Consultative Group on International Agricultural Research

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Soil, Water, and Nutrient Management Research, A New Agenda

At International Centers Week 1993, the Group asked the CGIAR Task Force for Agenda 21 to take a special note of the study then in progress under the auspices of IBSRAM, when preparing its proposals for developing marginal lands. That study has since been completed and its findings are contained in the attached report.

Members of the Group will be able to discuss the recommendations of this report in conjunction with those of the Agenda 21 Task Force.

Attachment

Distribution

- CGIAR Members
- Center Board Chairs
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IBSRAM Position Paper

SOIL, WATER, AND NUTRIENT MANAGEMENT RESEARCH - A NEW AGENDA

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Prepared under the auspices of:

The Australian Centre for International Agricultural Research
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The Swiss Development Cooperation
The U.S. Agency for International Development

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Foreword

Agriculturalists have long recognized human dependence on the conservation and management of soil, water, and nutrients. In our time, this concern is being felt more and more by the entire human community. For example, the price of soil erosion is felt more by the downstream water users than by the farmers from whose fields the soil came. All humanity suffers when water is poorly managed or inefficiently used. Likewise, the management of plant nutrients affects not only food productivity, but the quality of our water resources.

The growing universal concern for these natural resources is seen in the international fora concerned with environment and sustainable development. In Agenda 21 of the 1992 UN Conference on Environment and Development (UNCED), problems arising from the mismanagement of soil, water, and nutrients were recognized. Likewise, earlier international conventions referred directly or indirectly to the need for better management of these resources. The process of desertification that received so much attention in the 1970s and 1980s is basically a soil and water problem. Similarly, at international global-warming conventions it was noted that soil, water, and nutrient management greatly affect and will be affected by the climate change process. Likewise, the management of these three resources has a profound influence on biodiversity below- and aboveground.

The wise management of soil, water, and nutrients is critical in sustainable food production. Such management truly provides a "win-win" scenario for increased food production and simultaneous environmental quality enhancement. Unfortunately, however, the long-range benefits are sometimes not immediately obvious to today's farmers or business persons. As a result, some science-created and -tested technologies that increase yields and simultaneously conserve soil, water, and nutrients are not being used on farmers' fields. There is all too little motivational research to identify what needs to be done to stimulate farmers to use improved technologies and systems more effectively.

Another constraint on soil and water management research is the fragmentation of the efforts, along with the lack of a rational system, of sharing research information. Little attention has been given to the identification of research priorities and the development of strategies to carry out the scientific investigations. While additional financial support will be needed for this type of research, much can be done to better plan and coordinate the work that is already under way.

This report helps us understand more clearly the nature of soil, water, and nutrient management problems. It also identifies some areas of high priority and suggests mechanisms for better planning and information-sharing. It also shows how such research can be integrated with research concerned with genetic improvement and systems management.

IBSRAM and the authors of this paper should be congratulated on taking this important first step. Interaction with the scientific and development communities should help move the process to one that will return more from our current financial inputs, and in the future will attract even greater such inputs.

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PREFACE

To: Dr. Latham, Director General, International Board for Soil Research and Management

When we were asked to prepare this position paper we assumed it would be a relatively straightforward task assembling the basic facts about the current state of knowledge of how soil, water, and nutrients should be managed to sustain productivity and avoid environmental damage. Given that there had been several previous efforts to assemble the same information, the task did not appear too daunting. We met to prepare an outline at the International Board for Soil Research and Management (IBSRAM) offices in Bangkok in September 1993. The outline presented a conventional and rather comprehensive approach to the preparation of the position paper. It was circulated quite widely, and discussed at a meeting of the Steering Committee in Washington, DC in October 1993.

The responses received were divergent and conflicting, ranging from the need to broaden the scope to the need to sharpen the focus, to give more attention to implementation but to avoid proposing a strategy, and to concentrate on the farming systems but to use the watershed as the basic component in the system. The one thing that was quite clear was the keen interest in the topic.

We initially pursued a broad approach, on the basis that it would be easier to sharpen the focus than broaden it at a later stage. As we assembled the material, it became increasingly clear that we were restating technical problems and issues that had been rehearsed in several earlier papers. It also became evident that the conventional solutions to the problems of soil, water, and nutrient management (SWNM) were making little impact in the areas where needs were greatest, and environmental degradation was proceeding unabated. Thus when we came together in Bangkok in February 1994 to finalize the document, we felt that we had to concentrate on how existing scientific knowledge of SWNM could be made to work for the community of farmers and others living near the bottom of the unsustainability spiral and in danger of falling into the poverty trap with very little hope of escape.

The goal statement and terms of reference conclude by stating that we should propose strategies to improve resource management and to address the identified problems more efficiently. We have resisted the temptation to propose a strategy to provide additional resources for SWNM, in spite of an increasing conviction that time was running out for effective action to achieve positive results. We have confined ourselves to the suggestion that a mechanism be created to harmonize current activities, and prompt broader interdisciplinary approaches in tackling the problems. We have identified the critical issue as the failure to start the research process at the user level, and to establish a continuing mechanism for interchange of knowledge between the farmer and other practitioners and the researchers. We may have given insufficient attention to the specific technical problems of soil, water, nutrients, forestry, horticulture, and the management of grazing lands and vegetation. However, we feel that the basic changes in approach we are suggesting apply to these and other topics.

In assessing the relative significance of the problems, we found that the information presently available on which to base a rational prioritization of research needs was not adequate. A high priority must be given to assembling, analyzing, and making that information available.

As part of the exercise, we circulated a simple questionnaire to various organizations and a few individuals whom we thought were well informed of the problems. The responses we received strengthen our own conclusions that the greatest research need is to determine how to make existing knowledge work for the user by giving more emphasis to adaptive research, and greater attention to user perceptions.

The preparation of this paper has been an interesting but taxing exercise. At the very end, we have included a subtitle - 'A new agenda' - which was not what we were asked to prepare, but what we firmly believe is needed. As with other proposals for change, we expect a mixed reception as the contents are digested and the new flavours tasted. We will feel amply rewarded if even some small changes in funding arrangements occur which can benefit the environment and the many millions who are at the base of the spiral of unsustainability and perched on the edge of the poverty trap.

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Bangkok, 3 March 1994

The goal statement and terms of reference

Goal statement

Prepare a position paper to:

* evaluate the need for soil, water, and nutrient management research, including strategic, applied, and adaptive research;
* assess whether current international capacities are adequate to address the major issues related to sustainable resource management;
* enhance the interaction between the organizations involved in soil, water, and nutrient management research, and between such organizations and those involved in other areas of research related to sustainable land use and environmental impact; and
* propose strategies to improve resource management research.

Terms of reference

1. Define the major problems of soil, water, and nutrient management (SWNM) in relation to the sustainability of farming systems and the effects of different systems of management on natural resources. The definition should be based on previous studies made of the need for international action to tackle the problems of SWNM and on the information available in existing data bases.
2. Define the major research needs to:
   - ameliorate the problems of SWNM;
   - realize the potential of SWNM resources;
   - generate technology to increase production;
   - prevent further land degradation and deterioration of water resources;
   - develop methods for transfer of technology between sites and between researcher and farmer; and
   - evaluate the impact of these technologies.
3. Identify policy issues and social conditions which impact the amelioration of SWNM problems or hinder the adoption of new technology.
4. Identify those problems for which new knowledge of the relevant principles exists to provide a solution, but where it is still necessary to integrate existing knowledge of principles with indigenous knowledge and apply it to the local situation.
5. Propose priorities for future research, indicating where:
   - research addresses common global problems and may best be undertaken by international organizations, and facilitated by better linkages between them; and
   - research is primarily local-specific and may best be undertaken by national organizations or national organizations in liaison with international bodies.
6. Review the extent to which current international initiatives address:
   - the problems of SWNM; and
   - the capacities of national and international organizations to conduct the needed research.
7. Propose strategies by which the problems may be more efficiently addressed.

Executive Summary

- At present there is no global strategy for research on the problems of sustainable land management, although there are many institutions concerned with specific aspects of soil, water, and nutrient management. The 'new agenda' of sustainability is an attempt to conserve natural resources in the face of continuing pressures from population growth and food demands. The problems to which these pressures give rise merit urgent attention.

- This position paper proposes a new scientific and development agenda to convert existing soil, water, and nutrient management research into a relevant part of the solution to the environmental crisis, rather than allow unwise policy, faulty research systems, and inadequate farming practices to contribute to the problem. The 'new agenda' is based on the premise that sustainable production systems can provide adequate food and economic wealth, and at the same time conserve soil and water resources effectively, which is a win-win situation. Where such systems are not in place, there is a potential downward spiral of unsustainability, as increasing pressure is put on land and water by human and animal populations.

