraining Sustainable Agriculture

S.C. Gupta and J.F. Moncrief

Abstract

Two important constraints to sustainable agriculture in stressed environments such as the semi-arid tropics are: (1) the soil water loss due to evaporation and (2) the loss of fertile top soil and the associated nutrients due to soil erosion. This chapter discusses the role of tillage technologies, especially conservation tillage practices that leave part of the residue at the soil surface to help minimize the above mentioned constraints, in sustainable agriculture in the semi-arid tropics. This chapter also outlines research needs for assembling knowledge about existing tillage practices in various parts of the semi-arid tropics, synthesizing this knowledge into one or more expert systems, and using computer models in association with the long-term climatic data base to assess the long-term suitability of a given tillage system on crop and soil sustainability.

Introduction

"Sustainable Agriculture" means different things to different people. According to Lockeretz (1988), sustainable agriculture is a loosely defined term that encompasses a range of strategies for addressing many problems facing agriculture worldwide. These problems include loss of soil productivity from excessive erosion and associated plant nutrient losses; surface and groundwater pollution from pesticides, fertilizers, and sediments; impending shortages of nonrenewable resources; and low farm income from depressed commodity prices and high production costs.

Baier (1989) briefly reviewed definitions of agricultural sustainability as outlined by the Technical Advisory Committee of the Consultative Group of the International Agricultural Research Centers (FAO 1989), and the definition proposed by the Research Branch of Agriculture Canada. In all these definitions of sustainable agriculture there are at least two common elements: (1) increased crop productivity and (2) better environmental quality. In some definitions, there is more emphasis on crop productivity, whereas in the other definitions there is more emphasis on environmental quality. Irrespective of the emphasis in a definition, the sustainable agriculture concept started because of the concern in

degradation of our natural resources like soil and water. Therefore, this chapter focuses on the role of tillage in the sustainability of natural resources in a stressed environment.

Tillage

Tillage refers to the manipulation of soil by an implement powered by humans, animals or machines (Schafer and Johnson 1982). During tillage, soil is fractured and sometimes turned over leading to rough surface conditions. The purpose of tillage is to prepare a seedbed; break weed, insect and disease cycles; bury plant residues from the previous crop to give a neat appearance; allow for soil incorporation of fertilizers and amendments; break surface crust to increase water infiltration; and fracture plow pans or indurated horizons due to soil genesis to allow for deeper penetration of water and plant roots (Jones et al. 1990). Although tillage has many of the above advantages, it also has some disadvantages such as the tendency to increase water and wind erosion, loss of plant nutrients with soil sediments and organic matter, increased evaporation and degradation of soil structure.

Conservation Tillage

Since the dust bowl days of the 1930s in the US there has been an emphasis on methods and management techniques that conserve soil. During the 1950 to 1960 period, conservation techniques included contour terraces, grass water ways, shelter belts, and strip cropping. These efforts were more directed towards minimizing gully and sheet erosion. The underlying principles in these techniques were to slow the runoff velocity and to shield the soil surface from wind and rain (Sprague 1986). In general, these conservation methods are expensive to maintain and interfere with other farming practices.

As chemicals became available to control weeds, insects and diseases in the 1970s, more efforts were directed towards tillage and land management techniques that minimized soil erosion and were also sustainable. The basis for this newer technology was to limit mechanical disturbance to control soil erosion, use previous crop residues to reduce runoff amount and velocity and in turn increase water infiltration. In these conservation tillage systems, herbicide and cultural weed control techniques were used to control weeds. The added advantage of this newer technology was more efficient use of energy.

Soil inversion tillage involves the use of moldboard or disk plows to invert the upper soil profile sufficiently to bury or incorporate materials on the soil surface. Conservation tillage systems on the other hand, loosens the surface layer with variously shaped disks, sweeps, or chisel points, prior to seed placement. In this tillage systems, some plant residues are buried to shallow depths, while the remainder shield the soil surface as the crop becomes established. No-tillage systems rely on herbicide use for weed control and as little tillage as possible to provide good seed placement (Sprague 1986). The latter two systems collectively have been referred to as conservation tillage or residue management systems.

Constraints to Sustainable Agriculture in Stressed Environments

Two important constraints to sustainable agriculture in stressed environments such as the semi-arid tropics are the soil water loss due to evaporation and the loss of fertile top soil and the associated nutrients due to soil erosion. In stressed environments, like that of the semi-arid tropics, the disadvantages of tillage could be more severe if proper tillage is not followed in concert with the climate. For example, in degraded lands, tillage before the onset of rains could further erode the soil resource. Similarly in the semi-arid tropics tillage at an inappropriate time could enhance soil evaporation and thus further aggravate the limited availability of water for crops. On the other hand, tillage in concert with the climate could help capture more rainwater for infiltration, conserve existing soil moisture and reduce soil erosion.

This chapter discusses how soil inversion and conservation tillage techniques can help achieve the above objectives. The chapter also outlines research needs: (a) for assembling knowledge about existing tillage practices in various parts of the semi-arid tropics, and synthesizing this knowledge into one or more expert systems, and (b) to use plant growth and environmental quality computer models in association with the long-term climatic data bases to assess the long-term suitability of a given tillage practice for crop and soil sustainability.

Tillage Effects on Water Availability

Tillage and land management influence water availability for crops are through their effects on (a) water retention at the soil surface, (b) water infiltration and surface runoff, (c) water retention and storage in the soil profile, and (c) soil water evaporation (Unger and Stewart 1983). The following discussion briefly reviews the effects of tillage practices on these factors.

Water Retention at the Soil Surface

Tillage can be used to manipulate soil surface conditions that encourages surface retention of rainwater and thus promotes greater infiltration even in soils that are slowly permeable. Burwell et al. (1966) showed that the primary effects of tillage on soil physical properties was to increase surface roughness and tillage induced soil porosity. Most primary and some secondary tillage practices produce a roughened soil surface. Depression in the rough surface can substantially improve water storage provided these depressions are not connected or cultivation is done along a contour. The principle of nonconnected depression, like tied-ridges or scoop-tillage has been used to increase infiltration of rainwater by increasing its residence time at the soil surface. Since labor is relatively inexpensive and plentiful in the semi-arid tropics, adoption of such practices can be useful in increasing soil water storage. However, one must consider these practices with soil type and climatic conditions. These practices will be only effective if precipitation amount is less than the storage capacity of depressions. Precipitation greater than the storage capacity will become runoff and could lead to an even increased soil erosion since the soil has been mechanically disturbed.

Infiltration and Surface Runoff

It is well known that bare soils are more prone to surface sealing which in turn reduce infiltration of rainwater and thus greater runoff. Generally, surface sealing is much more noticeable in soils that are high in silt content. Using simulated rainfall it was shown that irrespective of the tillage practice final infiltration rates were higher in soils that had surface cover than soils that were bare. Surface cover reduces raindrop impact energy which in turn reduces soil detachment, a prerequisite to the development of surface seal.

It has been consistently shown that tillage systems that leave part or all the crop residues from the previous crop at the soil surface help increase water infiltration and reduce runoff (Onstad 1972). A wheat straw mulch of 0.56 t ha⁻¹ (34% surface cover) reduced runoff velocity to less than half that on a bare soil on a moderately permeable Fox loam (Typic Hapludalf) with a 15% slope. Onstad (1972) showed that, runoff (average of five years) from a silty clay loam soil with about 6% slope at Madison, SD, decreased by over 50% in the presence of surface mulch.

Increased infiltration due to the presence of residue mulch in conservation tillage or no-tillage systems is due to (a) reduced surface sealing, (b) reduced overland flow velocity and increased residence time for rainwater, and (c) presence of macropores due to enhanced activities of soil fauna like earthworms. Increased activity of soil fauna in conservation tillage systems results from (a) the presence of a food source at the soil surface, and (b) a decrease in soil disturbance by tillage.

Water Retention and Storage

Water retention in the soil profile depends upon its porosity and hydraulic properties. Soils underlain at shallow depths by natural or tillage induced layers impede water infiltration and decrease water availability for subsequent plant growth (Unger and Stewart 1983). Soils with dense clay layers or plow pans slowly recharge and may never reach their potential water-holding capacity unless the impeding layers are loosened by tillage. However, the loosening process must consider climate (timing and amount of precipitation) and crop characteristics like rooting depth. Subsurface tillage that drastically increases soil hydraulic conductivities could lead to excessive drainage and loss of nutrients due to leaching.

Soil Water Evaporation

Another factor that can be manipulated through tillage to increase water retention in the soil profile is a reduction of soil water evaporation. In the semi-arid tropics the loss of soil water through evaporation can be substantial and has a major consequence in determining the sustainability of a cropping system.

Soil evaporation occurs in three stages (Lemon 1956). The first is the constant rate stage where the water loss is rapid and steady. The water loss in this stage is limited by energy and is controlled by the atmospheric conditions like net

radiation, wind speed, and atmospheric humidity. The second stage is a declining rate stage and in this stage the rate of water loss is controlled by soil properties that affect the rate of water supply to the soil surface. In the third stage, the water loss is extremely slow and is controlled by adsorptive forces at the liquid-solid interface. The potential for reducing soil water evaporation by tillage practices is greatest in the first two stages (Unger and Stewart 1983). The basic principles for reducing soil water evaporation are: (a) reduce the turbulent transfer of water vapor across the soil-atmosphere interface, (b) decrease the capillary continuity just below the soil surface, and (c) decrease capillary flow and water-holding capacity of the surface layer.

Residue mulches are effective in reducing evaporation in the constant rate stage only. Residue mulch reduces evaporation by reducing (a) turbulent transfer of water vapor from the soil surface to the outer atmosphere, and (b) reducing the amount of energy available for latent heat due to the insulation and reflective properties of residue mulch. Tillage practices like conservation or no-tillage that leave all or part of the previous crop residues as surface mulch are therefore most effective in controlling soil evaporation. Greb et al. (1967) showed that a presence of 11 t ha⁻¹ of surface residues on a fallow soil increased its stored water to 34% of the precipitation as compared to 16% for the soil with no surface residue. During the fallow period, Unger (1978) showed that precipitation storage in a Pullman clay loam (Torrertic Paleustolls) at Bushland, Texas ranged from 23% with no mulch to 46% with 12 t ha⁻¹ wheat (*Triticum aestivum* L.) straw.

Primary tillage practices like moldboard, chisel and disk plowing are also useful in reducing evaporation since they break the continuity of capillaries and thus the supply of subsurface water to the soil surface. Management practices also suggest that compact surface soil can decrease evaporation by decreasing capillary flow and reducing water-holding capacity of the surface layer. However, primary tillage and compaction may not be viable options because of their subsequent detrimental effects on soil erosion, water infiltration and plant emergence.

Tillage Effects on Soil Erosion

Tillage has major consequences on the health of soil resources. Soil erosion not only results in the loss of sediments but also of nutrients that are associated with soil particles and organic matter. There are two types of soil erosion: (1) soil erosion due to water, and (2) soil erosion due to wind. Tillage practices can be used to manipulate soil conditions that will control/reduce both types of soil erosion.

Water Erosion

A large number of studies have documented the effects of various tillage practices on soil erosion due to water. These studies include watersheds and large plots under natural rainfall or small plots under rainfall simulation. McGregor (1978) and McGregor et al. (1975) showed that no-tillage soybean (*Glycine max* L.)

in a continuous soybean culture reduced soil loss to 15% of that from conventionally tilled soybeans. Several reports (Harrold and Edwards 1972, 1974; Harrold et al. 1967, 1970) on soil erosion from watersheds at Cochocton, OH showed that there is substantial reduction in soil erosion in watersheds where no-tillage was practiced. Johnson et al. (1979) reported that in small watersheds with 12 to 18% slope in western Iowa, soil loss over a three-year period decreased by about 90% with a no-tillage and 60% with a ridge tillage compared to the conventional system. Runoff volumes were reduced by about 40% with the no-tillage system and 35% with ridge tillage system. Associated sediment concentrations were also greatly reduced.

Similar studies have been conducted on small plots with artificial rain. Onstad (1972) reported an annual soil loss of about 17.5 t ha^{-1} from a fallow plot and 6.0, 3.7, and 3.5 t ha^{-1} for the conventional, mulch, and ridge treatments, respectively, from small plots with about 6% slope at Madison, South Dakota. Mannering et al. (1976) reported results of soil and water loss studies on four soils with four different tillage systems. The tillage systems evaluated were no fall tillage, fall moldboard plow, fall chisel plow, and fall disk. In all these cases, it was shown that soil loss was exponentially related to the surface residue cover irrespective of the type of tillage. Siemens and Oschwald (1978) showed a similar exponential relationship for soil loss to residue cover for several tillage systems on one soil in Illinois. The relationship was different for corn (*Zea mays* L.) than for soybean residue. Unpublished data of Moldenhauer (Laflen et al. 1980) for a silt loam soil on 5% slope showed that soil loss decreased exponentially with an increase in artificially applied corn residue cover and was unrelated to tillage practices of fall chisel, fall moldboard plow, and no-tillage.

The tillage, residue and plant cover effects are embedded in the C value of the Universal Soil Loss Equation. The processes underlying the C value are that (1) crop canopy and surface residue mulch dissipate rain energy and thus reduce soil detachment, (2) surface mulches obstruct runoff flow and increase infiltration, and (3) tillage and residue have some secondary effects on soil structure, organic matter content, soil density, surface roughness, soil porosity, and plant roots which in turn affect soil erosion (Allmaras et al. 1985). Using the relationships (Laflen et al. 1980) for estimating the subfactors, Allmaras et al. (1985) showed that C values are mostly a function of the relative residue cover, left after tillage. For wheat and corn, C values could be grouped into two categories: (1) higher C value for plow-disc-harrow and plow practices, and (2) lower C values for no-tillage, chisel and disc practices.

All the watershed, small plots and simulation studies show that soil loss from landscapes is directly related to surface cover. Any tillage practice that leave all or part of the crop residues at the soil surface will be most effective in controlling soil erosion due to water.

Wind Erosion

Factors that reduce wind velocity will also reduce its carrying capacity and in turn there is a reduction in wind erosion. Soil cloddiness has been shown to reduce wind erosion by providing a roughened surface. Therefore, any tillage

practice that produces large clods will lower the susceptibility of soil to wind erosion. Tillage effects on surface cloddiness, however, depends on the type and speed of the implement used, the soil moisture content, and the soil type.

Aggregates less than 0.84 mm have been characterized as a wind erodible fraction. Chepil and Woodruff (1959) noted that the effects of tillage are temporary, because the forces of weather like freezing and thawing or wetting and drying tend to break the clods to sizes small enough to be moved by wind. These authors also noted that as the clods at the surface are broken down, the clods below the surface are being formed. Hence, repeated tillage of a proper type is useful in maintaining cloddy surface. Moldboard plowing of a fine sandy loam increased the percentage of nonerodible aggregates by 18% whereas listing resulted in an increase of 8%. In this study, wind erosion during the months of March, April and May for moldboard plowing was 28% of that for chiseling and 33% of that for listing.