- For developing countries, and particularly the poorer of them, only through greater productivity can the threat of environmental damage be reduced. Attention must be given to ensuring high productivity from stable soils, restoring and sustaining the productivity of resilient soils, and conserving fragile and marginal soils. Necessary measures are best implemented on a communal basis.

- Low rates of farmer adoption of improved management practices arising from policy constraints, or a lack of adequate adaptive research, have frequently been the stumbling block. Unlike the relatively rapid adoption of improved crop varieties, fertilizers, and pesticides, the adoption of contour strip-cropping, alley cropping, green manuring, and conservation tillage have represented major challenges to farmer operations, as they make increased demands on labour, capital, or land area. These techniques are not readily translated from the technological improvements demonstrated by scientific research into farmers' practices, as they rely upon local-specific interpretation of the particular farmer needs.

- We know how to make most soils yield more than they do at present. What we do not know, in many cases, is how to make changes which are adapted to social, economic, and political conditions in regions threatened by unsustainability. In this paper, we propose a much closer association of farmers and technical advisers with the existing research providers, so that farmer needs and decision-making constraints can be incorporated into research directions, with an iterative feedback-feedforward process to adjust the scientific principles of sustainable land and water management into practical farmer realities.

- By and large, the organizations needed to conduct the necessary research already exist, but the research is fragmented, inadequately focused on major problems, with little coordination between different organizations - internationally, nationally, and non-governmentally. Too little account is taken of farmers' views, of indigenous knowledge, or of social and economic realities. Scientists of different disciplines often find it difficult to interact and work in multidisciplinary groups across agriculture, forestry, ecology, anthropology, and economics.

- To overcome such institutional and cultural constraints to more effective implementation of soil and water research, we suggest a new research strategy which acknowledges the need for a major shift in approaches, involving recognition of the following:
  - Natural resource management is a complex mix of biophysical and socioeconomic factors.
  - Government policy has a major role to play in effective land and water management.
  - Natural resources are not simply the base for higher yields of plants and animals, but have significant contingency value.
  - The methods needed for sustainability research differ greatly from the procedures of conventional agricultural research. Spatially, watersheds, villages, or regional scales of operation may be needed, while the longer time scales of sustainability issues require combinations of simulation modelling and reference-site monitoring.

- While the farming system is the level at which most soil, water, and nutrient management practices have to be implemented, the large number of local systems and farming communities make it difficult for national as well as international organizations to devise improved sustainable systems suited to all. We believe that the most satisfactory approach to this problem is through the formation of 'consortia' in which all those with relevant interests and expertise are involved.

- To support the development and operations of the consortia, we suggest that a facilitating organization be established which, for want of a better name, we refer to as a 'clearing house'. The 'clearing house' would provide the mechanism for harmonizing the activities of the many organizations involved, acting as a centre that would ensure that necessary information was shared between participants, and supporting the training activities of the consortia. We see that training will have an extremely important role in the application of sustainable land and water management practices, because the holistic approach required means that there is a larger demand for training and education in areas outside each individual's existing area of expertise.

- While the views of the national programmes must be paramount in determining how land and water management is conducted in their respective countries, we believe that the complexity and diversity of the problems implies that an international 'clearing house' will have a comparative advantage in supporting and facilitating the work of the consortia, and ensuring that results are shared amongst different organizations, duplication is reduced, priority-setting is properly established, and accountability is satisfied.

I SWNM AND THE CHALLENGE OF SUSTAINABILITY

"We are, during the closing decades of the twentieth century, approaching the end of the most remarkable transition in the history of agriculture. Before the beginning of this century almost all the increases in agricultural production occurred as a result of increases in the area cultivated. By the end of the century there will be few significant areas where agricultural production can be expanded by simply adding more land to production. Agricultural output will have to be expanded almost entirely from more intensive cultivation in areas already being used for agricultural production." (V.W. Ruttan, 1987)

01 A number of factors have combined to refocus attention on the problems of soil, water, and nutrient management in developing countries. In 1992 at the UN Conference on Environment and Development (UNCED), Agenda 21 drew attention to the many problems of development in relation to environmental degradation. Agenda 21 noted that most of the problems arose from the exploitation of soil and water resources induced by the need to produce more to meet the needs of a growing population. The importance of managing resources so that they were neither degraded nor depleted received strong emphasis. Land must be managed sustainably if it is to feed, clothe, and provide for the other needs of the community - not only now but for many years to come.

02 Undoubtedly soil degradation has been occurring widely in the past few decades. This has effected yields and also the wider environment. A recent assessment of global soil degradation (Oldeman *et al.*, 1990) presents a collection of data based on national appraisals, mostly rather subjective, and considers the extent of soil degradation due to different processes. While there is a need for a more detailed and objective study of the extent of the damage and its reversibility, the study makes it absolutely clear that better appraisal of the seriousness of the situation is required. It is not only land that is subject to damage. Damage to water-storage and distribution facilities and other off-site damage associated with soil erosion are giving new impetus to the importance of changes occurring on a watershed scale and on a scale which is larger than the watershed. Some of these changes occur slowly, and their significance can only be recognized when careful studies are pursued over several decades.

03 Although of less immediate concern, the potential effects of climate change on terrestrial ecosystems and their interaction with land-use changes also have to be recognized. There is good reason to believe that intensified land-use systems are contributing to climatic changes. Undoubtedly a need exists for better coordination of studies being conducted on the global significance of climate change and of the studies needed to intensify and sustain agricultural production and other land-use practices.

04 At the 1993 meeting of the Consultative Group for International Agricultural Research (CGIAR) in Washington, Per Pinstrup-Anderson, director general of the International Food Policy Research Institute (IFPRI), gave a realistic appraisal of the present world food position and of future prospects. While acknowledging the major gains made in recent years, the paper recognized that malnutrition is still prevalent in many countries, that stagnating per caput yields of the major cereals poses a serious challenge,

and that there is a pressing need to develop more productive and sustainable land management methods.

05 At the Food and Agriculture Organization of the United Nations (FAO) meeting of the Council of Ministers the following week, *Agriculture Towards 2010* (FAO, 1993a) was released, again recognizing recent progress in the world food situation, but also making very clear the seriousness of food production problems in many developing countries in relation to the sustainability of natural resources, the dwindling resource base, and the overall decrease in the rates at which productivity has grown. Both the IFPRI and FAO reviews addressed the problem on a global scale. At the national level there are many countries where the problems of food production are already serious, as the FAO study shows. In several countries stagnating or declining yields reflect declining soil fertility and the continuing expansion of cultivated areas onto marginal land. Problems are also emerging in some of the more productive irrigated areas. In specific regions within countries, there are problems which are much more serious than those in the country as a whole.

06 Underlying the problem of sustainable land management is the problem of increasing demographic pressure on the land resource. At the present time, the annual population increase is greater than it has ever been, and probably greater than it ever will be in the future. Although the world continues to be able to produce sufficient food to feed its burgeoning population, it is not always able to supply this food to the places where it is most needed. Where extra production has been achieved, it has been obtained by increasing yields using fertilizers, expanding the use of water for irrigation, growing crop varieties able to respond to higher inputs, and cultivating more land. The additional land was obtained by deforestation, or by using land under restorative fallow - or previously under rough grazing because it was considered unsuitable, or only marginally suitable, for cultivation.

The symptoms of unsustainability

07 The question - unsuccessfully addressed in the past - was how to raise yields on a per hectare basis. Greater production can be obtained by cultivating more land, or by cultivating existing land more frequently. The question that must now be addressed, and which is giving rise to serious concern, is whether we can continue to extend and intensify production sustainably. The reasons for concern are the declining and stagnating yields per unit of input (and in some cases per unit of land), the declining quantity and quality of land resources, declining water resources, declining soil nutrient reserves, and various forms of environmental degradation. Much has been written about these issues, and we will not review them here. A synopsis is given in Annex I.

08 For many, the problems we have outlined are now a matter of life and death. What unsustainability means to the individual farmer and his family in many of the poorer areas of shifting cultivation is that the land he or she is now cultivating fails to yield, and the fallow land to which the family would previously have shifted is already occupied by another farmer. Many farmers are faced with a choice of joining the mass of migrant labour moving to the city (adding to the mass of shanty-town dwellers), or moving to wherever they can find land - usually leading to conflict with those who had declared the

land a forest reserve or with those who considered they had a traditional right to that land when their own became exhausted. In some of the irrigated areas, the farmer is finding that the irrigation water on which he depends no longer arrives when he needs it because there is insufficient water in the reservoir. Yields may also be unexpectedly declining even though high-yielding cultivars have been planted and fertilizer applied - the hidden cause being rising salinization.

09 The remedies offered by modern technology, involving a range of improved soil, water, and nutrient management methods may be capable of producing sufficient yields. What is less certain is whether their use is known in the area, whether the needed inputs are available, and whether their use is economic. Finding ways to remedy the human problems of poverty must be a high priority in dealing with unsustainability.

10 The national average yields of the major staples in several countries in Africa are now abysmally low. Maize yields in Angola and Mozambique are now below 400 kg ha^{-1}, as are those of sorghum and millet in Niger. In the Sudan, the average annual yield of millet for the years 1989 to 1991 was only 166 kg ha^{-1}. Between 1960 and 1970, the yield of cassava in Zaire was more than 12 t ha^{-1}, but is now about 7 t ha^{-1}. It is often suggested that this is a result of civil strife. In fact, in most of the countries where strife is occurring, yields have been falling since FAO first reported national yield levels in 1960, well before current problems of internal warfare started. The declining yields are certainly a result of deterioration of soil conditions and the expansion of production onto more marginal soils. Political and socioeconomic conditions frustrate attempts to rectify the situation.

Management for sustainability

11 Yields can be enhanced by improving the characteristics of the plant and by improving the suitability of the environment for the growth of the plant. Genetic improvement has been a major and highly successful strategy in yield improvement (Evans, 1993). The advances in gene manipulation and other areas of biotechnology will ensure continuing advances in crop improvement. When plant varieties which are adapted to the environment in which they are to be grown, and which have greater yield potential and pest resistance than those in current use have become available, there have been no problems of farmer acceptance and adoption.

12 To realize the advantages of the improved varieties to the full, it has usually been necessary to improve the plant environment by the use of irrigation water and fertilizers. While the improvement in plant type, the spread of irrigation, and the increase in fertilizer use are likely to remain basic factors in the continuing ability of the world to feed, clothe, and provide fuel and building materials for a growing population, the problem that still has to be tackled in many parts of the developing world is how to integrate these factors into viable economic packages for farmers and other land users.

13 In order to create sustainable systems, more attention must first be focused on the human dimensions of the problems, the wider environmental effects of land-use changes, and the number of decades required for the sustainability of the changes to be established.

14 Any land-use system is unsustainable if it leads to irreversible biophysical changes in the ability of the land to produce equally well in a future cycle of similar land use, or if the costs of reversing the changes are prohibitive. Thus the unsustainability may be biophysical or economic. Sustainable land management is "combining 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;
- protect the potential of natural resources and prevent degradation of soil and water quality;
- be economically viable;
- be socially acceptable". (Dumanski, 1993).

15 The management of land must aim to satisfy these criteria - a task which is made more difficult when demands on the land are increasing rapidly. Historically, there have been only three methods by which sustainable agricultural productivity has been obtained, each based on the restoration of soil fertility after cultivation. They are:

- shifting cultivation systems;
- animal-based farming systems; and
- water-based systems for rice production.

16 Each of these systems has been viable as long as the demands made on the system were low and the land was plentiful. Larger populations could only be supported when the discovery of inorganic fertilizers enabled nutrients removed in crops to be not only replenished but actually to be raised to much higher levels.

17 In some areas, greater yields have been obtained by controlling water supplies through the construction of reservoirs, water distribution systems, and greatly expanded use of fertilizers, sometimes supplemented by manures. While in several countries yields continue to increase, in others doubts about the sustainability of some cropping systems, such as the rice-wheat systems, have been raised because of falling productivity and water supply and distribution problems. In areas where shifting cultivation and extensive mixed farming are still the principal form of agriculture (mostly, but by no means exclusively, the forest and savanna areas of Africa), the response to growing demographic pressure has been to bring land lying fallow into cultivation before fertility has been restored, or to cultivate marginal land only suitable for extensive grazing or to be left under forest. This has almost always involved the use of land of lower fertility, which is more readily subject to degradation. At this stage a downhill cycle of unsustainability commences (Figure I.1).

18 Many long-term experiments have been conducted in developing countries to examine the productivity and sustainability of farming systems. Data from long-term experiments in West Africa conducted for two decades or more show that while inorganic fertilizers can reverse the decline in the early years of cultivation, they will not do so indefinitely (Pieri, 1992). Problems of acidity, nutrient balance, and other factors must also be corrected. To correct these factors, the only practicable method for the great majority of smallfarmers in West Africa is to combine the use of inorganic fertilizers with some method by which levels of soil organic matter can be maintained.

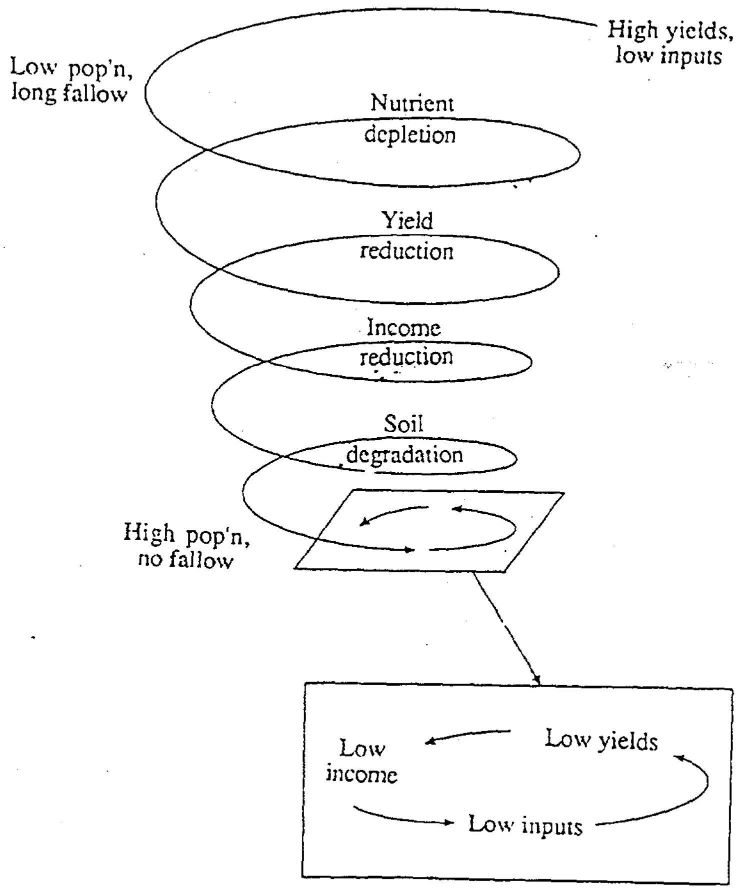


Figure I.1 The downward spiral of the poverty trap (McCown and Jones, 1992).

The role of international organizations in soil, water, and nutrient management

19 The response of the international community at the time of the threatened food crisis of the 1960s was to establish IARCs supported by the CGIAR.

20 The strong focus on improved crop varieties, allied to well-established high-input methods to increase yields, proved highly successful in removing the threat of an international food crisis. The limitations and inapplicability of the methods for certain conditions, and the threats now posed to the environment, have emerged in the course of the past two decades. The need to address these environmental problems has been recognized by the international system in the acceptance that some of the CGIAR centres should have an 'ecoregional' mandate, with a stronger focus on environmental problems.

21 IBSRAM and the International Fertilizer Development Centre (IFDC) were created to assist national organizations in tackling problems related to sustainable soil, water, and nutrient management. The Tropical Soil Biology and Fertility (TSBF) programme has also been established, recognizing the importance of soil biology to the sustained and efficient productivity of agriculture in the tropics. Further, in response to the problems which may

arise from global climate change, the Global Change and Terrestrial Ecosystems (GCTE) project has been established under the auspices of the International Council of Scientific Unions (ICSU).

22 Several UN organizations, notably FAO, UNEP, and UNESCO, have been strongly involved in many aspects of SWNM, in relation both to productivity increases, environmental problems, and the expansion of the knowledge base on which successful development depends. Research of national institutions in the developed world and some of their international programmes, such as those of ORSTOM (France) and the collaborative research support programmes of USAID, have added considerable information to this knowledge base.

Aims of the present paper: problem identification

23 Much information is available regarding the specific problems of soil productivity, of water management, and of methods to preserve the resource base. Of particular relevance are the papers prepared for the Technical Advisory Committee (TAC) by Pereira *et al.* (1979) and Sanchez and Nicholaides (1981), and for the meeting on *Priorities for Relieving Soil-related Constraints to Food Production in the Tropics* (IRRI, 1981). These papers and the report of the soil-related constraints meeting define fully the problems of SWNM as they existed at that time and as they now exist. The extra dimensions which have emerged in the subsequent years have related to the needs to give more attention to the environmentally related aspects, widening the time and spatial dimensions which must be considered. The importance of the socioeconomic factors which "must be taken into account" in generating sustainable methods of SWNM was also noted, although the full significance was only recognized in the paper relating to water management prepared by Pereira and his colleagues.