The wind erosion equation considers tillage effects in three factors (Woodruff and Siddoway 1965): the soil erodibility index, the soil-ridge roughness, and vegetative cover. The soil-erodibility index is based on the percentage of dry soil aggregates greater than 0.84 mm. Soil-ridge roughness is the height of soil ridges with an optimum height/spacing ratio of 1:4 at right angles to the wind. Vegetative cover is a mass per unit area located above or on the soil surface (Allmaras et al. 1985). Black (1973) and Smika and Greb (1975) showed that nonerodible aggregates increased by 5 to 8% for each 1000 kg ha⁻¹ of wheat straw maintained near the surface by the tillage system (excluding the moldboard plowing). In general, the tillage that retains surface residues gives the lowest soil erodibility index.

In wind tunnel studies Lyles and Allison (1976) showed standing stubble can be effective in reducing the critical friction velocity ratio (CFVR). CFVR is an index of the velocity needed to initiate the soil erosion and the larger the value of CFVR, the more effective the stubble is in preventing wind erosion of the soil. The CFVR for standing stubble uniformly spaced or in rows normal to wind direction, were 1.4 to 2 times larger than those for stubble in rows parallel to the wind. On a weight basis, 5.5 and 8.7 times more standing grain sorghum and corn stubble, respectively, than wheat stubble are required to provide the same protection. As expected, CFVR increased with an increase in the stubble height. For a given stubble height, increasing the stubble population increased the CFVR with larger effects occurring for taller stubble.

Research Needs

Development of Residue Based Tillage Systems

The above discussion has shown that conservation tillage practices that leave all or part of the crop residue at the soil surface are most effective in conserving soil water and reducing soil erosion. However, there are also some risks involved in the adoption of these management practices. Triplett (1986) listed some of the effects of moldboard plowing and no-tillage practices on factors affecting crop productivity (Table 1). Adoption of conservation practices must consider

Table 1. Comparison of tillage effects on factors influencing crop productivity¹

Factors	Effect on plow-tillage	No-tillage	Crop ²
<i>Soil Factors</i>			
Temperature	Warm days, cool nights	Little variation	±
Water intake	High following tillage, decreases with crusting season	Lower initial rate Maintained through season	+ 0
Surface-applied minerals	Mixed with soil to plow depth	Percolate slowly	0
Bulk density	Decreased by primary tillage	Little effect	0
Compaction	Broken by tillage	Little disturbance	-
Aeration	Initial increase	Little affected	0
Organic matter distribution	Mixed with soil	Near surface	±
decomposition rate	Rapid	Slower	±
Erosion hazard	Serious	Soil protected	+
Runoff rate	Rapid, when soil compact	Slowed by mulch	+
Evaporation	Rapid	Decreased by mulch	±
<i>Biological Factors</i>			
Weed control	Initially excellent	Reliance on herbicides	-
Disease organism	Inoculum buried	At surface (or incorporated)	-
Soil invertebrates beneficial	Disrupts life cycles	Little effect	+
destructive	Same as beneficial	Little effect	-
<i>Machine Function</i>			
Planting	Machine designed for loose soil	Special equipment for undisturbed soil	0
Cultivation	Effective in loose soil root pruning	More difficult in mulch	0
Traffic support (in wet soil)	Poor	Good	+
<i>Management</i>			
Timely operations	May be delayed	More timely to be reliable	+
Power demand	Increased by successive operations	Minimal	NA
Labor demand	Increased by successive operations	Minimal	NA
Dependability	Good	Can be erratic	

1. Source: Triplett 1986.

2. + = Positive benefit for no-tillage; 0 = Neutral or No effect; - = No-tillage detrimental;
NA = Not applicable.

all aspects of the tillage system and should be in concert with the weather and climate patterns of the area. Since subsistence level farming in the semi-arid tropics involves a multitude of crops that are intercropped or grown side by side, development of tillage practices must consider the total cropping system. Also, since crop residues are as precious a commodity as food grain in the semi-arid tropics, the recommendation of a tillage practice involving residues should be done in concert with changes in economic policies that will encourage the adoption of these practices.

Development of Tillage Expert Systems

Expert systems are rule based tools that consider various factors that are considered for decision making. In other words, the system tries to mimic how an expert selects a given tillage system. One of the earlier expert systems that was developed for selecting tillage practices is the one suggested by Galloway et al. (1977) for Indiana soils. The procedure involved placing 346 soil series in 23 groups based on drainage characteristics, organic matter, texture, and slope. Nine tillage-sowing systems, ranging from moldboard plowing to no-tillage, were rated according to their adaptability, for a corn after corn crop sequence, to each of the 23 soil groups. The major factors considered in the adaptability were crop yield and soil erosion. This rating scheme was later extended to the US Corn Belt for both corn/corn and corn/soybean rotations (Galloway and Griffith 1978).

Using a similar approach, Roberts et al. (1986) developed an expert system named CONSTILL for conservation tillage recommendations for Minnesota. This expert system considered soil drainage, soil steepness, wind erosion potential, soil texture and previous crop in making recommendations for conservation tillage systems for corn, soybeans, sunflowers (*Helianthus annuus* L.), potatoes (*Solanum tuberosum* L.), sugar beets (*Beta vulgaris* L.), alfalfa (*Medicago sativa* L.), wheat and barley (*Hordeum vulgare* L.).

A numerical rating system was also developed by Lal (1983) to assess a soil's suitability for no-tillage systems for the tropics. The rating system was based on soil properties such as soil erodibility, soil loss tolerance, rooting depth, available water-holding capacity, cation exchange capacity, pH, and others (Lal 1985). In this rating system, special attention was given to germination and seedling establishment, runoff and erosion, and soil structure. Clay activity and soil moisture regime were also considered. Friable, coarse-textured, self-mulching, and structurally active soils were considered to respond better to no-tillage or reduced tillage than soils with massive structure or which are easily compactable. Similarly, no-tillage was rated better for erosion control on coarse textured soils over the whole range of soil moisture regimes. No-tillage in this rating scheme referred to mulch management which embodies other requirements like seeding equipment, weed control, crop sequence, insect and pathogen control, methods and rates of application of soil amendments, seeding rate and plant establishment.

As Lal (1985) suggested, his rating scheme is too general and would require location-specific research before extrapolating it to other locations. Also, some

of the above rating schema are specific to one or two constraints. In all the above rating schema, more emphasis is placed on soil erosion control according to their suitability to tillage systems over other factors.

Currently, there are many indigenous tillage systems that are being used in various countries of the semi-arid tropics. In scientific literature there is only a limited description of these systems as to their advantages and disadvantages. Some of these systems might be adaptable to other parts of the semi-arid tropics. A research need for sustainable agriculture in the semi-arid tropics will be to assemble this information and present it as one or more expert systems. Once constructed, the expert systems based on the current knowledge should be analyzed to see how existing management practices can be modified to minimize the degradation of soil and water resources.

Development and Adoption of Computer Models

Deciding the suitability of tillage practices for a given soil requires a long-term data base on crop growth, soil erosion, water quality, and soil physical properties. Long-term data bases are needed so that the climatic variability of the area has been accounted for in the final recommendation. Experiments to collect this information for a whole range of tillage scenarios is expensive and time consuming. In the last two decades, scientific advances have been made in simulation models that integrate soil, climate and management information to predict crop growth, soil erosion, and chemical leaching past the root zone. These computer models can be excellent tools in narrowing the range of treatments where experimental information should be collected. Though most of these models are based on physical principles, they still use site and crop specific information. These models require field testing and validation before they can be used on a routine basis.

Once the management practices are identified through simulation, field experiments should be undertaken to validate the predictions and quantify the relative magnitude of treatment effects on soil and water resources, and crop productivity. Validated models will also be helpful tools in generating data like cost/benefit ratio that is often needed to develop public policy that will reduce erosion and increase crop productivity.

Summary

Sustainable agriculture in the stressed environment is constrained by the increasing loss of soil water due to evaporation and the loss of fertile top soil and associated nutrients due to soil erosion. Proper tillage and land cultivation in concert with the climate of the area can to some extent mitigate the above constraints. One of the simplest tillage technologies that conserves soil moisture and the soil resource is residue based tillage systems like the conservation tillage or no-tillage systems. These systems have not been widely adopted in the semi-arid tropics because of the increasing demand for food and fiber from the increasing population of both humans and animals. Harvesting crop residues from land not only lead to soil depletion of crop nutrients but also affect the water loss due

to evaporation and soil loss due to water and wind erosion. If the agriculture in the semi-arid tropics is to be sustainable in the long-term, research is needed to find ways to leave at least some part of the residue at the soil surface after each crop harvest. This research should include the percent residue cover needed when the need is most severe, the rate of decomposition of crop residues, and the height and spacing of stubble mulch that might be effective in reducing soil erosion. Furthermore, expert systems should be developed based on knowledge of existing tillage practices. These practices should be further analyzed to see how they can be improved to minimize the constraints to sustainable agriculture in the semi-arid tropics. Since long-term experiments are time consuming and expensive, computer models should be developed that can identify tillage practices that are suitable to long-term climate of the area.

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Sustainable Management Technologies in Rice Ecosystems

S.K. De Datta

Abstract

*In the developing world, the need for increased food production has never been greater than it is today. The population numbers are alarming with 241,000 more people to feed and clothe with every passing day, 7.3 million every month and 88 million every year. Among cereals, rice (*Oryza sativa* L.) is a major food grain in the world. The demand for rice is expected to rise globally up to 760 million t by the year 2020 from the current level of about 500 million t. One of the greatest resources of mankind is the existing 135 million hectares of riceland, a resource base of immense size and significance.*

Physical resources like soil, water, nutrients, and energy-determine whether land is favored or less endowed or marginal. Improved germplasm was the shortest and most effective path to better food production in the 1960s and 1970s. In the 1990s, most of the future gains in productivity on favored and less-favored lands are expected to come from better management of the production processes. These include research as well as the policy environment. Global research agenda should be aimed not only at breeding sturdier and more productive crop varieties, but also management technologies that will better protect and use soils and water, and introduce user-friendly systems for "Integrated Pest Management" (IPM) and nutrient supplies and in developing more equitable land-use programs and policies.

With increasing complexity of the environments for sustaining productivity growth of rice and rice-based systems, the need to improve the management and utilization of limited resources in rice production is vital—particularly in view of the rapid dissemination of modern rice technology, especially the spread of modern varieties and associated technologies which have been the cornerstone of increased rice production in the developing world.

The development of research methodologies which will comprehensively address the key management agendas in the rice production systems is a formidable task in the coming decade. Rice ecosystems that contribute to global climate change is also a concern which needs to be addressed with research and economic incentives.

Introduction

Asian lowland rice production is a vast monoculture on a scale incomparable

to any other (De Datta 1981). Ricelands, especially the irrigated ones, are already an intensively used production resource—yet there is no alternative but to use them even more intensively. In addition to producing much more rice, rice lands must also produce a wide range of other commodities in rotation with rice to improve nutrition and to create purchasing power among the poor. But, can the productive potential of the riceland resource base be sustained in the face of such a pressure?

The amount of rice production in many countries is not keeping up with the demand due to rapidly increasing population. There is increasing concern that the growth in aggregate rice output has peaked and is starting to decline (Herdt 1988). For example, aggregate rice output growth rate for Asia increased from 2.1% per annum during 1955–1966 to 3.3% per annum during 1964–1981. However in the past decade, it decreased to 1.5% per annum. Demand for rice in Asia during the 1990s should grow at a rate of 2.1–2.6% every five years to keep up with production.

Barker and Chapman (1988) suggest that the productivity declines could occur due to the following reasons: (a) lack of significant breakthrough in the yield ceiling in Asia since the first modern varieties were released; (b) decline in the irrigation investments and the poor maintenance of existing irrigation infrastructure.

For the irrigated rice environments, Pingali et al. (1990) characterized the post green revolution phase as follows: (a) modern variety use has extended most of the favorable areas and some unfavorable areas and the rate of growth in farm yields is beginning to slow down; (b) land-use intensity is high and so is input use, especially fertilizers; (c) the efficiency of input use is low and hence in association with (1) and (2) the productivity decline is a distinct possibility.

The area of land suitable for rice production is declining in many countries while the extent of saline, alkaline, and waterlogged areas is rapidly increasing. In rainfed upland areas, soil erosion and nutrient depletion continuously depress rice yields. Yields are also unstable due to droughts and floods. Under intensively grown rice-rice systems, the rice plants coexist with dozens of insect and disease pests, and epidemics occur from time to time generating near-panic among farmers and governments. Accelerating the application of a vigorous monitoring system to integrated pest management, including advanced research in breeding tolerant/resistant genotypes is the only dependable weapon to avoid disaster in the fragile rice ecosystems.

This chapter provides examples of management technologies for rice production systems taking into consideration environmental and sustainability concerns.

Resource Conservation and Input Use Efficiency

The critical feature of this brief overview of the resources used in rice production is the long-term vulnerability of production systems. This is of particular significance in the favorable areas where production depends on relatively high crop intensity and input levels such as water and chemicals. Five main issues emerge from a brief analysis of the rice scenario and the rice research setting.

For example: (1) forecasts of rice supply do not adversely affect the long-term security; (2) the factors affecting production apply equally to both unfavorable as well as favorable rice ecosystems; (3) in the foreseeable future, the vulnerability of these systems to degradation will receive increased attention, and (4) a wide range of factors—political, economic—contribute to increasing and sustaining rice production, protecting the environment, and improving the well-being of farmers (IRRI 1989).

Attention to the impact of high yield-producing technologies on ecological sustainability becomes urgently necessary as cropping intensifies. Concern for various components of mankind's life support system—land, soil, water, flora, fauna, and the atmosphere must be translated into specific research activities. Some examples to these agenda items are as follows: (1) the role of irrigation water in waterlogging, salinity, and alkalinity; (2) the efficient use of chemical inputs by the rice plant and their effects on the environment; (3) the contribution of rice culture to climatic change; and (4) the impact of rice technologies and associated resource management systems on socioeconomic factors. These concerns are briefly described as follows:

Land Degradation

About 260 million hectares, 17% of the world's arable land areas, is irrigated as of 1987. Unfortunately, there is great difficulty in maintaining the productivity of irrigated lands. More than half of the world's irrigated land has already been damaged to some degree by waterlogging, salinity and alkalinity and much of the additional land expected to be irrigated by the 1990s is highly vulnerable to irrigated related damage.

Riceland degradation is becoming increasingly critical in both favorable and unfavorable rice agroecosystems due to increased cropping intensity and increased population pressures. Upland soils often end up silting irrigation waterways.

Soil Losses

Soil losses from bare or cultivated lands from the upland rice production systems is often serious. With the loss of top soil, nutrient losses make upland rice production relatively less attractive than lowland rice production systems. Research should be aimed at sustainable land, soil and resource management that will reflect the concern over ecosystem degradation resulting from land-use intensification, in equitable land access, and destruction of cover vegetation. Management systems alternatives should be designed to rehabilitate soils and prevent erosion, to be sensitive to low resource endowment and highland-use pressure, and to increase or stabilize income while improving, or at least not diminishing the well-being of farm families (De Datta 1989). The loss of top soils results in the declination of organic matter content which directly affects the nitrogen, phosphorus and sulfur supplies to the crop. It indirectly affects these and other nutrient ions through exchange reactions and complex formation. Other indirect effects arise from its influence on the microbial activities in the soil, and through its effects on soil physical properties.