24 At the soil-related constraints meeting, the need to make better use of the biophysical knowledge of soils was recognized, and led ultimately to the establishment of IBSRAM with its clearly stated purpose of supporting NARS in the conduct of adaptive soils research.

25 In the past decade, it has become increasingly clear that while we have accumulated a great deal about knowledge of biophysical and socioeconomic factors related to land use and SWNM, and have succeeded in using that knowledge to increase production in favourable situations, we have been remarkably inept in applying that knowledge to the development and implementation of more productive and sustainable land management systems for less-favoured areas. We believe that the ineffectiveness lies in the divorce of the research agenda from the real problems of unsustainability as they affect the land user - farmer, forester, or pastoralist - in the field. The challenge is to make the solutions work for the smallfarmer.

26 The problems we identify are not those of conventional biophysical soil research, of which sufficient has already been written, but of integrating research on socioeconomic issues and biophysical processes into SWNM studies for the end-purpose of designing practical, operational approaches for the implementation of improved SWNM.

II AN INTEGRATED APPROACH TO SWNM

27 Creating sustainable agricultural and natural resource management systems from unsustainable ones can only be achieved by finding solutions to whole-system deficiencies as well as to component problems. It is futile to attack only technical problems - as has been common in the past - without addressing the overall pattern of degradation caused by socioeconomic pressures. Human behaviour driven by poverty, population dynamics, and myopic government economic and land policies is the underlying cause of land and water degradation. A future research agenda for SWNM must therefore offer a way in which the social, economic, and policy issues and biophysical processes are linked.

The cycle of unsustainability

28 Visualizing unsustainability as a 'process' can illustrate how many agricultural systems become locked into a degenerating spiral driven by interlinked socioeconomic and biophysical factors. Although the process will vary from place to place, a generalized 'cycle of unsustainability' (Figure II.1) can be identified, as can its components. Both biophysical and socioeconomic problems play key roles in the process, each feeding on the other.

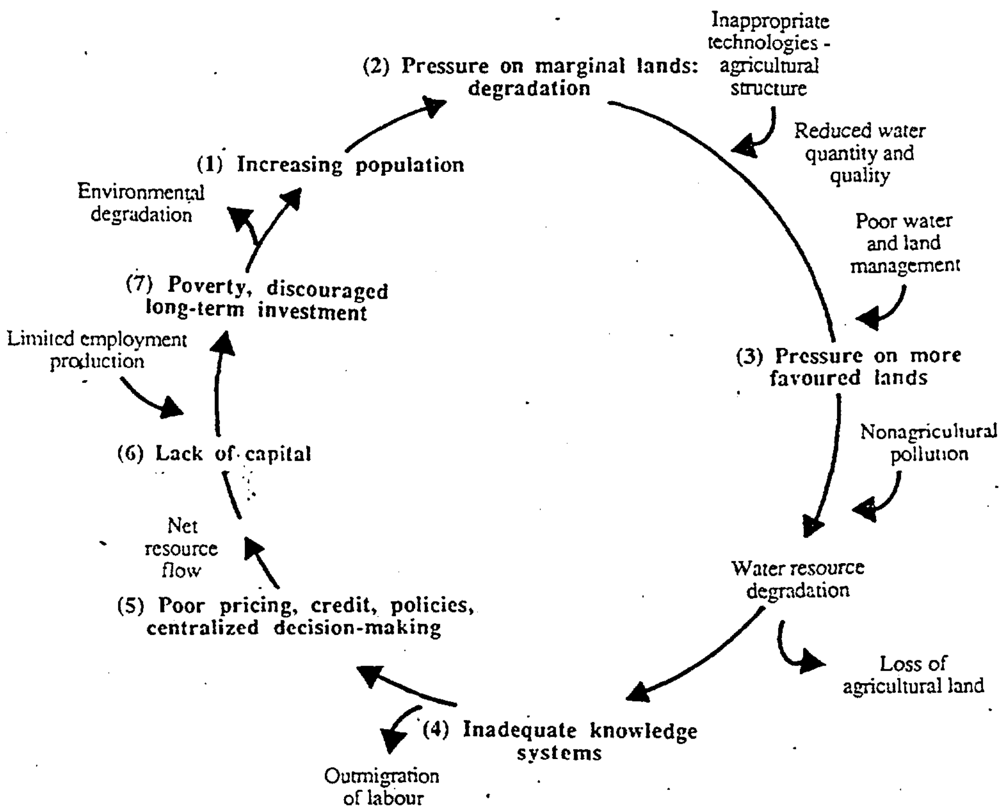


Figure II.1 The cycle of unsustainability (Rhoades and Harwood, 1992).

29 The processes underlying the unsustainability cycle (Rhoades and Harwood, 1992) are:

- An expanding rural population places pressure on urban and rural environments, especially marginal areas (uplands, rainforests, deserts, and wetlands) where land is still available and land prices are low.
- Pressure on this production base and marginal environments are exacerbated by structured inequities in returns to agriculture and farmers' and governments' needs to meet short-term survival goals.
- Simultaneously, pressures in favoured areas, such as irrigated and fertile coastal lowlands, grow from:
  - inappropriate land use in adjacent marginal areas, creating unevenness of water flow (surges, flooding, and runoff) to lower elevations, and increased silt and other containment loading;
  - water and land resources as a result of competing urban uses and poor management resulting in uneven distribution, salinization, and waterlogging;
  - increased land and water pollution from chemical-dependent urban agricultural and nonagricultural pollution; and
  - rapid urbanization.
- Due to rapid changes in all farming systems, scientific and indigenous knowledge alike become inadequate to meet a society's and users' (farmers', foresters', or pastoralists') needs.
- Driving the unsustainability cycle are ill-advised pricing-credit policies and land policies which work against long-term investment because:
  - pricing policies may change unpredictably, while international pricing (subsidies) may undermine returns to local agriculture;
  - land-use policies, including tenure and rights, provide incentives for unsustainable land and water use;
  - political bias and expediency, especially the undervaluation of food, cause a net flow of resources out of rural areas, which in turn leads to further rural impoverishment; and
  - neglect of investment in the rural sector is accompanied by centralization of natural resource management and bureaucratic control of resources, which leads to nonlocal development planning and a consequent reduction in local responsibility and incentives.
- Given the undervaluation of the rural sector, society (politicians) are reluctant to invest in the three types of 'capital' required to turn soil, water, and nutrient unsustainability around:
  - the physical infrastructure for irrigation and drainage systems, terraces, dams, waterways, wells, etc. which usually requires a cash investment with credit at reasonable cost;
  - biological capital, which is investment in long-term production through planting trees and other perennials, building organic matter, etc., and can be generated by local people by giving them land rights, access to other resources, and social stability; and
  - human capital, which is investment in people and their social institutions at all levels for purposes of creating better-educated citizens, better national scientists, and better local development workers.
- Finally a disenfranchised rural population degrading and inappropriately using resources further reduces production potential and thus the ability to correct factors

that lead to poverty. The poverty cycle deepens, leading to an increase in social instability, decreased investment and productivity, and further soil and water degradation.

The need for new models and methods

30 Reversing the above cycle will require an integrated research strategy involving new models, methods, and institutional arrangements significantly different from earlier production approaches. Four major reasons account for this required shift:

- Natural resources are no longer perceived by the scientific or policy communities as merely the medium to produce more food through high yields of plants and animals, but rather in terms of local and global ecosystem functioning. In addition to contingent values (production output), noncontingent values (ecosystem maintenance, biodiversity, water recharge, clean air, even sacredness and bequeath value) become important topics in the research effort. Conventional science is poorly equipped to deal with these 'ecological' and ethical arguments.
- Compared to crop and pest management, natural resource management is more complicated technically and managerially for both farmers and scientists. Natural resource science is in its infancy compared to such disciplines as genetics, crop physiology, or even agricultural economics. It involves a greater number of systematic relationships which are highly interactive. One land user can impact the health and production of many others. This complexity of natural resource systems also raises the new issue of linkages within sociopolitical hierarchies and scales of intervention.
- Conventional policy tools are deficient in their ability to manage, regulate, and encourage sustainable use of natural resources. Despite the often-heard statement that governments have longer planning horizons than farmers, officials and state bodies have their own agenda which may counter the long-term interests of sustainable development at the local level.
- Sustainability raises new issues such as time and spatial dimensions, social hierarchies, and societal *vs.* individual benefits, and therefore requires new approaches to solving problems. Although lessons can be learnt from farming systems research (FSR), the goals of FSR and earlier approaches differ from those of natural resource management research (NRMR), including SWNM research (Table II.1). A consideration of the temporal, spatial, and beneficiary dimensions will illustrate the difference.