Microbiological Management of Rice Fields

Organic manure and its recycling may be the key to sustained agricultural production. Research on rice nutrition has shown that, at the levels at which inorganic fertilizer is usually applied in rice fields, most N absorbed by the plant originates from the soil. Available N is mostly released by the turnover of a microbial biomass which represents only a small percent of total soil N (Watanabe et al. 1988). Crop residues, rhizospheric exudates and the photosynthetic aquatic biomass (algae and aquatic plants) contribute nutrients and allow replenishment of microbial biomass. An important aspect is to understand and predict how factors associated with crop intensification, especially agrochemicals, may affect the soil microbial biomass directly or indirectly by decreasing the productivity of the photosynthetic aquatic biomass and the populations of invertebrates responsible for the recycling of nutrients in soil.

Recently (Roger et al. 1993) summarized important findings on the microbial management of rice fields. They are as follows:

- Azolla has proven useful as a N fertilizer in some rice-growing countries. Environmental, technological and economic factors limit use of azolla. Recent progress in strain hybridization and recombination has opened new ways to alleviate some environmental and nutritional constraints.
- Biomass estimates, acetylene reduction assay (ARA) measurements, and inoculation experiments point toward free-living blue-green algae as an additional source of N for rice, with a moderate potential of about 30 kg N ha⁻¹ per crop cycle, which may result in a yield increase of 300–450 kg ha⁻¹.
- The key roles of the rhizosphere, the photosynthetic aquatic biomass and their N₂-fixing components in maintaining soil fertility of rice soils under intensive rice-cropping has been recognized (Watanabe et al. 1988).
- The selection and breeding of rice varieties' ability to fix N₂ and efficient utilization of soil N [De Datta and Broadbent (In press)] have shown potential.
- Genetic engineering may contribute to the microbial management of lowland rice fields; however, it is not yet known how engineered strains can establish or compete with the indigenous microflora.

Legumes in rice-based cropping systems. In irrigated environments of the tropics and subtropics, legumes can be grown in rotation with one or more crops per year. In rainfed lowlands, which comprise about 40% of the total rice area in south and southeast Asia, only one rice crop is generally possible per year. Production of a second rice crop is limited to regions with a supplemental water supply or a long, reliable rainy season. Food legumes can be grown in the post monsoonal period following rice when soilwater is sufficient. When grown after the wet-season lowland rice, legumes can encounter excess water during the vegetative phase and water deficit during the reproductive phase. Postrice legumes depend primarily on residual soil water, and their roots may follow a receding water table. Water deficit reportedly reduces N₂ fixation more than it reduces plant growth and N uptake.

When grown immediately before the wet-season, rice legumes can encounter water deficit during the vegetative phase and excess water during the reproductive phase.

Green manure legumes. Green manuring with effective N_2 -fixing legumes can increase the soil N pool while also improving physical and chemical properties of soil through the addition of organic matter. The use of green manure in rice-based cropping systems has declined worldwide. Figure 1 shows decline in green manure use in Japan and China. In the tropics *Sesbania rostrata* and other species, are used as green manure in rice cropping systems. The use of leguminous green manures in rice cropping systems is currently found primarily in irrigated environments (Buresh and De Datta 1991), worldwide. Rainfed rice environments prone to soil waterlogging appear to have the greatest potential for future green manure cultivation (Garrity and Flinn 1988). The two green manure species which have received recent attention are *Sesbania rostrata* and *Aeschynomene afraspera*. Production of seeds and scarification requirement, frequently are constraints in the use of leguminous green manures, such as *Sesbania rostrata*.

Efficient Use of Purchased Inputs

It is important to reduce dependence on purchased inputs in tropical rice production. However, irrespective of the levels of input use, efficiency of purchased inputs must be improved.

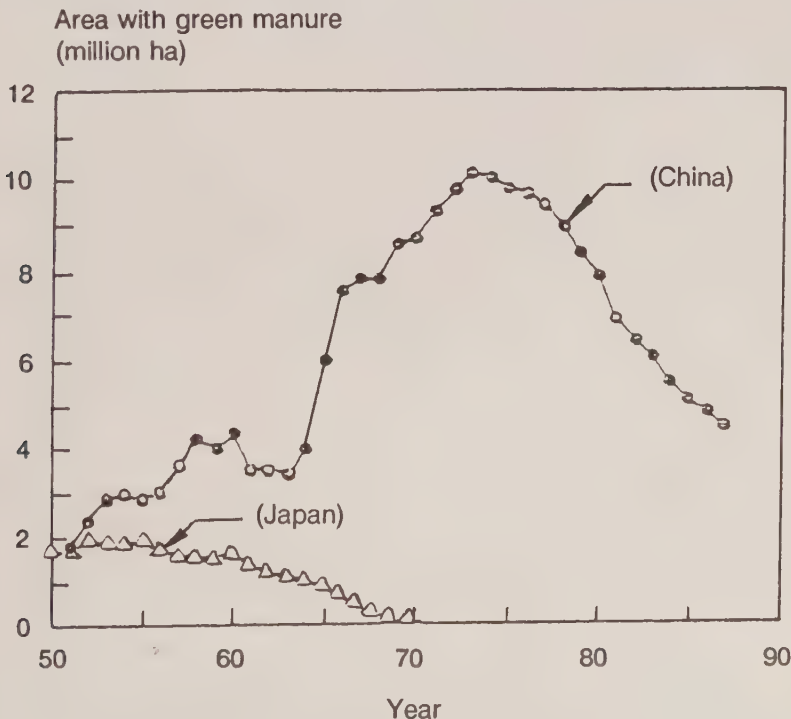


Figure 1. Area with green manure in China (1952-'87) (Stone, 1990) and in Japan (Watanabe, 1984)

Nutrient use. The future increases in rice production will require ever increasing quantities of nutrients from soil and fertilizer. The effectiveness with which rice utilizes these nutrients is influenced by dynamic interacting of physical, chemical, and biological processes in the soil/rice system. Nitrogen is the nutrient that mostly limits rice production. Within Asia, approximately 60% of the fertilizer used, mostly urea, is applied to rice. However, this N fertilizer is not efficiently utilized.

Nitrogen loss processes. Typically, less than 40% of applied N is absorbed by rice because substantial amounts of N are lost as gas to the atmosphere by ammonia volatilization and nitrification/denitrification. Ammonia volatilization is now recognized as a major mechanism of N loss from urea fertilizer in tropical rice fields (Mikkelsen et al. 1978). Recent results show ammonia volatilization losses are substantially lower in broadcast-seeded flooded rice than transplanted rice (Figure 2). This is because wind speed just above the floodwater-rice seedlings in broadcast-seeded flooded rice system is lower than that of the transplanted

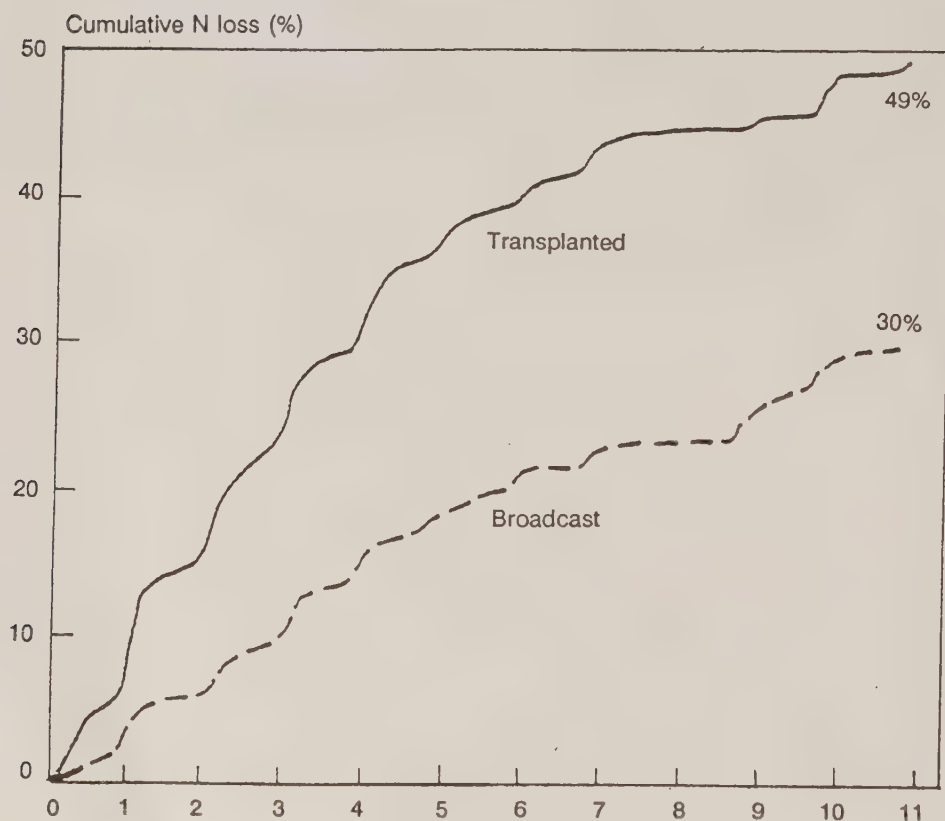


Figure 2. Cumulative NH_3 loss from urea applied to broadcast seeded and transplanted IR 66 in circular plots. Calauan, Laguna, Philippines, 1988 dry season. (S.K. De Datta, 1988. IRRI, unpublished)

system at the same height (De Datta et al. 1988). Results further showed that incorporated green manures such as *Sesbania rostrata* and *Aeschynomene afraaspera* reduce ammonia volatilization losses (Figure 3).

Nitrogen fertilizer can also be lost as dinitrogen (N_2), nitrous oxide (N_2O), and nitrogen oxides (NO_x) through nitrification-denitrification.

A few direct measurements of denitrification loss have been conducted with puddled rice soils. Field studies were conducted in Thailand, Indonesia and the Philippines to measure $(N_2 + N_2O) - ^{15}N$ flux, $(N_2 + N_2O) - ^{15}N$ trapped in the soil, and total gaseous ^{15}N loss following basal application of ^{15}N -labeled urea to irrigated rice grown on puddled soils. Total gaseous N loss determined from a ^{15}N balance 10 days after N application without incorporation was 34% of the applied N in Thailand and 31% in Indonesia. Incorporation reduced total N loss to 22% in Thailand and 10% in Indonesia. In the Philippines, the measured $(N_2 + N_2O) - ^{15}N$ flux during 15 days immediately following urea application with incorporation was 2.2–3.0% of the applied N (Buresh et al. 1991). Ammonia volatilization appeared to be much more important than nitrification-denitrification as a mechanism of urea-N loss at the three irrigated lowland rice sites.

Pesticides and pest management of rice fields. Sustainable agricultural systems should have characteristics pertaining to the ecosystem, the technology, the physical environment, the economic environment and the social environment. Pests are a major cause of instability in yield production and productivity. It

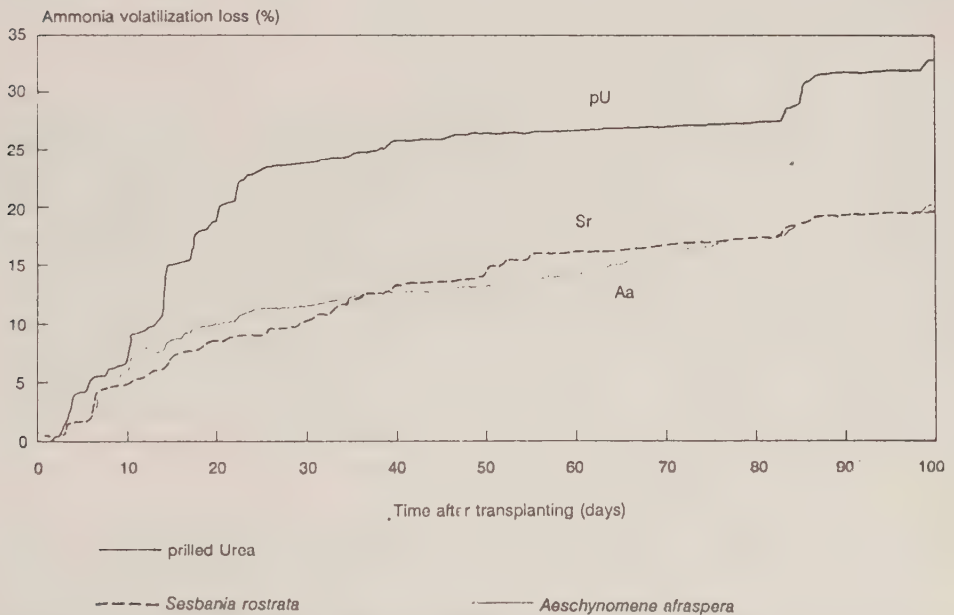


Figure 3. Ammonia volatilization loss from flooded puddled rice fields amended with prilled urea or green manures. Victoria, Laguna, Philippines, 1991 dry season (S.K. De Datta 1991, IRRI unpublished)

is of major concern that pesticide application in developing countries is expected to more than double by the year 2000 (a three-fold increase is possible if recent rates of increase continue). Pollution of persistent chemicals in irrigated canals, ponds, and rice fields in Asia is already serious, causing death of fish, frogs and other farm fauna. It is therefore imperative that pest control practices should have no lasting adverse effects on water quality.

The economic environment in sustainable agricultural systems should (a) maintain or increase net income to farmers by (b) maintaining or slightly increasing productivity.

More recently, there is an increased recognition of the importance of the social environment in management aspects of sustainability. Growing environmental awareness of influential consumer groups will help to provide "Integrated Pest Management" (IPM) and improve judicious use of pesticides. Surveying and some drastic decisions by governments like that in Indonesia have shown that more can be achieved with less chemicals.

The goals for the ecosystem component is to maintain an ecologically sound and stable environment through biodiversity and yield stability, to be achieved by an integration of control tactics for single or multiple pest situations.

Sustainability Concerns

It must be understood that rice production system is part of the farm production system. As sustainability issues become more important in research programs, there will arise a need for a rigorous diagnostic tool for establishing priorities for research on sustainability.

Genetic Vulnerability

There are contrasting views on whether genetic vulnerability in modern agriculture is much greater today than it was before the modern varieties were introduced. A recent example of the blast disease (*Pyricularia oryzae*) on hybrid rice in China in 1985, which affected over one million hectares (Swaminathan 1988) suggests that "elite" high-yielding modern varieties grown in large areas are vulnerable to disease and pest pressures. At one time IR-36 rice variety was grown in 10 million hectares which might have caused total crop failure, had one of the biological stresses such as the resistance or tolerance to insect or disease, broke down. Further research is needed to help compensate for the erosion of biodiversity world-wide and to clarify the often ill-defined patterns of variations in crops.

Yield Decline and Its Reversal

Although the evidence is incomplete, the cumulative effect of stresses on natural resources should not be underestimated. In Thailand, for example, rough, rice yields in the Chiangmai valley increased from 4 to 7 t ha⁻¹ per year when farmers changed from traditional to intensive cropping practices. Ten years later, yields have slipped back to the original levels, despite continued high inputs of lime and other fertilizers (Gyspantari et al. 1989). Yields of some modern varieties

under optimal management at IRRI and three other locations in the Philippines have declined by 0.1 to 0.3 t ha⁻¹ per year over a 20 year period (Flinn et al. 1982; Flinn and De Datta 1984). Figure 4 shows grain yield from long-term trials at IRRI farm from 1964–1988 dry and wet seasons.