Temporal dimensions of sustainability

31 Sustainability requires that time frames well beyond annual cropping cycles are studied. Three diachronic issues arise:

- the need to learn from the past;
- perceptions of impacts of current practices (good and bad) on the future; and
- intergenerational issues, wherein payoffs may not come in the lifetime of the community or farm household which implements a practice but to future generations.

Table II.1 Selected comparison of approaches: cropping systems, FSR, and NRMR.

Parameter	Cropping systems	FSR†	NRMR‡
Temporal	Annual cycle	1-3 year cycle	5-25 years
Spatial	Field-plot	Field-village	Watershed-region
Beneficiary	Farmer	Family	Multiple
Technology	Component	Farm production system	Natural resource system
Target	Self-sufficiency	Profits	Monetary/nonmonetary intergenerational equity
Role of farmer	Recipient of technology	Provider of information	Participatory
Policy	Input/prices	Marketing	Multiple
Environmental concern	Minimal, on-site	Marginal, on-site	Maximum on- and off-site

† FSR = Farming systems research
‡ NRMR = Natural resource management research

Degradation of natural resources often occurs gradually so that each generation only glimpses part of the historic process. The outcome is not known in advance. Slowly, people adapt to negative changes, which in turn accelerate further degradation, until disaster becomes discernible.

32 In many traditional, closed corporate communities intergenerational equity or 'bequeath value' is as important as it is in developed countries where farmers expect their families to continue to farm their land long into the future. Indigenous communities with a 'sense of place' are aware of the value of land, and strive toward long-term sustainability. Andean Indian communities, for instance, carefully regulate, through village assemblies, the rotations of land parcels, the use of communal pastures, the cleaning and maintenance of irrigation channels, herd size, and even the types of crops planted. External exploitation of land is limited, since only members of the community have inheritance rights to land. Problems in these systems arise as population pressure and penetration of commercial markets stimulate the breakdown of traditional land-use systems (Malcolm, 1993; DANIDA, 1989).

33 Tenancy arrangements which give no permanent rights can result in suboptimal use and management of natural resources (Southgate, 1988). Tenants are simply unwilling to incur short-term costs for the sake of benefits which will occur after the tenancy ends. Without right to land in perpetuity, farmers are reluctant to invest in the future. Similarly, 'slash-and-burn' practiced by displaced persons without title to the invaded land is often extremely destructive. In such situations, policies which enable individual title to be established can result in land improvement.

34 Even if small-scale farmers are aware of the benefits which may occur in the longer term from changes in their practices, such as those designed to limit erosion or increase soil organic-matter, they do not give them high priority because they occur over a time horizon not relevant to their immediate needs (Izac, 1992). Changes which give an immediate and obvious return, such as the introduction of fertilizers with an improved responsive crop variety for which a ready market exists, stand a much better chance of adoption. Farmer interest in short- rather than long-term benefits is of course by no means unique to developing countries. The sustainability of farming in western Europe needed

government subsidies for drainage and liming of soils to make it secure, and in the USA government support for erosion-control measures was needed before they were widely adopted.

Who benefits: society or the individual?

35 Many societal benefits arising from improved SWNM (e.g. reductions in siltation and flood damage, enhanced biodiversity, reduced water pollution) occur beyond the farm gate, at the level of village, region, and nation. For instance, measures to increase the organic-matter content of the soil often have limited immediate benefit to the farmer - the extra nitrogen can usually be obtained more cheaply from fertilizers - but more substantial benefits to the farmer and the community are likely to arise over a longer time scale (Table II.2, adapted from Swift *et al.,* 1994).

Table II.2 : Individual and social benefits of soil management practices.

Benefits	Time			
	1 year	2-5 years	6-10 years	11-50 years
Monetary and individual benefits				
Increased yields through increased soil fertility	++	++	+++	+++
Nonmonetary, individual, and social benefits				
Increased sustainability of system through:				
- reduced risk of yield fluctuations with manual climatic variability	0	+	++	+++
- enhanced soil resource base	0	0	+	++
- enhanced capacity of system to adjust to exogenous changes without generating increased flows of pollutants	0	+	+	++
- increased biodiversity of soil biota	0	+0	++	+++
- reduced risk of erosion	0	+	++	+++

Note: 0 = no measurable benefit,
+, ++, +++ = measured benefit, with intensity of benefit ranging from low (+) to high (+++).

36 Given that voluntary adoption by individual farmers may often be socially suboptimal, policy intervention is needed. Policies used in developed countries are difficult to implement in developing countries (e.g. regulations are difficult to enforce; taxes and subsidies are costly to administrate). Price policy (reducing prices for inputs, support for conservation crops), land reform, food for work, and direct community incentives have been attempted with mixed results (Izac and Swift, 1992). Direct incentives, for example, may instil the belief in farmers that conservation is something someone else pays for and benefits others instead of themselves.

37 India is encouraging farmers to form their own 'land-use associations', where available land is classified into (i) conservation areas (ii) restoration areas, and (iii) sustainable intensification areas (Swaminathan, 1994). Similar action adopted elsewhere would meet the wider need for communities to manage their land and water resources effectively. The formation of such groups can be greatly encouraged by linking them with

land tenure rights (Cernea, 1987; Moorehead, 1989). Community-based support has low implementation costs: the community can share risks, communal arrangements are implemented in simple ways, and economies of scale are realized by pooling resources of labour and capital. By basing operations on the community, the results are more likely to be adapted to local ecological landscapes, as they effect the whole village area and not the fields of an individual farmer (Izac, 1994).

Social hierarchies and spatial dimensions: multiple clients

38 Unlike conventional crop and livestock improvement in which researchers study a component or system on a relatively small-scale (plot, field, agroecological zone), SWNM needs to deal with a much broader range of interacting hierarchical levels, including households, village communities, irrigation societies, tribal groups, provincial governments, nation states, and even larger entities. These increasingly complex social units reflect the larger spatial units which have to be considered - ranging from the plot, the catchment, or watershed to the wider landscape and to the geographic boundaries of nation states. Successful SWNM will require intervention at each of these levels to achieve results.

39 Much confusion in sustainability research derives from researchers studying different scales and then mixing levels in analysis. Each level requires its own analysis to permit systematic scaling up or down between levels. The catchment, for example, is the hydrologically determined unit of regulation of water, nutrient, and sediment flow over the landscape. It integrates the overall environmental effects of the mosaic of vegetation and land uses, and is a logical scale for interdisciplinary efforts to improve environmental management and the conservation of resources.

40 The relationship between rangeland management, forestry, and hydrology has also to be included in this consideration. However, many soil scientists work at the level of constituents of the pedon, agronomists at the plot level, anthropologists at the village level, and economists at the scale of regional markets. Recognition of how different levels link must be central to any integrated design for SWNM.

41 The farming system is probably the most realistic level at which to operationalize sustainability (Lynam and Herdt, 1992; Izac and Swift, 1992). As the smallest scale where biological, economic, and social considerations are integrated, households make decisions concerning the distribution and allocation of resources between different components. Often such allocations of human and financial resources also involve transfers of energy and nutrients between levels. A farmer manipulates available resources, which may include resources on the farm (crop residues), imported from elsewhere in the watershed (manure), or purchased from outside (fertilizers). These interactions of decisions, along with those concerning irrigation, drainage, tillage, and mechanization, are all part of a given soil management strategy. The benefits of using one technique rather than another must be set against the value of the resource for other uses (e.g. fodder for fuel or livestock instead of soil enhancement), and the benefits of allocating labour to soil management rather than taking advantage of other opportunities (Izac and Swift, 1992).

A user-participatory approach to SWNM

42 An approach to solving problems at the farming system or catchment level must incorporate the factors of time, hierarchy, benefits, and costs in such a way that sustainability is enhanced, as measured by spatially and socially determined baseline indicators. This implies a participatory approach involving farmers, policy-makers, NGOs, scientists, and others within the zone of influence. If recommended SWNM technologies are not being used, it is seldom due to farmer ignorance, but to a flaw in the technology-generation process. Natural resource methodology must be multiperspective, drawing on ecology and systems analysis, natural-resource economics, and indigenous knowledge sought through anthropological studies.

43 Feedback must be provided to the researcher, and flow through the whole research chain from adaptive to basic research (Figure II.2). This is not to deny a place for curiosity-driven basic research, or to suggest that targeted research (primarily using new knowledge coming from basic research) cannot make a contribution. It is possible, for instance, that the largest contribution to most farming systems may come from basic studies of the enzymatic processes of nitrogen fixation. But in applying and adapting existing knowledge, little progress is likely without an integrated approach in which land users and researchers from different disciplines are involved from the earliest stage of the research-planning process. The farmer-back-to-farmer paradigm (Rhoades and Booth, 1982) provides a basis for conducting research in this way (see Annex IV and Figure II.3).