The possible reasons for the yield decline are as follows: (1) lodging, which reduced grain yield by 1.0 t ha⁻¹ in the dry season; (2) use of varieties with increased per-day productivity and pest resistance; this has largely been emphasized by the breeding program rather than developing rice varieties that will produce the highest yield per crop and; (3) lack of cultural practices to increase grain yield of short-duration rice varieties.

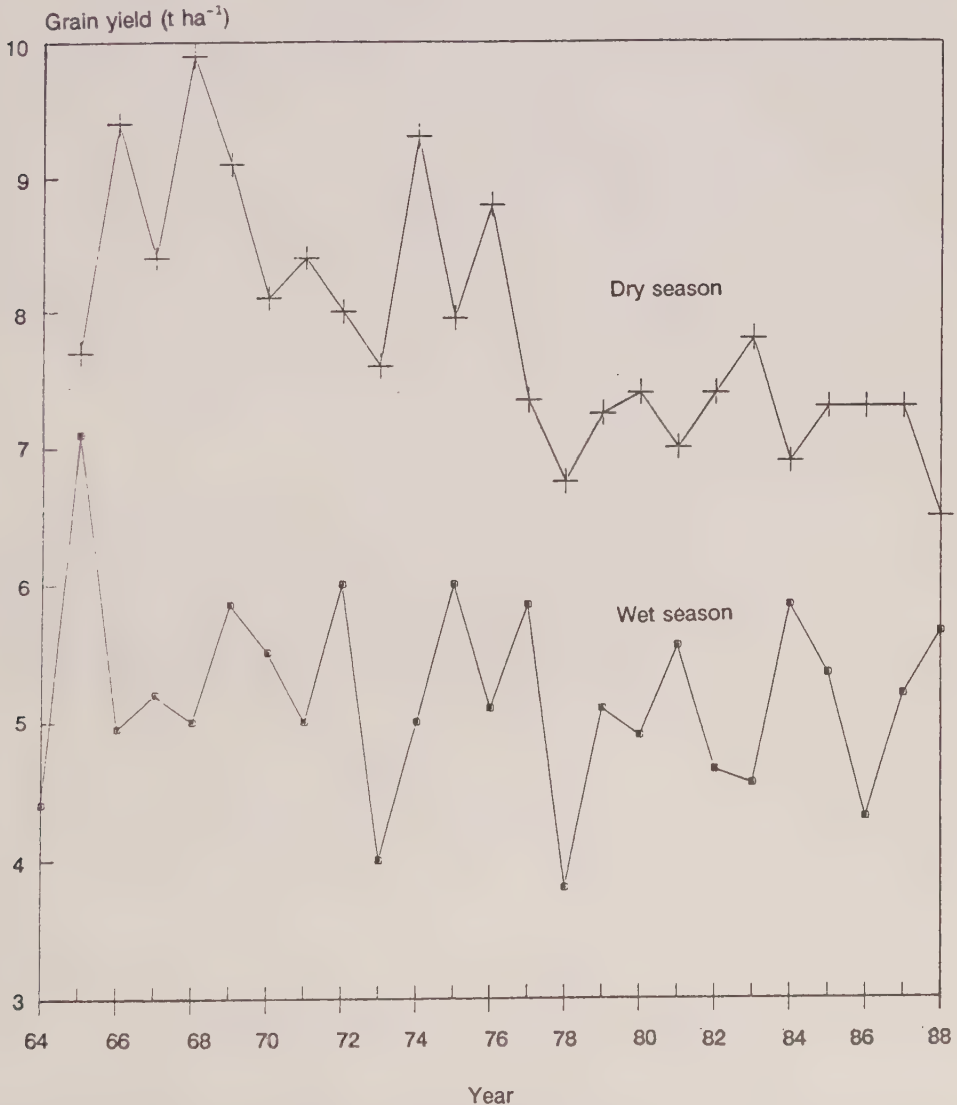


Figure 4. Highest yielding test rice in the long-term fertility trials. IRRI. 1964–1988. (De Datta, 1989)

Increasing Yield Potential in Irrigated Rice Varieties

Two approaches are being used to improve rice yield potential by 20–25% within the next 5 to 10 years: Changes in plant architecture (Dingkuhn et al. 1991) and exploitation of hybrid vigor. Based on strategic research on nitrogen dynamics and yield potential, plant type concept has been developed. The following are the basic plant characteristics required for breaking the yield frontier.

Modern rice varieties have 20–25 tillers. Only about 15–16 of these produce small panicles and most remain unproductive (sterile). The unproductive tillers compete with productive tillers for nutrients, water, and space. New plant type suitable for direct seeding should have 4–5 productive tillers with large panicles. These rice^s must have sturdy stems to hold 250 filled spikelets per panicle, dark green and erect, thick leaves, and vigorous root systems. Recently Dingkuhn et al. 1991 suggested the following modifications of N and assimilate partitioning which would improve rice yields.

- prolong the ripening phase
- maintain a high N concentration in leaves
- allocate more assimilates to leaf growth in young crops
- reduce leaf growth during the late vegetative and reproductive phase
- expand the assimilate storage capacity of the stems

With respect to broadcast-seeded flooded rice; these improvements should be combined with the following characteristics:

- improved seedling anchorage
- reduced tillering ability
- longer life span and larger size of flag leaves, and
- larger panicles and higher sink capacity

Grain yield increases from a combination of these changes would probably exceed 25% (Dingkuhn et al. 1991).

Based on these and other research studies, IRRI breeders have identified donor varieties with large panicles, very sturdy stems, and low tillering. These donors are used in developing germplasms with new plant type and higher yield potentials. It is the top priority breeding activity in the irrigated program of IRRI. However, the progress in developing varieties with this type of plant architecture is 7–10 years away.

Hybrid rice has been successfully developed and used in China over 15 million hectares. The progress in tropical Asia has been constrained by the lack of an appropriate seed industry to support this effort. Nevertheless, it is envisioned that hybrid-rice varieties for tropical locations should be available within the next five years (IRRI 1989).

Increase Yield Stability

Three approaches are being used for developing rice varieties for stable rice yields. They are: (1) through durable resistance to diseases and insects; (2) including alien gene transfer; use of novel genes and; (3) horizontal resistance (particularly for blast resistance).

Rice Production Systems in Relation to Global Climate Change

Rice yields are characterized by floodwater overlying a thin aerobic soil layer. Algae and aquatic plants that develop in the rice field floodwater (Photosynthetic aquatic biomass): (1) conserve soil-evolved C and N; (2) recycle nutrients in water and soil; (3) constitute a major source of available N for rice (Watanabe et al. 1988) and (4) provide 5 to 50 kg N ha⁻¹ per crop through photodependent biological N₂ fixation.

In flooded rice soils, unlike in well-drained aerobic soils, organic C is decomposed to methane as well as carbon dioxide (Takai 1970). Both methane and carbon dioxide can be released from rice fields to the atmosphere, and rice fields are considered to be an important source of atmospheric methane (Cicerone and Shetter 1981). Figure 5 shows methane emission rates are closely related to wetland rice production.

Methane and nitrous oxide are important greenhouse gases that influence global climate change. Both methane and nitrous oxide have been linked to depletion of the *ozone* layer. The concentration of methane in the atmosphere appears to be increasing and is of modern rather than fossil origin. The atmospheric concentrations of nitrous oxide are also increasing.

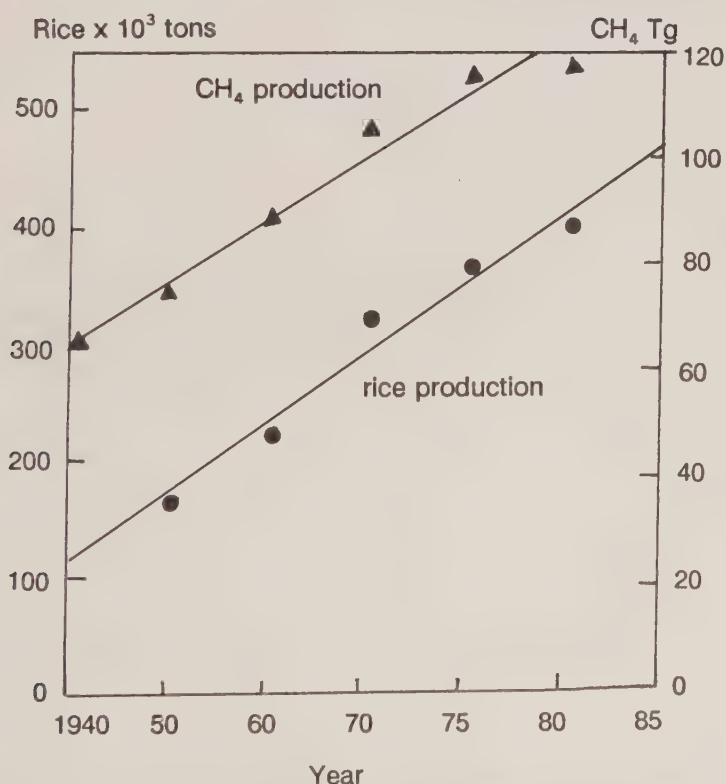


Figure 5. Rice production and methane emission rates. (Neue and Roger, 1992)

Maximum release rates from rice fields were reported between tillering and flowering (Holzapfel-Pschorn and Seiler 1986) and at the end of flowering. Nitrogen fertilization, particularly the use of urea reportedly increases emission of methane (Cicerone and Shetter 1981). Climatic changes leading to increased soil and floodwater temperature might accelerate gas fluxes from rice fields. Increased emission of methane and nitrous oxide from rice fields might then have a feedback effect of further accelerating global change in climate.

A recent study (Neue and Roger 1992) suggested that rice soils are prone to methane production and mainly belong to the order of Entisols, Inceptisols, Alfisols, Vertisols and Mollisols. In calcareous and alkaline soils methane production may occur within hours of flooding an air dried soil (Figure 6). In acid soils it may take weeks before methane is formed. In very acid soils, methane may not be formed at all. The partial pressure of carbon dioxide (PCO_2) directly influences CH_4 production since CO_2 is the carbon source for methane. The following agronomic practices mitigate CH_4 production from lowland rice fields.

They are: (1) degree and pattern to which flooding is controlled; (2) encapsulating methane inhibitors in fertilizers; (3) use of preemergence herbicides to control weeds. (The mechanical disturbance of soils during weeding increases release of gases trapped in the soil). Incorporation of green manure increases methane production in wetland soils (Neue and Roger 1992).

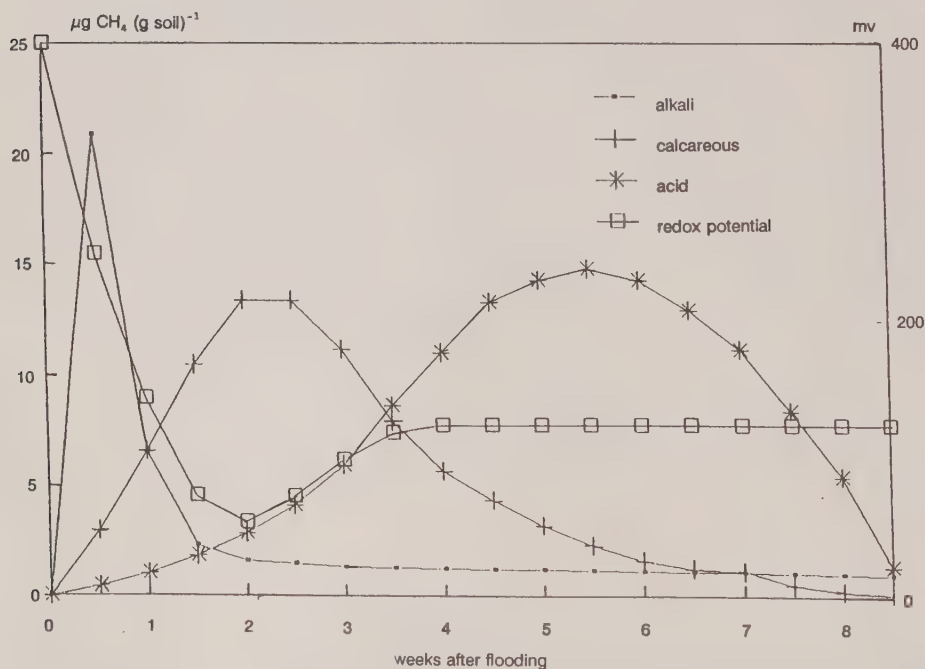


Figure 6. Methane formation in alkaline, calcareous and acid soils. (Adapted from Neue and Roger, 1992)

From the current research, the following conclusions have been drawn:

1. Up to 90% of the methane released from rice soils to atmosphere is emitted via the rice plant (Bont et al. 1978).
2. Irrigated rice ecologies seem to be the major source for increased global methane emissions from rice fields.
3. Global extrapolations of emission rates are still highly uncertain and tentative.
4. Adjusting a basic emission ratio of $0.5 \text{ g m}^{-2} \text{ day}^{-1}$ results in global emission of about 40 Tg year^{-1} from rice fields.
5. Global methane emission rate from rice fields is surmised to be higher than 40 Tg year^{-1} .

Summary

Sustainable rice production to meet future demand will largely depend on continued success in strategic and applied research. Conserving natural resources in all rice ecosystems will be a challenge, with greater challenge in stressed environments such as in the uplands and other drought and flood-prone rainfed environments than in non-stressed environments. Economic returns from investments through increased input and resource-use efficiency will be determining factors for sustainable production of rice in rice-based systems.

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VII. Supporting Papers

Stressed Agroecosystem: Concepts, Assessment and Monitoring

J. Sehgal and D.K. Mandal

Summary

A stressed agroecosystem retards the optimal performance of soils and/or other resources in terms of their productivity. Productivity is impaired due to the limiting conditions imposed by one or more factors and each of these must be corrected, simultaneously or successively, before the performance returns to its original or near original state. Aspects of assessment of the resource base, needs for monitoring, and considerations for research are outlined.

Introduction

More than 85% of agricultural land area in the world depends on rainfall for crop production. Some of these areas receive assured rainfall, where moisture may not be a limiting factor, but other physical and chemical conditions of the soil may cause stress to crop growth. However, large areas falling under semi-arid and arid agroecosystems, wherein crops are grown under rainfed or limited irrigation, do show moisture stress due to low rainfall and/or its erratic distribution resulting in poor and/or unpredictable crop performance.

Concept and Definition of a Stressed Agroecosystem

A stressed agroecosystem retards the optimal performance of soils or other resources in terms of their productivity. Productivity is impaired due to the limiting conditions imposed by one or more factors and each of these must be corrected, simultaneously or successively, before the performance returns to its original or near original state. Performance is impaired even if only one of the factors is constrained as it may control the whole production process. One of the major problems frequently encountered in multi-stressed conditions, is the uncertainty of identifying the responsible factor; a systematic research is needed to decipher this.

Stress-inducing Soil-site Conditions

The two natural resources considered here are climate and soils. Climate induced stresses have been discussed earlier (Virmani, this book). Atmospheric climate is translated into soil moisture conditions. The ideal soil is one that provides

adequate amounts of soil moisture as and when the plant requires it. Stresses result when this is not adequately met. In the higher latitudes, moisture is not available when the soils are cold but this is of lesser importance to the plant. Frequently, due to slopes or the presence of impermeable layers in the soil, there is considerable runoff and so, despite the fact the atmospheric supply of water is adequate, there is insufficient soil moisture for plant growth. A third situation may arise when the soil is recharged with water during a short rainy period, but as the water-holding capacity of the soil may be low, it is unable to supply moisture to the roots when required, especially during the dry spells in the rainy season or in the postrainy dry season.