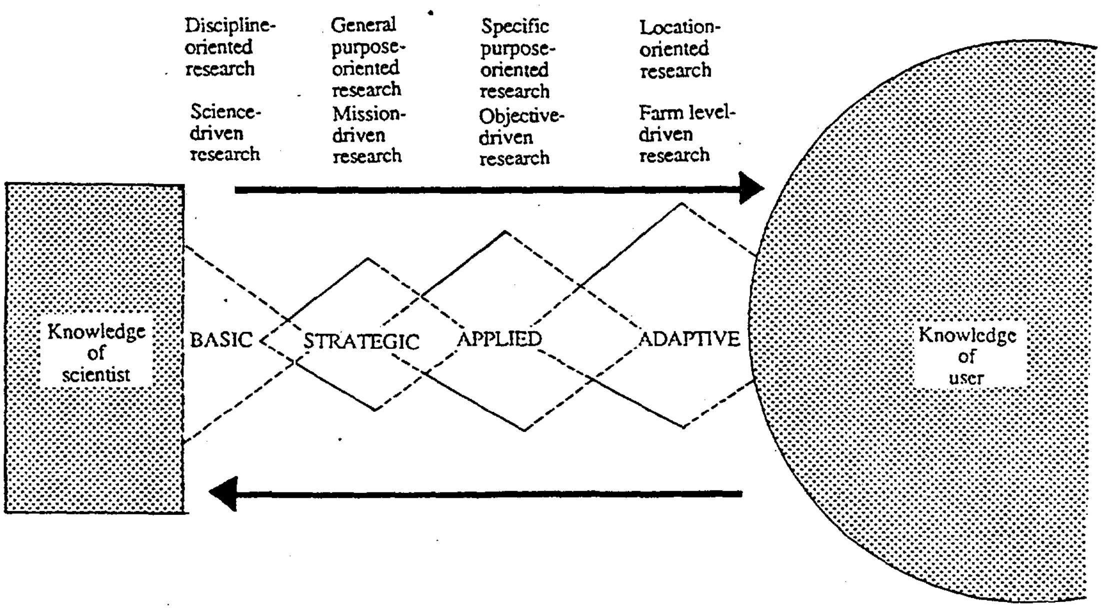


Figure II.2 Building and exchanging knowledge of SWNM.

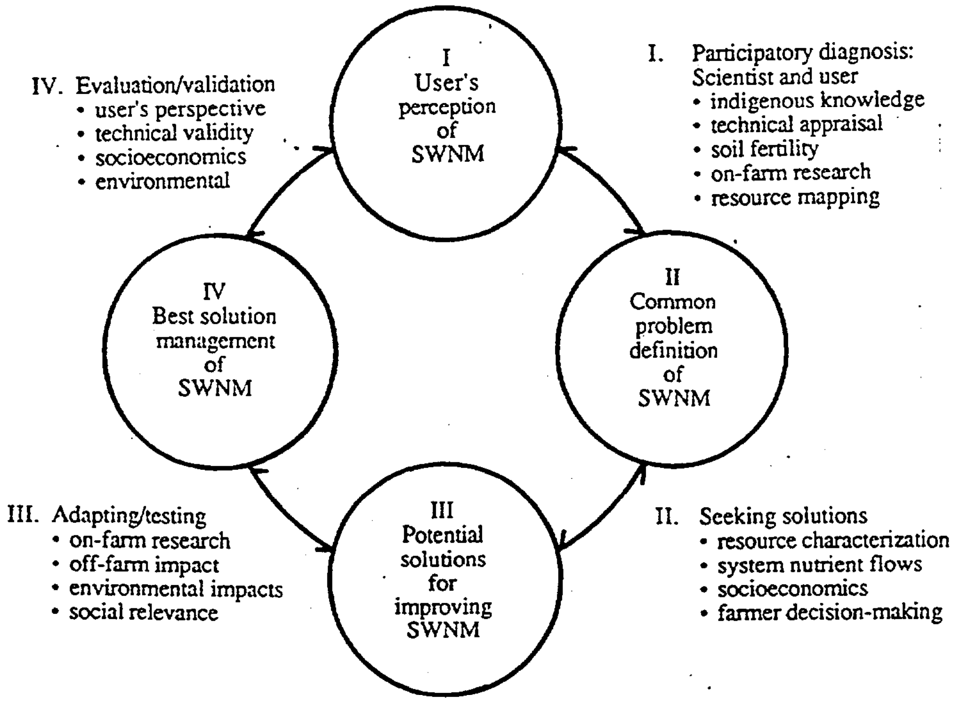


Figure II.3 The farmer-back-to-farmer adaptive research model.

Nine principles to reverse the unsustainability cycle

44 A new approach is called for in which national and international organizations work in a unified manner on both socioeconomic and biophysical problems to deal with the system deficiencies of the cycle of unsustainability. Nine basic principles should guide this new effort.

45 **Principle one**. Contributions of research organizations are only valuable to the degree that they ultimately address real points along the cycle of unsustainability. For example, refining soil typologies for scientific study is seldom relevant to solving the problems of sustainability.

46 **Principle two**. It is legitimate for SWNM specialists to attack 'problems' (technical or socioeconomic) at any point in the cycle of unsustainability as long as the proposed solutions are understood not to stand alone, and can only succeed if other closely linked problems/processes are addressed. For example, erosion-control engineering must be linked with cropping patterns and economic incentives.

47 **Principle three**. The systematic nature of the cycle demands that scientists be part of broadly interdisciplinary teams, and that research organizations be multi- and inter-disciplinary. A prerequisite must be that trying to correct 'symptoms' of unsustainability

(e.g., gullies and polluted water) must be part of a deeper, more theoretically sophisticated analysis involving all relevant sciences.

48 **Principle four**. The most appropriate research scale is at the watershed or catchment level, although research at the plot, field, cropping system, or regional level is legitimate - and must be related to the 'cycle of unsustainability', which is driven by forces operating on a larger scale.

49 **Principle five**. While SWNM researchers realize that some processes in the unsustainability cycle are beyond their direct influence (e.g. urban sprawl, global commodity trade, and national land policies), there is a continual obligation to raise awareness among donors, policy-makers, and government officials that technical problems cannot be solved in isolation.

50 **Principle six.** Platforms of negotiation between scientific understanding and local folk knowledge (including that of women) of SWNM must be constructed. This will combine, at the watershed level, knowledge of the 'reality' and particulars of the reality with the power of science, including results obtained in distant research sites.

51 **Principle seven**. Research must be a much longer-term proposition than conventional agricultural research, but it must nevertheless still address points along the cycle. Impact can rarely be expected from short-term projects.

52 **Principle eight**. Technical solutions cannot be generated in laboratories or experiment stations isolated from real-life conditions - and then 'sit on shelves' awaiting ungrateful farmers. The process must be reversed. The mythical 'shelves' must be replaced with palatable technology 'cafeterias', in which solution-hungry farmers select and taste to their liking (see the farmer-back-to-farmer model in Figure II.2).

53 **Principle nine**. SWNM researchers should not work in isolation, but should benefit from comparative, common workplans which reach across well-selected global sites where long-term experiments are being conducted. This principle implies development of a global network of researchers, organizations, and projects, in which everyone understands how his efforts fit into a global plan to reverse the 'cycle of unsustainability'.

54 By following the above nine principles it should be possible to develop research programmes by which the cycle of increasing unsustainability can be gradually transformed into a cycle of sustainability. These sustainable systems will be characterized not only by a population in balance with its resource base, but also by agricultural systems which blend with the environment, provide clean water, regenerate soils, give a fair return on land, labour, and capital to the farmer, enjoy decentralized decision-making, and offer research potential for the agrarian sector. While this may sound like a pipe dream, failure to reach for the dream could spell disaster for the global village.

III SWNM RESEARCH: NEW DIMENSIONS.

55 Why is it that it has not been possible to develop technology to help less well-endowed areas commonly encountered in tropical countries? Varieties of most crop species with at least partial tolerance to adverse conditions and much-improved yield potentials are already available, but have seldom had an impact on productivity in these areas. Methods of soil, water, and nutrient management to increase productivity are available for many areas, but most of them are not adopted - mostly because they lack social and economic viability. The solution to the economic limitations may be to make changes in policy; but the reality in many countries is that policy will not be easily changed, and better-adapted technology must be sought through further research (Crosson and Anderson, 1992). A brief discussion of the research opportunities given below is elaborated in Annex III.

Components of SWNM research

56 *Plant nutrients.* Responsible husbandry of plant nutrients, avoiding nutrient mining, is a major key to sustained productivity at both the farm and national level. Traditionally, replenishment of nutrients removed in crops has been by nutrient redistribution through animals, trees, or water. Such transfers are now generally unable to restore the higher rates of removal required for current food, fuel, and fibre needs. In Africa at the present time, removal rates far exceed replenishment rates (Figure III.1). There is no escape from having to supply nutrients removed in crops, or lost by leaching or erosion, from other sources - most commonly and cheaply from inorganic fertilizers. In developed countries, problems from excessive use of fertilizers and other agricultural inputs are widespread. In developed countries, such problems are mostly confined to limited areas in certain countries. In Africa, for instance, the average per hectare inputs of inorganic fertilizers are of the order of 10 kg ha^{-1}, as compared with the rate in Europe (exceeding 500 kg ha^{-1}).

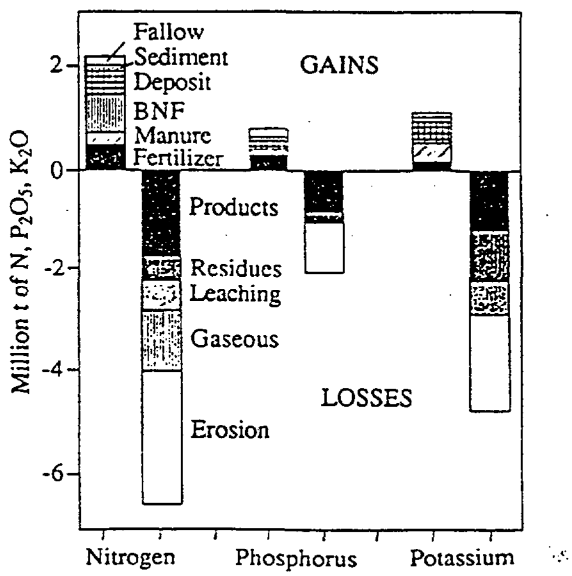


Figure III.1 Nutrient balance for sub-Saharan Africa (Stangel *et al.*, 1993)

57 The challenge is to provide farmers with fertilizers at economic prices, and to ensure that fertilizers are used as efficiently and effectively as possible. At the applied and adaptive research level, there is still scope for location-specific studies of timing, placement methods, and residual values of applied nutrients. At the applied and strategic levels, there is considerable scope for plant studies on the efficiency of nutrient use, management in agroforestry, relay- and multiple-cropping systems, and adapting fertilizer practices to water availability as indicated by long-range weather forecasting.

58 A key component in efficient nutrient management is the use made of nitrogen-fixing pasture plants and grain and tree legumes. There is no doubt that the quantity of nitrogen supplied by fixation could be increased considerably in many areas by inoculation technology suitably tailored to local needs, the selection of inoculants to compete effectively with less-efficient local strains, and the selection of genotypes with high nitrogen-fixation capacity.

59 *Soil water.* The second pillar of productivity and sustainability is the proper management of soil water. Soils have to be managed to ensure that sufficient water enters and is stored in the soil for crop growth. There is, of course, a strong interaction between water and nutrients in their effects on crop production. Research again requires synergism between soil and plant scientists. In drier areas, management to improve water-harvesting, e.g. by establishing microcatchments and developing appropriate tillage methods, is needed, together with the production and management of organic matter on and in the soil. To increase the effectiveness of water use in both rainfed and irrigated systems, strategic research is necessary to support applied and adaptive studies on the need for water at different growth stages of the plant. Strategic studies on genotypic differences in plant water use and water-use-efficiency in production are also needed, and of water use in mixed-cropping and agroforestry systems.

60 Leaving aside the political and economic problems of extending the presently irrigated areas - and recognizing that irrigation has been a major factor in increased production over the past 30 years - the efficiency of use of irrigation water has been lamentably low, and poor irrigation practices have often resulted in large-scale salinization. In some places, salinization has also resulted from changed aquifer flows following deforestation, and from the recharge of some irrigation aquifers on coastal areas. Reclamation of saline areas is difficult and expensive, but some use of these areas may be possible if salt-tolerant plant species can be developed, especially if their use is combined with measures to reduce the salinity level.

61 *Soil physical conditions.* The best managers of soil physical conditions for crop production are the soil fauna, which create the pores through which air and water move, and mould and stabilize the soil aggregates. As organic matter is lost from a soil under cultivation and the return of organic matter is reduced, soil structure deteriorates, and the farmer must attempt to improve it by tillage. Some soils have an inherently poor structure, and are prone to surface crusting and compaction, both of which can be exacerbated by poor soil management. The structural deterioration not only reduces the amount of water available for plants, but also increases runoff and contributes to the susceptibility of the soil to erosion. Although there is a need to gain more understanding of the factors placing some soils at particular risk, recuperation of the soils is most likely to come from applied and adaptive research. Mechanical methods of reducing compaction and soil crusting are

seldom a viable option to the developing-country farmer, and neither is the addition of soil improvement agents such as gypsum. Viable answers to ameliorating soil physical conditions have to come from the management of crops, trees, and ground covers to promote increased returns of organic matter to the soil.

62 *Soil biological conditions.* Until recently the importance of soil biota to sustained soil productivity has received little more than lip-service. There is now more general recognition of the importance of maintaining biodiversity amongst the soil flora and fauna (Hawksworth, 1991); but much more needs to be done at a strategic level to appreciate the potential and possibilities of managing components of the biological soil population. It should be a cause of embarrassment to the scientific community that even now there is little recognition that losses of up to 30% of the yield may be occurring in a great many crop-production systems due to the failure to recognize the damage caused by root pests and diseases - in spite of the availability of simple methods to evaluate the losses - and such phenomena may often be a cause of declining yields in high-input systems. There is a real need for diagnostic research to establish the extent of such problems in tropical conditions, and the effects of intensified cropping on the problem.

63 *Soil erosion.* Wind and water erosion are widespread and serious in India (Abrol and Sehgal, 1994) and elsewhere. They are a major cause of unsustainability, although often a secondary rather than a primary cause. The primary cause is often inadequate land management practices. While more strategic research on factors determining the relative susceptibility of soils to erosion, and on the environmental factors inducing erosion (such as rainfall patterns and wind characters) may contribute to a better understanding of the problem, the need to find farmer-acceptable control and mitigation methods is of primary importance. Farmer reluctance to adopt vetiver grass as a control measure because of its unpalatability to stock, and farmer aversion to alley cropping because of the costs in labour and land, are excellent examples of the need for greater farmer involvement in the research process. While foresters, agronomists, economists, and soil scientists may collaborate, their labours may be better directed to achieving the early involvement of farmers themselves in the design and planning of the research.

64 The scale at which erosion control must be planned is also important, and this means that the community or communities must also be involved. By and large, technical solutions are available - terracing in the steeplands, strip-cropping and grass barriers, zero-tillage and mulching, and agroforestry systems. The most urgent need is to identify methods acceptable to land users. There is always a cost for erosion control, as for other factors of sustainability. The critical research need is to identify acceptable methods by which the costs can be met.

The alternative agriculture option

65 Recognition of the importance of organic-matter maintenance, and of the long-term and off-site effects related to sustainability, has led to renewed interest in so-called 'alternative agriculture' methods. Here, maintenance of soil productivity is sought from the use of organic material, the maximization of biological nitrogen fixation, and the minimization of nutrient losses - while avoiding the use of inorganic fertilizers and synthetic pesticides. Wherever such methods are economic and will lead to the production of

sufficient yields, they constitute a desirable basis for sustainable production systems. However, certain difficulties have to be recognized. The most serious for soils in the tropics is that many are of low or very low inherent fertility. Traditional methods of fertility maintenance, which involve the use of trees or animals to allow nutrients to be concentrated on the cultivated area, are mostly no longer viable because of the increased demands being made on the land. While recycling of all available organic residues is important, recycling will not raise the productivity of soils of initially low inherent nutritional status. Such soils are unfortunately widespread in tropical regions. Recycling by itself does not provide an avenue of escape from the poverty trap. Integrated organic/ inorganic management methods will most commonly be needed to raise productivity and ensure sustainability.

66 An essential component of any alternative agricultural strategy must be the maximization of biological nitrogen fixation in the system. Mostly this will be from the inclusion of legumes - and as noted above there is still an opportunity for major contributions to be made by strategic research on several aspects of nitrogen fixation, as well as by inputs from applied and adaptive research.

67 A frequently mentioned obstacle to the practice of returning crop residues to the soil is the demand for the residues for other uses, such as stock feed, fuel, and roofing material. Solutions to this problem are an important part of research on sustainability. It may mean that the plant breeder has to redesign the crop plant, or the agronomist has to find a way to produce the organic material needed to satisfy the plant requirements.

68 Considerable energy inputs are also often needed to ensure adequate water entry into the soil, whether by irrigation, water-harvesting techniques, or tillage. The amount of energy required for soil tillage can often be reduced by increasing the organic-matter content of the soil, but the advantages to be derived from the mechanization of soil manipulation methods are often of compelling interest to the farmer who has to do the work. Tillage is also needed for seedbed preparation and weed control. The work at IITA and elsewhere (Lal, 1991) has shown that in humid regions minimum and zero-tillage techniques offer considerable advantages in terms of energy requirements, but may need to be combined with herbicide use for weed control.