Soil moisture stresses have also indirect control on plant growth and development. Due to unavailability of moisture, root proliferation does not take place and so the plant is unable to exploit the soil for nutrients. Consequently, soil moisture stress has impacts beyond the simple moisture relations between soil and plant. In addition, moisture stress may result from soil characteristics and not merely because there was an inadequate supply of water. Agroclimatologists frequently ignore this aspect and in addition, this is one of the weakness of defining agroecological zones based purely on atmospheric climate.

Stresses attributed to soils may be inherent or induced by anthropogenic activities. Extreme conditions such as low or very high pH, alkalinity, sodicity, toxic or deficient levels of elements, very sandy or very clayey textures, all result in stresses. These are the intrinsic properties of the soil and cannot be easily changed through management or use of amendments.

Some stresses may be induced by inappropriate management of the soils. Continuous use of heavy amounts of ammonium fertilizers acidifies some soils under some climatic conditions, creating pH related stresses. Erosion removes the organic rich surface horizons, and thus reduces effective soil volume. This may result in soil moisture and/or nutrient related soil stresses. Heavy application of insecticides and pesticides generally residually accumulate, affecting subsequent use of the soil or may contaminate the ground water. Continuous cultivation of the soil for thousands of years, as in India, accompanied with almost complete crop residue removal and little or no replenishment of residues to the soil nutrient base, is an example of one of the most severe anthropogenically induced soil stresses in India.

The anthropogenic induced stresses are increasing in most countries of the world due to misuse of soils. This is one of the reasons for the call for sustainability. Ameliorating these stresses is not easy and requires large inputs and in some instances, a rehabilitation of the system.

The fact that stressed soil systems are increasing is evidenced by the decline in yields reported by long-term experiments. In addition, population increase in many countries is forcing landless people to utilize marginal or fragile ecosystems. Such lands are very prone to easy degradation and therefore result in serious loss of productivity. Although mismatch between land-use and land quality is the reason for stresses (Beinroth et al. this book), the mismatch is generally the major cause in fragile ecosystems.

The challenge of modern human society then becomes one of preventing the use of fragile or stressed systems. The only way this is possible is by providing viable alternatives to the landless, which is not easily done in land-constrained countries such as India. The alternative is to reduce the demographic pressure on fragile ecosystems by making the better endowed systems more productive via labor-intensive farming systems and by providing alternate work options for the excess population.

Assessment of a Stressed Ecosystem

The assessment of a stressed ecosystem is a sequential procedure comprising soil resource mapping, agroecological zoning and monitoring.

Soil Resource Mapping

To assess the nature and degree of a stressed ecosystem, it is imperative that one prepares an inventory of soil, climate, vegetation, and other resources of an area. Such inventories only provide an assessment of the current conditions. A comparison with similar previous assessments provides an assessment of the state of soil condition and changes that have occurred during the time frame.

An assessment of degradation is subjective and is determined on preestablished criteria on the quality of the soil with respect to what it is today and what it could have been during some undefined past. This subjectivity makes the process less satisfactory. Sometimes comparisons between paired locations—cultivated and noncultivated sites—are used to arrive at similar conclusions regarding state of the soil quality. This approach is less subjective but it still is in the realm of interpretation. The development of less subjective approaches is urgently needed and is one of the priorities for research in the study of soil degradation.

There are a few reliable methods to evaluate rates of degradation. In most cases, such as in chemical degradation, degradation is slow and imperceptible and consequently is not easily quantified. However, degradation follows the principle of chaos: when a threshold is reached, the system collapses. Thus, indicators and thresholds of degradation must be established and monitored. There are very few countries in the world where soil properties are monitored in a systematic manner. In its absence, the subject is still speculative.

If causes and rates of degradation are known, the information becomes very useful for developing technologies to retard or mitigate the processes. An important consideration in this respect is the behavior of individual soils and this is the concept of resilience. A knowledge of the resilience capacity of different systems enables the making of decisions on a rational scientific basis. There is little or no information on the resilience capacities of soils and this is a very important area of research.

Conclusions

To sustain productivity in stressed agroecosystems and maintain soil integrity,

it is essential to have reliable information on soils, their problems, existing land-use, moisture availability period, etc. Some major research initiatives towards this goal, from biophysical resource considerations, include:

- detailed soil and other resource inventories;
- establishment of monitoring sites;
- development of indicators and thresholds;
- use of historical data to evaluate changes;
- development of methods and concepts to measure and monitor soil resilience.

Agroclimatology and Sustainable Agriculture in Stressed Environments

R.W. Arnold

Abstract

Environmental stresses can be identified by evaluating the sustainability indicators. These can be divided into 2 classes: (1) response indicators which quantify and classify the condition of the ecological resource classes, defined in this case as 'agricultural production units with common management practices and common environmental problems' and (2) exposure and habitat indicators which identify and quantify changes in exposure and physical habitat that are associated with changes in response indicators. To successfully monitor subtle and highly significant structural changes of land cover as indicators of land degradation or impending ecological changes, an increased application of physical models is needed for the interpretation of remotely sensed data. Advances in coupling numerical physical models to remotely sensed data and the interface with geographical information system (GIS) will provide useful monitoring tools. This reinforces the need to understand processes in the agroecosystem and to identify ways in which they can be monitored so that 'early warnings' can be given as to when critical thresholds within key processes are being approached.

The Food and Agriculture Organization (FAO) definition of sustainability indicates that it involves the management and conservation of the natural resource base and the orientation of technological and institutional change such that the activities are environmentally nondegrading, technically appropriate, economically viable and socially acceptable.

To make it possible for countries to give major attention to sustainable agriculture and rural development, first of all the immediate issues of food security and energy sufficiency must be addressed.

Agricultural activity is most essential to human survival and well-being and it is most dependent on the natural environment. The economic sector affects it the most.

Goals of Sustainable Agriculture

Three essential goals of sustainable agriculture and rural development are (a) food security by ensuring an appropriate and sustainable balance between self-sufficiency and self-reliance, (b) employment and income generation in rural

areas, particularly to eradicate poverty, and (c) natural resource conservation and environmental protection (FAO 1991).

Often major changes and adjustments are necessary to create the conditions of sustainability. Some of these include:

- active involvement and participation of rural people
- decentralization of decision making authority and responsibility
- providing incentives and resources for initiatives
- enhancing local status and management capacity
- allocating clear and fair, legal rights and obligations, with regard to use of natural resources
- adjusting policies to promote production systems and technologies
- incentives favoring crops and animals that can be produced and which process sustainability
- promoting systems that safeguard human health and environmental quality
- promoting off-farm livelihood opportunities in rural areas, such as processing, and facilitating the accommodation of migrating populations

Principles of Ecologically Sustainable Development

Six principles of ecologically sustainable development are briefly described below (Australian Government 1991):

Improvement of Well-being

The thrust of economic policy should be directed to achieving basic social justice objectives, in particular full and meaningful employment, while ensuring that the nature and scale of human activity is consistent with the conservation and protection of biodiversity and the maintenance of the integrity of ecological systems and processes.

Increased wealth provides society with the capacity to repair environmental problems which are the result of past indiscriminate activity. Of central concern is the issue of natural capital. Natural capital is the stock of natural assets; productive soils, mineral resources, plant and animals, clean air and pure water. There are many aspects of natural capital for which no human capital can substitute; there is no prospect of recreating a species which has been made extinct by human activities.

Improving material and nonmaterial well-being depends in part on maximum efficiency of resource use resulting in a lower level of resource inputs for a given output, and also on bringing the true costs (economic and environmental) to bear in the process.

Intergenerational Equity

Intergenerational equity accepts that the current generation should not leave an impoverished environment for the next generation. Knowledge of resilience of natural systems to human intrusions is vital in determining the ecologically

appropriate level of resource use and management strategies in order to prevent foreclosure of options to future generations. Damage to the natural environment brought about by the current generation will, in some instances, be reversible. However, there is a pervasive risk that human activity may lead to losses of biodiversity and also irreversible damage to ecological systems and processes, at least locally.

Intragenerational Equity

Unsustainable development brings with it economic, social, and environmental costs which are likely to be borne disproportionately by certain sections of the community. Corrections include tightening of environmental standards and shifting relative prices in the many different production/consumption processes. Policies to usher in ecological sustainability must incorporate some equity measures in order to ensure the equitable distribution of costs and benefits.

Maintenance of Ecological Systems and Protection of Biodiversity

Under an ecologically sustainable approach to development, all species, their genetic diversity and their habitats would be conserved such that the natural process or evolution and ecosystem functioning can continue ad infinitum. Maintenance of natural processes is important for ensuring the regeneration of renewable natural resources, and that the natural environment has the capacity to absorb and clean society's waste products. Minimizing the extent of on-site and off-site environmental degradation from economic activity and avoiding irreversible damage and loss of species are fundamental to meeting this principle.

The traditional concept of sustainable yield applied to organisms and to ecosystems will need to be broadened to include the protection of biological diversity and maintenance of ecological integrity.

Global Ramification

The impacts of policies and activities are not necessarily restricted to a localized area or even a country. Global sustainable development is dependent upon the achievement of international equity in trade and other structural relations. Without a change in consumer demand patterns, unilateral action to enhance environmental management may merely result in a shift of producer countries, without ecologically sustainable development objectives.

Dealing Cautiously with Risk and Irreversibility

Knowledge of the interrelationships and interdependencies within the natural environment and the likely impact of human activity is still limited. Where there is a reasonable risk of unacceptable irreversible damage to environmental assets, those risks need to be avoided or reduced. Allowing risk and uncertainty to characterize development may lead to a situation where incremental changes in an ecosystem give way to systematic changes that are unable to be reversed or contained by technology. Risk evaluation is likely to be assisted by the

development of indicators of ecologically sustainable development in each sector of the economy as well as on an intersectoral basis.

Measuring Sustainability of Agriculture

Two main options are (1) to measure time trends in productivity or (2) to directly sense the condition and trend of the natural resource itself.

The main problem in using agricultural productivity trends is that inputs change with time, especially animal breed or plant variety, and use of chemicals and fertilizers. In addition, cultural practices and climatic conditions may also vary.

Direct measurement of conditions and trends of systems and practices to assess their long-term sustainability appears to be more feasible.

Application of ecological principles in agricultural production will undoubtedly lead to a greater understanding of the biotic and abiotic structure of these systems, to the pathways of material and energy flow within them, to their response (stability and resilience) to stresses and perturbations, and to thresholds beyond which their capacity to withstand degradation is diminished. With such knowledge, it should be possible to identify those aspects of the system which best indicate its satisfactory functioning, at least from the perspective of maintenance of the biophysical resources, and hence which should be constantly monitored.

Objectives of a Monitoring System

There are numerous environmental parameters that could be nominated but unless the parameter provides insight into the 'health' of the system as a whole, much time and effort could be wasted in collecting data which are inadequate for this purpose. Several objectives are listed for systems to monitor the ecological sustainability of agricultural practices (Australian Government 1991). Any system:

- must provide information on the condition of the resource base, biodiversity, contamination, and productivity.
- must provide information on the ecological processes that help sustain the resource base and agricultural productivity
- must provide information at several scales ranging from farm, to catchment, to region
- must include methods that are relatively simple and readily usable by the farming community without substantial input of outside expertise
- must have indicators that are able to show long-term trends, that is, not be subject to wide annual fluctuations
- must be capable of being supported in the long-term. A monitoring system that is labor intensive and costly may prove difficult to maintain.

Indicators for Agroecosystems

Several workshops have been held to discuss candidate indicators of agroecosystem health, structure and function; for example those by the US EPA. A total

of 130 potential indicators were proposed and from these 18 were finally selected.

The indicators were divided into two classes:

- Response indicators which quantify and classify the condition of the ecological resource classes, defined in this case as 'agricultural production units with common management practices and common environmental problems' and
- Exposure and habitat indicators which identify and quantify changes in exposure and physical habitat that are associated with changes in response indicators.

To successfully monitor subtle and highly significant structural changes to land cover as indicators of land degradation or impending ecological changes, an increased application of physical models is need for the interpretation of remotely sensed data. Advances in coupling numerical physical models to remotely sensed data and the interface with geographical information system (GIS) will provide useful monitoring tools.

This reinforces the need to understand processes in the agroecosystem and to identify ways in which they can be monitored so that 'early warnings' can be given as to when critical thresholds within key processes are being approached.

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Research Needs for Mitigating Abiotic Stresses

R.G. Hanson and J.P. Srivastava

Abstract

Stress can be defined as a constraining force or influence. Abiotic stresses are those stresses caused by nonbiotic sources. These could be constraints associated with the inorganic chemicals and the physical characteristics of the ecosystem, and the climatic parameters that restrict sustainable productivity within a given environment. Abiotic stresses in this chapter are viewed as constraints in the soil environment due to which plant and animals in the ecosystem are unable to sustain the expression of their true genetic potential. Discussions will be limited to the stresses most associated with the semi-arid tropics.

Methods that can measure relative intensity in soil systems nutrient requirement of plants, and quantify other inorganic chemical constraints are in an advanced scientific state. Plant nutrient status and nutrient supplying capacity of soil systems, due to adequate laboratory facilities, can now be routinely analyzed, nutrient inputs recommended and databases for nutrient status of soils compiled. Likewise, knowledge on the nutrient contents of many economic plants is sufficiently quantified so that, based on the degree each plant specie is harvested, the nutrient removal can be calculated. With adequate databases and support systems, available nutrients status of plant-soil environments can be modeled and monitored not unlike bank accounts. More research is to be done before these scientific technologies can be globally applied so as to mitigate all nutrient abiotic stresses.

Management to overcome soil abiotic stresses is often referenced as soil resource enhancement, whereas soil degradation is an outcome of depletive human activities and their interaction with the natural environment. Processes of soil degradation are mechanisms responsible for increasing soil related plants stresses and therefore the decline in soil quality. Indexing and quantifying soil related abiotic stresses down to the management unit will require considerable research and development effort.

Introduction

Stress can be defined as a limitation, a constraining force or influence. Stress can be a natural occurrence or created by man, animal and other external forces. In the context of sustainable agriculture, abiotic stresses on the environment would be those constraints on soil and water resources that mitigate the production of basic human needs in the form of food, fiber, fuel, and construction materials

due to increasing demand pressures. One must keep in mind that there are manageable stresses that can be managed and stresses which are unmanageable, that need to be managed. Some of the most important abiotic stresses in the soil resource system are: (1) water stress (deficiencies and excesses); (2) nutrient deficiencies and losses; (3) elemental toxicities; (4) salinity; (5) sodicity; and (6) soil physical problems (crusting, compaction, impermeable subsoils, shallow soils, topography, eroded soils, textural related). Soil resource stresses can be referred to as stresses for which good science can produce management technologies. Climatic stresses would include: (1) temperature; (2) precipitation; (3) solar energy; and (4) wind. These are often referred to as the unmanageable or minimum correctable abiotic stresses. The focus of this chapter does not attempt to discuss specific research needs for mitigating abiotic stresses across the semi-arid tropics, but does attempt to point out potential manageable and nonmanageable sources to abiotic stresses. The semi-arid tropics, for this chapter, are agroecosystems with protracted dry seasons of 6 to 9 months.

Major Sources of Abiotic Stresses

For the purpose of this discussion abiotic stresses shall be divided into three problematic areas: (1) chemical problems; (2) physical problems; and (3) climatic problems.

Chemical Problems

Chemical problems that can induce abiotic stresses can be grouped as six constraints to sustainable productivity. The constraints are: (1) water deficiencies; (2) water excesses; (3) nutrient deficiencies; (4) elemental toxicities; (5) salinity; and (6) sodicity (Figure 1).

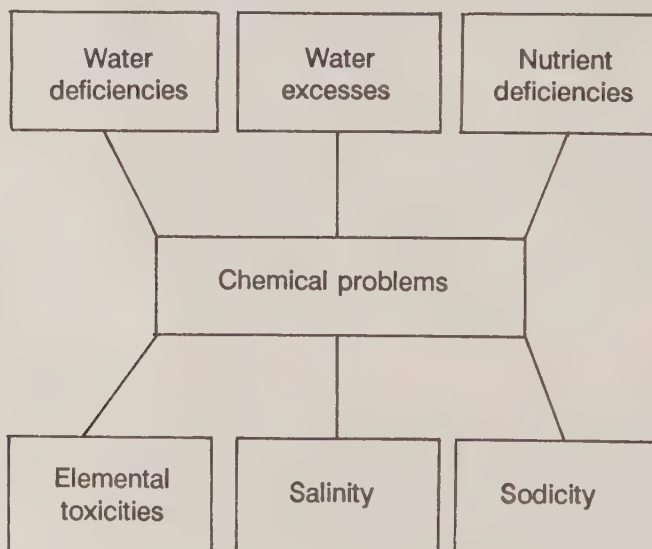


Figure 1. Chemical sources of abiotic stresses

Moisture problems in the semi-arid environment can be expressed as deficiencies and periods of excesses often dependent upon soil characteristics and landscape position. Rainfall in semi-arid agroecosystems can be characterized as, low in quantity, often high in intensity, poorly distributed and lacking in dependability. Soil management technologies for sustainable agriculture production must be developed based on these characteristics. In many semi-arid regions, total rainfall might not be the major constraint, because intensity, distribution and dependability are the characteristics governing moisture management. Research will need to focus on maximum utilization of available rainfall so as to minimize stress on the biotic systems. Soil management research will need to include moisture capture and storage, integrated nutrient management, agronomic practices, crops and cultivar selection and reduction in surface evaporation. The moisture infiltration and storage capacities are important soil properties that control capture and storage of rainfall and need to be characterized for soil systems. Excess moisture constraints are commonly found in low position on the landscape or on soils with very low permeability, and/or soils with poor surface drainage. These ecosystems will require special management technologies or crop production programs based on their capacity to store soil moisture.

Maximum genetic expression on improved crop cultivars cannot be achieved in the semi-arid regions when the soil system is deficient in one or more essential nutrient. Payne et al. (1990, 1991), working in semi-arid Niger, West Africa, quantified the strong influence and interaction of phosphorus and water supply on pearl millet growth. Water supply cannot be effectively managed for pearl millet without addressing the soil fertility constraint. When studying extreme variability in pearl millet stands in Niger, (Wendt et al. 1988) concluded that the soil chemical properties of Al and Mn toxicity and/or deficiencies of K, Ca, Mg, and P account for most of the variability in pearl millet stands in the sandy Ustalfs in semi-arid Niger. Soil nutrient status (low, adequate, high), elemental toxicities and problems with salinity and sodicity can be analyzed in soil testing laboratories. Based on adaptive field research, remediation technologies can be developed and tested for economic feasibility.

Physical Problems

Soil physical problems that are commonly associated with abiotic constraints are: (1) crusting; (2) compaction; (3) generic hard pans; (4) formation hard pans; (5) management hard pans; and (6) textual limitations (Figure 2).

The effect abiotic stresses have on plants caused by soil crusting or surface sealing, can be direct such as emergence problems, and/or indirect such as, reduction in water infiltration resulting in low water capture and potential increase in water erosion. The processes of crust formation as functions of soil properties needs to be understood, in order to develop management technologies that can mitigate their effect on the plant. To benefit small farmers in developing countries, soil management technologies to reduce soil crusting will need to have low-input type technology and not be highly dependent upon high-input technology or extensive mechanization. It is to be expected that research on soil crust

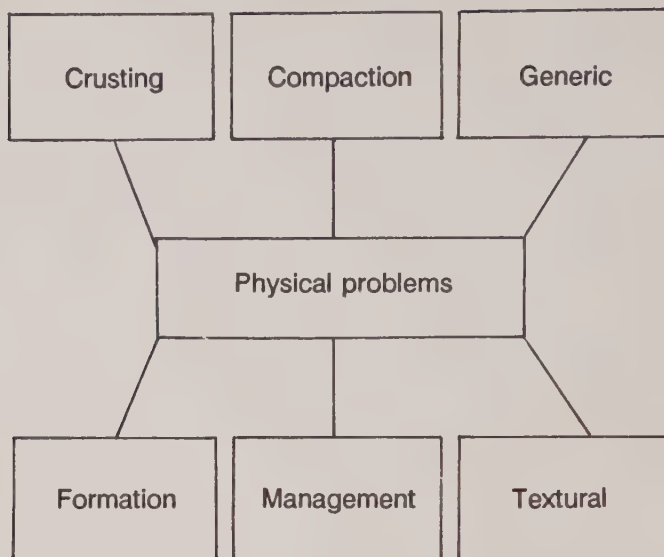


Figure 2. Physical sources of abiotic stresses

formation and abiotic stress effects will be somewhat site specific for soil and plant systems.

Soil compaction can be associated with processes of soil degradation, usually with a massive effect rather than a layer effect, which is commonly referred to as management or tillage pans. The abiotic stresses caused by compaction and tillage, can be similar such as the limiting of root penetration resulting in reduction in use of available soil moisture and potential crop failure. The physical problems and the soil management practices that cause the problem must be clearly identified before preventive or remedial technologies can be developed.

Dense or hard pans in the soil profile which are generic in origin or are through long-term soil formation offer little opportunity for remedial technologies. The challenge lies in trying to manage around this abiotic stress by way of research into their origin, magnitude and quantification of effects. The determination of the soil productivity index, PI index, (Kiniry et al. 1983; Gantzer and McCarty 1987; Thompson et al. 1992), for each soil system would be an important knowledge base to assist in crop production and land-use decision making.

Soil texture, should not always be considered as a soil property that is a causal factor to abiotic stresses, but is a soil property that must be managed around. Soil surface and subsurface texture is a standard measurement of soil survey used in Soil Taxonomy and therefore intensive soil surveys will provide this information. Potential soil moisture holding capacity and other potential effects as functions of texture on abiotic stresses will need to be verified before mitigating or management technologies are developed.

Climatic Problems

The climatic factors that can be counted as abiotic stresses are: (1) temperature; (2) precipitation; (3) solar energy; and (4) wind direction and velocity (Figure 3). With the exception of wind direction and velocity, there is little that can be done about climatic factors other than manage around these problems to mitigate as much as possible the effects of climatic factors on abiotic stresses. Long-term recorded climatic data can serve agrometeorological modeling and can be very valuable in making correct management decisions.

Research Needs for Abiotic Stresses

Research into mitigating abiotic stresses will need to develop uniform systems for the collection and storage of standard soils and climatic data. The data collected will need to serve not only the semi-arid region but will have to be intensive enough to serve local ecosystem needs. Soil characterization at a useable level will need to be a part of the database. An inventory of existing data sets should be the first step taken before new initiatives are undertaken. This will require the coordination of efforts between national institutions with some support and/or coordination from the international level.

This chapter lists broad concepts, specific abiotic stresses requiring research. Breakdown by watersheds or large management units, inventory of resources, indigenous technology will need to be included in the baseline study. This is one approach that will ensure bringing local level input into the planning processes of research needs.

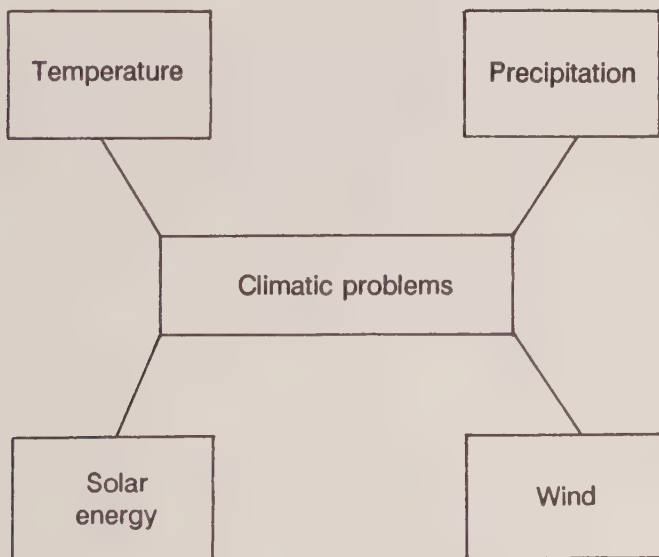


Figure 3. Climatic factors affecting abiotic stresses

Because of the numerous possible variations in abiotic stresses as functions of ecosystems, the specificity or priority stress requiring research might best be identified during the process of technology transfer or outreach activity. It is only then that specific constraints can truly be identified to implement research at the project activity level. This will require a new approach to research, not common, in past prioritization methodologies used to identify specific topics for research. Therefore, in this chapter and for the purpose of planning, only general or relatively generic constraints will be identified.

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National Policies and Strategies for Mitigating Stress in Semi-arid Tropics

P.V. Shenoi

Abstract

Sustainable agriculture in the semi-arid tropics requires not only sound agricultural technology but also a farmer-friendly socioeconomic policy framework. Agricultural scientists will have to work closely with economists, sociologists and government administrators to ensure that the dryland farmer gets incentives to adopt technologies that increase his farm production on a sustainable basis. Once this is assured, it is the farmer who will energetically chase the agricultural scientists for viable technologies to secure an optimal output of crop/food, fuel and fodder. Agricultural research has two primary responsibilities: firstly to help the farmer optimize the productivity of soil, water, sunlight, and other natural resources, and second to employ the right combination of crop (food/fodder/fuel/nonfood cash crop) and animal production technologies without compromising long-term sustainability. We should build on the accumulated experience in Africa and South Asia to help the agricultural scientists to respond to this challenge.

The bulk of semi-arid tropics (SATs) and stressed environments therein are situated in sub-Saharan Africa and in South Asia, particularly, India. A study made by the Commonwealth Secretariat in the mid 1980s shows that population density will exceed the carrying capacity of land and other natural resources by 2000 AD in Zimbabwe, Swaziland, Malawi, and Lesotho; and this excess will be 100% or more in Uganda, Nigeria and Kenya (Commonwealth Secretariat 1988). India will be in a very uncomfortable position in this respect by 2000 AD. This desperate situation calls for a very deliberate attempt to review the adequacy of the prevailing policy framework regarding social, economic and technology requirements. The purpose of this chapter is to attempt the following:

- evaluate national policies for attaining sustainable agriculture in SATs of Africa and South Asia;
- define policy areas that need attention; and
- identify the role of research in developing long-term strategies.

Sub-Saharan Africa

The World Development Report (1992) published by the World Bank (World Bank 1992) has cited rapid population growth, agricultural stagnation and

environmental degradation as the common maladies of most sub-Saharan countries in recent decades. These three factors have been and are mutually reinforcing. The World Bank recently completed a study of this nexus for gaining a better insight into the causal links and possible remedies. Its preliminary findings are presented in the following paragraphs.

The Problem

Abundant land, scarce capital and limited technology in sub-Saharan Africa dictated shifting cultivation and grazing as the strategy for subsistence. As population density grew slowly in the first half of the twentieth century, these extensive systems evolved into more intensive systems, (as in Rwanda, Burundi, the Kenyan Highlands and in parts of Zaire) which however, failed to adapt to sharply accelerated population growth over the past four decades. Traditional uses of land and fuel have depleted soil and forests and contributed to an agricultural crisis. Stagnant incomes and the absence of improvements in human welfare have impeded the demographic transition. A combined effect of high population densities and low investment has caused arable land per person to decline from 0.5 hectares in 1965 to 0.3 hectares in 1987 (a 40% decline in one generation !). As a result, in many parts of sub-Saharan Africa, fallow periods are no longer sufficient to restore fertility. Population growth has resulted in people cultivating land not previously used for farming. There is thus strong evidence that economic stagnation is delaying the decline in human fertility; family size is higher (to provide additional labor) where the land damage is the greatest and fuel wood supplies are depleted.

The Solution

In its detailed study on sub-Saharan Africa (World Bank Report 1989), the World Bank cites the FAO finding that only 30% of Africa's land is capable of sustained production of rainfed crops; only about one quarter of this is used, but much of the rest is under primary forests that need to be conserved for environmental reasons. The necessary productivity gains can come only from technological and structural changes. This will involve a more intensive use of chemical, biological and organic inputs; the integration of livestock into farming systems to use animal power and manure; the introduction of new higher value crops; and improved animal and crop husbandry. A blend of economic and scientific policy environment will be required to make these changes profitable to farmers through:

- installation of better rural infrastructure, particularly roads to reduce the cost of input supply and marketing;
- introduction of greater security of land tenure to encourage investment and land conservation (the widespread prevalence of laws regarding common property rights, maintaining traditional rights of communal land tenure, tend to militate against efficient and sustainable use of land);
- provision of improved financial services to help farmers to save as well as to borrow for investment;

- adoption of better methods of farm technology, e.g., the development of higher yielding varieties, expanding fertilizer use on a sound basis, better control of pests and diseases, more efficient provision of irrigation, farm equipments and other supplies. Improvement of agricultural research and extension are also essential; and
- provision of rural infrastructure, developing farmers' associations and recognizing the role of women.

The World Bank study commends the example of Rwanda, one of the few African countries in the semi-arid tropics whose agricultural production grew faster than population between 1966 and 1982. This growth was without using chemical inputs or improved varieties. The key was the Government's forbearance from over regulation and its willingness to allow market forces, to fix the level of agricultural prices, to regulate the value of foreign exchange, to respect farmers priorities in fiscal matters and also through effective rural institutions. The study strongly urges that the traditional development approach, emphasizing that the government participation in supplying services and technologies, must be complemented by a strategy of promoting demand for appropriate agricultural practices and inputs, for planned families and for resource conservation. Demand for these things can be promoted by:

- removing subsidies that distort prices and introducing incentives to promote more efficient use of resources;
- improving land-use planning to promote intensification and protect valuable natural ecosystems;
- clarifying resource ownership and land tenure, giving legal recognition to traditional common property management and private ownership, and reducing state ownership to encourage investment;
- supporting programs for girls, women, health, nutrition, family planning and NGOs; and
- expanding investment in public health to improve labor productivity.

Some Successful Examples

The above structural policy changes are essential for encouraging farmers to adopt progressive technology for stepping up their output and revenue as well as to create an interest in conservation. Several African success stories have underlined the soundness of this approach. As example, in Kenya's national soil conservation program, (launched with Swedish funding in 1974 and continuing through Kenya's national extension project) has helped introduce conservation effective farming systems on thousands of small holdings, with farmers doing most of the work without wages. Other successful techniques include the use of surface mulches, the introduction of crop varieties that emerge early and protect the soil against early rains, and intercropping which provides a denser soil cover, thus increasing output and providing more stable yields. Minimum tillage (sowing crops through a sod of dead weeds or stubble) can reduce erosion and increase yields. In undulating areas, sowing of vegetative bands of grass (such as vetiver) along the contours can reduce soil erosion and promote water infiltration. In Burkina Faso, farmers place lines of stones across contours of land prone to soil erosion;

these porous stonelines slow down runoff, increase water infiltration and collect top soil. They can restore desertified land. To create an impact, the soil conservation practice must improve crop yields, cost little or nothing in cash, and involve no expensive machinery. If tree sowing is involved, it must produce timber and fuel wood or fodder and should not conflict with the labor needs for crop production.

The Next Steps

The fuelwood crisis in many parts of Africa can be alleviated only by communal woodlots and plantations of fuel wood species, along with systematic management of forest cover. This is beyond the capabilities of the forestry services in many sub-Saharan countries; there is a reasonable chance of success if local communities can be motivated and charged with the responsibility to limit forest exploitation—to what is needed to meet rural every day needs and a part of the urban energy needs without causing environmental damage. This can succeed only when wood becomes a marketed commodity and prices are attractive to growers; this is already happening in most parts of eastern Africa.

While the above paragraphs outline the basic prerequisites for promoting efficient and sustainable dryland farming in semi-arid regions, it has to be recorded that in most sub-Saharan countries, there is no distinct and deliberate policy to promote such dryland farming. Many of these countries are primarily concerned with maximizing output from their high potential regions. A lower priority is attached to semi-arid regions. No special policies seem to exist for low-potential zones, where sustainability is of critical importance. The closest we can get to, in terms of a policy is the encouragement given to small farmers to grow more drought tolerant crops. But this is not backed by a specialized policy support. Notable exceptions seem to be Kenya, Botswana and Namibia. In Kenya, there is a separate Ministry for the development of arid and semi-arid regions; and it works closely with the Ministry of Agriculture to focus on sustainable agriculture, amongst other avocations, in the drier areas of Kenya. Botswana and Namibia have a very high proportion of land under semi-arid conditions; but here again, the emphasis is on maximizing production with available inputs, with sustainability taking a lower priority.

Policies for Development of Indian SAT

For the last 10 years, the Indian planners have recognized the socioeconomic and environmental implications of the rapid agricultural growth achieved in relatively small irrigated tracts and the extremely slow growth in rainfed (i.e., nonirrigated) areas. The Eighth Plan (1992–97) (India: Planning Commission 1992) accords a high priority for nationwide demonstration of dryland technologies, mainly through the establishment of micro watersheds (500 to 5000 ha each) in the development blocks where the coverage of irrigation is less than 30%. Rs.8000 million (1 USD = Rs.30), to be spent over a period of five years (1992–97), has been earmarked for this project. To protect the project from financial limitations of the implementing agencies (i.e., the state governments) the central

government has fully funded the scheme. A holistic approach has been adopted, including, inter-alia, the diverse production systems, be they seasonal cropping, perennials like horticulture, forestry or animal husbandry activities. Use of vegetative barriers is the principal means to prevent soil erosion and to conserve moisture. Arable and nonarable lands as well as drainage lines will be treated in an integrated manner. The watershed projects seek full involvement of beneficiary farmers both in planning for development and for execution of various activities. Successful demonstrations of in situ moisture conservation is expected to trigger further investment by farmers' groups. An important part of the program is to demonstrate cultivars which are of short-duration and which can withstand drought stress.

The Support Program

Apart from market-oriented policies which will provide incentives to farmers to adopt improved technology and participate in the project, following critical factors have been identified. These factors are:

- availability of sound databases and expertise in helping draw up feasible watershed plans;
- assistance in the application of appropriate technology to make investment cost-effective;
- Centralized overseeing of integrated planning by all public agencies dealing with agriculture, land administration, forests, animal husbandry, irrigation, and drainage, panchayats (county government) etc; and
- encouraging full participation by farmers, who would have the dominant voice in collectively resolving the conflicts between private and public interests while safeguarding their own interests.

There are early indications that the scheme is making better progress than the projects implements earlier.

Role of Scientific Institutions in Developing Effective Strategies

It is clear from the foregoing discussion that sustainable agriculture in the semi-arid tropics requires not only sound agricultural technology but also a farmer-friendly socioeconomic policy framework. Agricultural scientists will have to work closely with economists, sociologists and government administrators to ensure that the dryland farmer gets incentives to adopt technologies that increase his farm production on a sustainable basis. Once this is assured, it is the farmer who will energetically chase the agricultural scientists for viable technologies to secure an optimal output of crop/food, fuel and fodder. In my view an agricultural scientist has two primary responsibilities: firstly to help the farmer optimize the productivity of soil, water, sunlight, and other natural resources, and secondly to employ the right combination of crop (food/fodder/fuel/nonfood cash crop) and animal production technologies without compromising long-term sustainability. The accumulated experience in Africa and South Asia recounted earlier should help the agricultural scientists to respond to this challenge.

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Agrometeorology and Sustainability

B.V. Ramana Rao

Abstract

Most of the stresses experienced by the agricultural production systems are either directly or indirectly induced by the changing weather conditions. Therefore, the current interests in agrometeorology are focused on:

- *evolving agrometeorological data base management systems for agricultural planning and to guide day-to-day agricultural operations on the basis of weather forecasts;*
- *increased understanding of the interaction between weather and management practices on crop growth and development through simulation modeling for developing sustainable agricultural production systems;*
- *developing early warning systems on occurrence and spread of pests and diseases using real time weather data to so as adopt plant protection measures with minimum use of chemicals;*
- *assessment of global climatic change and its impact on biological productivity to evolve strategies for environmental protection and ecological security.*

To extend the benefits of agrometeorological research for sustainable agriculture, we may consider the following:

All the products that are available from the meteorological services are not used effectively at present. There is need to clearly demonstrate the economic and environmental benefits that can be achieved through agrometeorological inputs in agricultural planning and management.

Applications of agricultural meteorology cut across political boundaries. International collaboration has to be strengthened particularly in the areas of crop modeling, modeling weather effects on pests and diseases and in monitoring global climatic change and its impact on agricultural production.

Soil degradation is a universal phenomenon observed in arid and perhumid climates. The problem has to be tackled through cooperative research all over the world.

The agrometeorological research should ensure a sustainable agricultural production system and enhancement of the quality of environment for future generations.

Introduction

Most of the stresses experienced by the agricultural production systems are either directly or indirectly induced by the changing weather conditions. Therefore, the current interests in agrometeorology are focused on:

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- increased understanding of the interaction between weather and management practices on crop growth and development through simulation modeling for developing sustainable agricultural production systems;
- developing early warning systems on occurrence and spread of pests and diseases using real time weather data to adopt plant protection measures with minimum use of chemicals; and
- assessment of global climate change and its impact on biological productivity to evolve strategies for environmental protection and ecological security.

Agrometeorological Database Management

This will require:

- collection, scrutiny, processing, and analysis of agrometeorological data for respective locations/subzones/regions/states and transforming these into computer compatible format;
- development of computer software to monitor weather based decisions in agriculture for effective utilization of long-, medium- and short-range weather forecasts to minimize shortfall in agricultural production induced by vagaries of weather; and
- feeding of information to the farming community.

Efforts have been made to evaluate the length of the growing season using information on climate and soils (Cochme and Franquin 1967; Virmani 1975). Contingency crop plans have been worked out to minimize the risks associated with the variability in the length of the growing season as affected by the date of commencement of sowing rains (Venkateswarlu 1983). Droughts occur due to failure of rains either in the beginning or in the end of season and also due to long gaps in between successive rainfall events. Depending on the time of occurrence, droughts are characterized as early, mid-season and terminal droughts. Technological options to manage terminal droughts are still at large (Singh and Ramana Rao 1988). Serious efforts have to be made for creating a data base to make use of real time weather data and operationalize weather forecasts.

Crop Modeling

There is a need to:

- conduct multilocation experiments for generating data on phenology, radiation interception by the crop canopies, water use pattern, and partitioning of dry matter production;
- build subroutines for crop response to weather, input use, management practices, biotic and abiotic stresses, and integrate these into crop growth models;

- test validity of models using independent data sets generated from varied agroecological situations; and
- integrate crop growth models with geographical information system (GIS) to classify growing environments and develop sustainable agricultural production systems.

Crop growth simulation models though still in a developing stage are proving to be useful in decisions related to global warming. Crop models should become increasingly important in decision making. When coupled with the appropriate weather, soil, management, economic and genetic information, the models can provide an output that is quite useful in improving management strategy and policy decisions.

Weather Effects on Pests and Diseases

In this area, there is need to:

- standardize techniques for collection of data;
- study spatial distribution of the occurrence of pests and diseases in relation to weather parameters; and
- develop forecasting/warning systems for the incidence and spread.

Disease warning models utilizing meteorological data have been developed by Jones et al. (1984) for apple scab, and Coakley and Line (1981) for stripe rust in wheat. To aid farmers in determining the need for crop protection, research efforts have to be made for better understanding of weather conditions that give rise to disease, the dynamics of ensuing epidemics and the physiology of disease induced reductions of yield.

Most of the organisms in the ecosystem are beneficial including those members of the insect world which are recognized as pollinators, predators, parasitoids, soil processors, etc. Less than one percent of insects are pest species and many of them occur sporadically in nature. Quantification of relationship between time of occurrence of pests and their intensity with weather phenomena will enhance our ability to provide early warning systems to minimize excessive use of plant protection chemicals.

Global Warming and Climate Change

Carbon dioxide is the most important greenhouse gas followed by chloroflurocarbons, methane, nitrous oxide and tropospheric ozone. There is a growing concern that atmospheric abundance of these gases is increasing. Global circulation models predict 1.5 to 5.5°C increase in global temperature due to greenhouse warming by the year 2030 which will in turn cause widespread changes in precipitation patterns, monsoon circulations and in sea level rise. Most climate models predict that doubling of carbon dioxide would reduce current food production by 3 to 17% (Raghubanshi and Singh 1991). Global warming will also affect natural biota as species ranges are expected to shift poleward by 700 to 900 km within the next century. Therefore, there is a need to:

- critically review the sources of greenhouse gas emissions;

- examine the policy options for reducing the buildup of greenhouse gases in the atmosphere; and
- design and develop agricultural production systems and management practices that can moderate the impact of global warming and climatic change.

Conclusions

- All products that are available from the meteorological services are not being used effectively at present. There is a need to clearly demonstrate the economic and environmental benefits that can be attained through agrometeorological inputs in agricultural planning and management.
- Applications of agricultural meteorology cut across political boundaries. International collaboration has to be strengthened particularly in the areas of crop modeling, modeling weather effects on pests and diseases and in monitoring global climatic change and its impact on agricultural production.
- Soil degradation is an universal phenomenon observed in arid and perhumid climates. The problem has to be tackled through a cooperative research, all over the world.
- Agrometeorological research should ensure a sustainable agricultural production system and enhance the quality of the environment for future generations.

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Agrometeorology for Sustainable Agriculture in Stressed Environments

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Abstract

The report of Working Group I on Agrometeorology considers agroclimatic resources, their monitoring, use of agroclimatic databases for mitigating or managing climatic risks, present status of research in India, and research and development (R&D) gaps for regional and international cooperation. The agricultural production system consists of three major entities: the geosphere, biosphere, and sociosphere. All these are dynamic entities which encompass various subsystems; their components are continuously interacting and integrating with one another both within and beyond the boundaries of their respective systems. The consideration of inter-relationships revolves round agrometeorological goals, i.e., all aspects of weather and farming conditions.

A sustainable farming system needs a management strategy that has to select appropriate varieties, cultural practices, soil fertility program, and pest management approaches with reduced costs of purchased inputs, minimize the impact of the system on the immediate and off-farm environment, and provide a sustained level of production and profit from farming.

***Air** (humidity, temperature, wind speed and direction), **water** (precipitation, soil moisture, irrigation), **land** (soil fertility, slope and orientation), and **energy** (solar and other inputs) have tremendous effect on an agricultural system. In a stressed environment, all aspects connected with soil aeration, moisture, thermal, and wind stresses and their impact on increased toxicity, impeding growth and development of plants, excessive transpiration loss in high temperatures, injury at the cellular level under cold conditions, and lodging and uprooting in a windy environment need to be considered to reduce malevolent effects on crop production.*

The assessment of agroclimatic resources requires knowledge of climatic classification [adopting cluster, principal component analysis, and the use of geographic information system (GIS)]; adequacy of sowing rains; onset and withdrawal of monsoon to determine the length of the growing season; dry and wet spells to optimize irrigation; occurrence of pests and diseases to apply plant protection measures in time to reduce crop losses, and advance crop yield forecasting for assessment of food availability. All this information needs to be collected, collated, and presented in a user-friendly mode so that all sections of the farming community can take advantage of the available knowledge.

In general, agroclimatic databases are widely distributed and are not readily available for short time intervals. The data compiled by the combined effort of World Meteorological Organization (WMO) and Food and Agriculture

Organization (FAO) for global databases on a monthly basis cannot be used for day-to-day farming operations. The database in India is also limited. Location-specific information for a small area or administrative unit, i.e., a taluk or district, is not available. The agrometeorological forecasting has limited applications for the farmer's day-to-day planning and management of the crop system. The National Center for Medium Range Weather Forecasting was instituted to provide area-specific, crop-specific prevailing weather and predicted weather information to farmers.

There have been very useful studies conducted by India Meteorological Department, Indian Council of Agricultural Research (ICAR) institutions, state agricultural universities, and other international organizations in defining the parameters relevant to agriculture. But they are not comprehensive at the level required for delineating agroclimatic zoning and subzoning of the country. Even if the prevailing and predicted weather information becomes available, the existing knowledge on crop-weather relationship is rather fragmentary.

The areas which need R&D thrust in the field of agrometeorology are outlined.

The advancement of agrometeorology can play a significant role not only in sustaining the agricultural production but also in improving the production system, economizing external inputs, minimizing the losses and use of nonrenewable energy sources, and maximizing the use of renewable natural resources.

Introduction

A sustainable farming system needs management strategies with respect to varietal selection, soil fertility programs, and pest management approaches in order to reduce the input cost and provide a sustained level of production and profit, from farming.

For planning an efficient agricultural production system, information on weather and climate is vital and also a major resource for agricultural productivity and sustainability, especially in a stressed environment. Considering the complete agroecoclimate system it is necessary to develop farming systems that are sensitive to climate and weather, sustainable, and not susceptible to degradation on account of climate.

For an ideal farming system, a precise temporal and spatial weather information is needed so that the agriculturists can optimally plan their strategies to achieve the above objectives. Unfortunately, there is a limit to predictability and the problem becomes more formidable with the extension in the temporal range and decrease in space. Considering these limitations, a method is presented for optimal use of information on climate assessment and weather prediction as available for economically and environmentally viable, agricultural planning and management.

Weather and Climate

Climate is defined as the long-term average conditions of weather at a particular

place or region along with its statistical variances. Weather relates to instantaneous atmospheric conditions at a place or region. Thus, variations in the weather are ever prevailing, and the changes or variation in climate is slow, within the various statistical extremes as defined in the long-term data.

The weather of a place is generally defined in terms of the various weather elements, i.e., temperature, humidity, wind speed and direction, pressure, rainfall, sunshine, and cloud cover. Of these, rainfall is normally the single most important element for agriculture as it determines the moisture supply to crops. Wide fluctuations in rainfall from year to year and from place to place cause a stressed environment in the form of drought and floods. Next in the hierarchy could be considered the extreme values of temperature, sunshine, or wind because the crops often can tolerate these until and unless they are accompanied by rain-induced stresses.

Weather Forecasting

Weather forecasting has been done from time immemorial but the present-day scientific weather forecasting practices are of recent origin, beginning with the invention of the barometer by Torricelli in 1643. This led to the systematic observations of weather elements all over the world. To derive a three-dimensional picture of atmospheric circulation, observations are made on the surface as well as in the upper atmosphere. The various elements observed include temperature, wind direction and speed, humidity, atmospheric pressure, cloud, and rain.

Weather forecasts can, with respect to time, be categorized into:

- Short-range weather forecasts valid for the next 72 hours or less.
- Medium-range weather forecasts valid for 3 to 10 days in advance.
- Long-range weather forecasts valid beyond 10 days.
- Assessment of climate changes in decades or greater time spans.

Short- and Medium-range Weather Forecasting

Weather forecasting is basically an initial value problem. The techniques in use can be divided into three broad categories: (1) conventional or synoptic methods, (2) statistical methods, and (3) numerical weather prediction techniques (NWP). Each of these is discussed in brief here.

Synoptic methods. Synoptic methods involve detailed analysis of current weather reports from a large area (a few hundred kilometers on either side of the area of interest). The current weather patterns are associated with the past analogues and forecasts are based on the assumption that a current situation will evolve on the lines of the past weather patterns. Often, selection of the analogues is based on the experience and memory of the human forecaster. But with the advent of computers, picking up of analogues has become faster and more objective. Recent studies have shown that such methods can only provide useful forecasts for a short range (less than 3 days).

Statistical methods. Statistical methods establish suitable regression equations or, in certain cases, more sophisticated statistical relationships between the predictant and the predictors.

Normally, selection of the predictors is based on a possible physical relationship with the predictant. Such techniques have been useful for short- and long- range forecasting. Though tested for medium range forecasting too, the success has been limited. Statistical techniques have, however, become popular with improved output products from numerical weather prediction (NWP) models for predicting specific events such as hail or no hail, fog, minimum temperature, cloud cover, and rainfall.

Numerical weather prediction. The NWP technique considers that the behavior of the atmosphere can be represented and governed by physical laws which can be expressed by differential equations with their boundary conditions. These equations, when expressed as a closed system, are known as an atmospheric model. The basic equations which form the atmospheric model are:

- Equation of horizontal motion; two-dimensional Navier–Stoke equation
- Continuity equation for dry air
- Equation representing conservation of moist air
- Equation representing the First Law of Thermodynamics
- Hydrostatics equation
- Equation of state

For a numerical solution of these equations, it is necessary to discretize the atmosphere in horizontal and vertical planes. The solution of these atmospheric model equations is carried out iteratively, every time step. A one-day forecast would need 1200 steps and solving all equations at each grid point means about 10^{13} operations. Considering that the reasonable time needed for a 10-day forecast is four to five hours, only very powerful supercomputers, can meet the requirement. That is why the most powerful computers available at any time are put to solve meteorological forecasting problems.

Long-range Forecasting (Seasonal Forecasting)

For the preparation of long-range (seasonal) forecast, say for the monsoon season, different antecedent meteorological parameters over the monsoon region and the rest of the globe have been considered and screened. On this basis important parameters have been identified which are used to forecast the monsoon rainfall in India. These parameters are physically connected with the monsoon circulation and are related to temperature, wind, and pressure. Snow cover over the Himalayas and Eurasia during winter also seems to have connection with the monsoon.

After elaborate research on the physical connections between monsoon flow and meteorological parameters, 16 parameters have been selected. The relationship of monsoon rainfall with individual predictors exhibits a nonlinear relationship. To take care of this nonlinearity, a curvilinear relationship with all the parameters has been combined and a power regression model has been developed. The forecasts from this power regression model (Gowariker et al.

1989, 1991) has been found encouraging both during the sample period (1958–1980) on which the model was developed and during the independent test period (1981–1988).

This newly developed long-range forecast model has given an excellent seasonal forecast during 1988 to 1992.

Climates Studies for Sustainability

Every living being tends to adapt to the climate of a place of living, but any variation beyond a limit (say beyond one standard deviation) disturbs the balance. Considering specifically, agriculture and livestock, with the present stage of research in genetics, it is possible to develop a genotype which produces maximum output in a given climate and soil, or what may be termed agroclimatic conditions. A country such as India, has diverse climate and soil conditions. For efficient planning of the cropping strategy, it is necessary to divide it into well-defined agroclimatic zones. The Indian Meteorological Department, purely on the basis of rainfall homogeneity and to some extent considering state boundaries divided the country into 35 subdivisions. The Planning Commission (Khanna 1989), however, divided India into 15 agroclimatic zones. Recently, the National Bureau of Soil Survey and Land Use Planning of ICAR, considering the agroclimatic resources and soil conditions, has divided the country into 21 zones (Sehgal et al. 1990). Further subzoning has also been carried out on the basis of detailed climatic analysis along with soil characteristics.

Climate fluctuates naturally in various degrees and various time scales, over years, decades, or even longer periods.

The assessment of these climatic variations is very important for planning and ensuring sustainable agricultural production. It is more important for India, because here we want not only sustained but increased production to meet the needs of a growing population.

Predictability

Predictability is the period up to which the forecast variables are well correlated to the realized field and the forecast products have adequate skill or use. The various parameters which set the limit of predictability are: (1) hydrodynamic instability inherent in a nonlinear set of governing equations and growth of errors starting from a small uncertainty at the initial state; (2) lack of understanding of physical processes and their inclusion in the atmospheric models; and (3) lack of precise information on the initial state because of data gaps.

Theoretically, therefore, the predictability of the deterministic forecast can only be about 14 days, but the practical limit is far lower. Deterministic forecasts have a predictability of about eight days in the middle latitudes of the northern hemisphere and less than three days in the tropics. Present research is dedicated to increasing the practical limit to three to five days in tropical areas and 10 days and more in the mid-latitudes. In terms of mean forecast (seasonal forecast), in complete contrast, the same conditions lead us to conclude that the tropical regions are more predictable than the middle-latitude areas. This concept is being

exploited by Indian meteorologists for producing successful seasonal forecast. Figure 1 illustrates the limit of predictability.

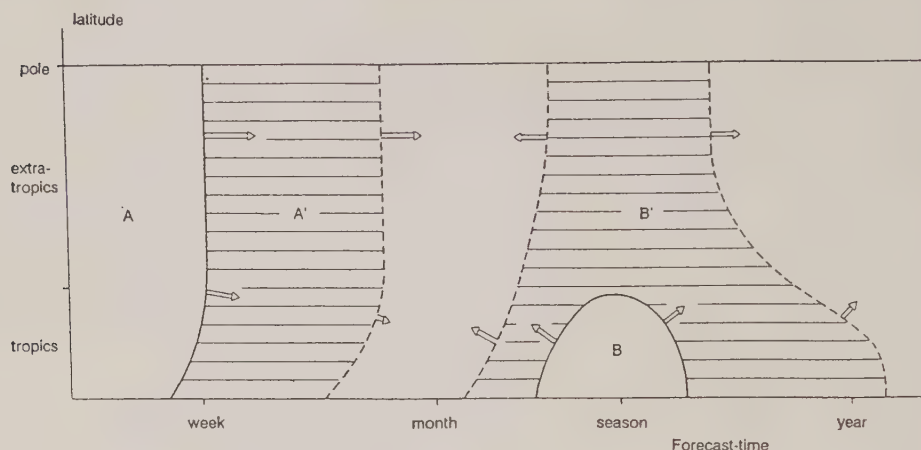


Figure 1: A schematic diagram with forecast time on a logarithmic scale along the horizontal axis and latitude along the vertical axis. The solid lines show present limitations for forecasts in an appropriate way, while the dashed lines show the same at some future time. Arrows indicate the directions of improvements. The various areas signify the models which may be characterized as follows:

- A. Forecasts performed using the most sophisticated available computer models of the atmosphere.
- A': The possible future expansion of A.
- B: Forecasts with a high statistical content, performed using a combination of statistical techniques and a variety of models representing the atmosphere and the coupled atmosphere-ocean system.
- B': The possible future expansion of B.

Weather-based Farm Planning

Long-term Planning

For long-term planning, the scenario development based on the global climate models (GCMs) becomes important. The prediction of the long-term climate fluctuations in the present state-of-the-art is far from precise, certain indicators are available that can help in long-term planning of cropping strategies. As discussed elsewhere, all the work related to global warming and its projection at present should be taken for general guidance and not for any policy or economic decision-making process. It is hoped that the on-going research on more sophisticated coupled GCMs which would take into account the feedback processes of the complete climate system will help understand the scenario more accurately.

Medium-term Planning

Medium-term planning options include considerations of water and energy balance for an agroclimatic zone over a period of several months or a season

in advance: for example, how the different varieties or crops are affected by the weather of a season so that if the seasonal weather can be forecast in time, the appropriate crop or variety can be planted. This assessment may also be based on the probabilities of different season types.

For planning of the cropping strategy a season in advance, the seasonal forecasts, for example, of the monsoon rainfall are of great use. The long-range forecasts or the seasonal forecasts primarily give information on departure of rainfall from the normal for the country as a whole and the season as a whole. This, therefore, is of limited use for planning at the microlevel but could be of use for overall planning at the central level. To further define the seasonal forecast for the country as a whole in terms of months and subdivisions, the studies by Saseendran and Datta (In press) are of great help. Such analyses provide the probability of a particular subdivision having assured rainfall in any specific month of the monsoon season. This could help in planning the crop type and variety, depending upon the scenario built up. But then, the information being not precise, it is necessary to work out associated risks or threat which could help the farmers in being fully prepared to meet or absorb these risks, as a consequence of their decisions based on the information derived from long-range forecasts.

Short-term Operation Decisions

Short-term operational decisions relate to a period ranging from a few hours to a few days. These often involve decisions, based on the state of the crop and current and forecast weather (short and medium range), for such farm operations as weeding, irrigation, harvesting, chemical spraying, and fertilizer application.

The need for prior information on variability of pentad or weekly rainfall pattern (Biswas and Khambete 1979; Sarkar et al. 1978) and day-to-day precipitation forecast is of great importance for dry farming of the arid and semiarid regions of the country. In addition to rainfall, a correct forecast of extreme temperature conditions, strong winds, dew, unseasonal rains, cloudiness, humidity, and other conditions is of great importance for the increase in productivity and to save the costs of inputs (WMO 1990). However, for this purpose, farmers have to be told in their language, sufficiently in advance, enabling them to take appropriate actions. The authorities must provide the necessary inputs so that the farmers can act on the advice.

Current Status in India

Noting the usefulness of agroadvisory services, the Government of India recently launched the National Center for Medium Range Weather Forecasting (NCMRWF) and established the agroadvisory services. This was primarily because Indian farmers need a longer reaction time to gear facilities for remedial actions based on weather-based agroadvisories. This Center has started initial experiments based on its global spectral models through the state agricultural universities (SAUs). In March 1991, issue of weather-based agroadvice was started from five state

agricultural universities where a department of agrometeorology and its nucleus infrastructure were available. This was extended in 1992 to 10 universities and it is now planned to cover most of the state agricultural universities. The NCMRWF supplies the weather information for the next three days, which the agrometeorologists of the universities interpret in terms of the agroadvisories with the advice of other area specific scientists and disseminate to identified progressive farmers to start improving the operational as well as R&D aspects of weather forecasting and crop-weather relationships.

The above said experiment is unique—nowhere in the world, a systematic way of integrating the weather and agriculture information is known to exist. This is a multidisciplinary effort of the departments dealing with agriculture, meteorology, communication and information sciences which are involved in developing as well as implementing the project. It is expected that in a couple of years this integration will take place at the zonal level. India has been divided into 127 agrometeorological zones (Ghosh 1991). Each zone has a zonal agricultural research station of state agricultural universities. These zonal stations are supported by ICAR under the National Agricultural Research Program (NARP) to strengthen the regional faculties of the universities (Ghosh 1991). It is proposed that the agriculture expertise at these Centers and meteorological information from the NCMRWF be used so that area-specific, crop-specific advice can be issued through radio, television, and other media to the farming community. Through this process it is expected to not only integrate the agroclimatic and soil databases but also to considerably improve their use in optimizing the agriculture production system.

Research Gaps and Proposed Research Thrust Areas

In spite of the fact that agrometeorology was first started in India, the progress in the subject has not been fast. Out of the 27 state agricultural universities, hardly 20% have agrometeorology in one form or the other. Even in ICAR research laboratories the R&D on agrometeorology is carried out only at a few institutes. The All India Coordinated Research Project on Agrometeorology needs to be strengthened in all the agroclimatic zones. The information on crop weather relationships at the zonal level is rather fragmentary. The use of a simulation model is again limited to a few R&D projects in the country. To generate opportunities out of the vagaries of weather it is absolutely necessary to exploit the meteorological information as a resource along with information on soil and other plant phenology needs. Information on the crop-soil-atmosphere system may be integrated so that decisions can be made depending upon the prevailing and predicted weather scenarios and losses can be minimized, for improvement in production without degrading the soil or the ecosystem. Keeping the above in mind, following are some of the areas which need R&D thrust in the field of agrometeorology.

- Development, validation, and documentation of crop growth simulation models for area-specific principal crops
- Optimization of regional agroclimatic resources for crop production and selection of cultivars

- Development of predictive models for outbreak and spread of pests and diseases
- Development of an expert system for on-farm decision making
- Evaluation of alternative strategies to deal with aberrant weather conditions
- Development of indigenous agrometeorological instruments including automatic weather stations and their networking
- Development of efficient agrometeorological forecast system including threat analysis at various time and space scales
- Coordination of R&D efforts on national, regional, and international level

In short, what we now need is a sustained and systematic research on agrometeorology at the zonal and the subzonal levels for development of meaningful agroadvise for our farming community on a continuous basis using weather information as a resource input for sustainable agriculture.

Recommendations

- Methods must be developed for optimal use of the products available from the meteorological services for economic and environmental benefits through agricultural planning and management.
- A model program is needed to demonstrate that international, national, and regional, meteorological and dryland research centers can come together to deliver advice for farmers that will help them sustain their production and improve their lot. This program should serve as a model for technology transfer and should focus on important crops in stressed environments.
- International collaboration in research, human resource, and infrastructure development must be strengthened in the areas of agrometeorology such as crop modelling, modelling weather effects on pests and diseases, and monitoring global climatic change and its impact to ensure sustainable agricultural production systems and enhancement of quality of environment for future generations.
- Use of Phytotron and similar equipment should be encouraged to develop strategies for farming practices under various climatic scenarios. This is the best course to prepare for possible threats of climate changes.
- Exploitation of the availability of powerful work stations, and the geographic information system (GIS) for precise delineation of agroclimatic zones and subzones needs to be encouraged.

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