69 Thus while organic farming and other alternative agricultural techniques offer significant advantages in terms of sustainability, in many instances it will be essential to combine the principles of organic farming with methods to replace nutrients and apply other forms of inputs to provide yield levels which enable the economic survival of the farm family.

The environmental dimension - sustainability

70 Even in the developed world, conscious assessment of environmental costs is only recent, and the inclusion of environmental costs in land management budgets is now becoming imperative. However, developing policy initiatives to address the issue of internalizing environmental costs is difficult until productive agriculture is a reality.

71 Off-site damage resulting from poor farmland management have included additional costs which are not perceived by farmers. By comparison to on-farm losses, this damage is much greater, and affects a wider range of people. Off-site damage includes sedimentation of aquatic resources, siltation of reservoirs, and the confounding effect on the ecosystem as a whole. Finally, the increased use of land which agriculture has demanded may damage habitat and biodiversity.

72 Sustainable use of current agricultural land can reduce environmental off-site pressures. Coupled with other socioeconomic policy decisions, it can also reduce the pressures on marginal land or stressed ecosystems. Thus the outcome of appropriate soil, water, and nutrient management policies and a widescale implementation of these policies will not only enhance productivity but also protect the environment.

73 Apart from the physical availability of land, the desire to maintain an ecosystem balance will also place pressures on land use. The nonagricultural uses of land, specifically for forestry and biodiversity reserves, will increase the pressures for increased productivity of currently cultivated land. There are large areas of fragile ecosystems, specifically steeplands and wetlands, which demand protection and conservation. Agricultural creep into marginal areas, especially into steeplands and swamps, is a major environmental problem in many countries. The urbanization of agricultural land is also becoming a problem in many developing countries. In almost every country, prime land is already under agriculture, and available land that could be brought under agriculture is usually of inferior quality, requiring high inputs in management. Serious consideration has to be given to competing claims of land use for agriculture and forestry.

74 Problems associated with point-source pollution are increasing in many developing countries. At present, the data is inadequate to make an assessment. However, damage from mining activities has been reported in many countries (such as Brazil and Malaysia). Off-site contamination of whole river basins are often of sufficient concern to warrant the use of bioremediation and other techniques.

75 Other problems may arise from the impending threat of global climate change. The impact of climate change may be particularly important in areas such as desert fringes and savannas, and where population growth is most rapid and the ecosystem most severely stressed. At the present time, intensification of cultivation is leading to increasing losses of soil organic matter, contributing to increasing levels of important greenhouse gases, such as carbon dioxide, methane, and nitrous oxide in the atmosphere. By using agricultural practices which increase rather than decrease the organic-matter level in the soil, a win-win situation can be created, in which soil productivity rises and carbon dioxide is removed from the atmosphere. It has been calculated that an average increase of 0.1 to 0.2% in the amount of organic matter in the soil would be sufficient to offset the annual additions to the atmosphere from fossil-fuel use (Lal and Kimble, in press).

The temporal dimension - long-term experiments and modelling

76 To assess the relative significance of factors related to sustainability, it is absolutely essential to have a series of long-term experiments in different agroecological zones, some of which are conducted on a catchment basis. Only in this way can organic-matter dyna-

mics and water use and nutrient flow associated with changes in SWNM be studied experimentally. Catchment experiments are large and costly. The value of a few catchment experiments supported by relatively simple long-term plot experiments and by simulation modelling (Nye, 1992), will be inestimable in providing a continuing factual basis for determining productivity changes and the biophysical effects of land-use changes. These experiments would also provide important international reference sites for studies of organic-matter dynamics and the release and assimilation of greenhouse gases. Possibly, and most importantly, they would provide a reference point where indicators of sustainability could be factually assessed.

77 There is no doubting the power of modelling in association with agricultural research, both for its indication of the probable consequences of alternative treatments in various systems, and also for the indication which modelling can give of the most sensitive parts of a system which may be responsive to treatment. Other types of models important in soil resource management include an estimate of the sustainable human carrying capacity of a target zone as a function of different levels of inputs. Econometric models, models predicting the long-term impacts of global climate change on the resource base and resource performance, and models evaluating irrigation practices all have valuable contributions to make - not only to understanding the complex processes involved, but also to research efficiency and cost-effectiveness. However, without an experimental base for validation their value is limited and may be dangerously misleading.

The spatial dimension - location specificity

78 The problems of SWNM differ considerably in significance and extent in different parts of the globe. To assess their relative significance, it is necessary to have some means of categorizing them in relation to major land and land-use characteristics. There is, of course, much spatial variation. One of the great difficulties in agricultural development and in the application of research related to SWNM is its location-specificity. Soils are not only individually complex, but their properties vary considerably over short distances, and vary in time as well as in space. This variation requires that management methods must be flexible. Consequently land management methods also show considerable variation. Management has to respond to climatic differences, soil differences, land differences, and the human factors related to land use. Farmers living in close relation to their land are always aware of this, and adjust their management accordingly, recognizing their prime need to produce sufficient food to survive. A categorization of the problems of SWNM is therefore not an easy task.

79 FAO, through its Agroecological Zones (AEZ) project (FAO, 1991), has approached the problem of land categorization in terms of climatic suitability. Allying this with the extensive information from the FAO/UNESCO *Soil Map of the World* and national soil surveys gives a biophysical base for further refinement. Satellite data from the UNEP GRID project provides some indication of current land use and land-use changes, but little about the factors inducing change, or about soil degradation.

80 A data base incorporating more information about population, farming systems, and other factors is essential to a proper analysis of the priorities for SWNM research. In the absence of an adequate categorization of the extent of the problems, we have used six

ecologically defined regions or 'target zones' which give some internal consistency in the major problems of SWNM as a background to our assessments. They are:

- the desert fringe;
- the nonacid savannas;
- the acid savannas;
- the humid forests;
- the wetlands;
- the steeplands.

81 The principal soil and climate characteristics of each region are given in Annex II. While there is some consistency in the problems within each target area, there are also considerable variations due to landscape position, soil-type differences, and the past history of land use. The location-specificity problem can perhaps best be appreciated in relation to the problems of the Machakos area in Kenya. On the better soils of the area, a successful land-settlement scheme has been implemented supporting a relatively high population density and a farming system in which sustainability appears to have been established (ACIAR, 1992), while in other parts the struggle with the descending spiral of unsustainability continues (Figure I.1).

82 The dominant farming systems in the desert fringe and the nonacid savannas are animal-based, ranging from nomadism to mixed farming with improved pastures. In the acid savannas and forest areas, the dominant farming system is shifting cultivation - with some animals and grazed fallows in the savannas, and tree-based systems in the forests; the trees may include some which produce a cash crop. In the wetlands, there are mainly rice-based systems, and in the steeplands various forms of sedentary agriculture and livestock production, usually with some form of terracing to control erosion, predominate.

83 Nutrients are liable to depletion everywhere, and are subject to continued removal by crops. Methods to maintain nutrient levels as cultivation becomes more intense are critical in almost all areas. Traditional replenishment of nutrient levels is from animal manure in animal-based farming systems, and from nutrients accumulated in the fallow vegetation which regenerates on cultivated land. The organic matter added in manure or from fallow vegetation is critically important to the sustainability of traditional agricultural systems. It contributes not only to nutrient levels, but also to water entry and retention, resistance to erosion, control of acidity, and biological activity in the soil. Several previous assessments of the soil-, water-, and nutrient-related constraints to crop production have been made, and references to these constraits are given at the end of this paper. More details about each target zone and the dominant farming system in the zone are given in Annexes IV and V.

84 Problems of water shortage and of methods to improve water collection dominate in drier areas, and problems of flooding and water excess are of major concern in wetter areas. Difficulties with water collection and distribution are exacerbated on a landscape scale by sedimentation, mostly arising from erosion in adjacent areas. Water shortage for both agricultural and horticultural use will be one of the most serious problems of the 21st century. The use of water for irrigation must not only be made more efficient, but also integrated with forestry into national and community planning of development at the village and catchment levels. Problems of water collection and distribution must always be associated with proper planning of drainage to ensure that salinization, flooding, and

waterlogging difficulties are precluded. More than half of the areas which are presently irrigated have been affected by salinization, and every year several million hectares have to be abandoned because of salinization (Ahmad, 1991). The special problems of irrigated areas are discussed more fully in Annex V.

85 There is at present inadequate data available regarding the extent and numbers of people involved in each zone, and the extent of different farming systems. Data collected by the World Resources Institute show that the relative order of size of the target zones we use is: humid zone > acid savanna > nonacid savanna > wetlands > steeplands > desert fringe. For population, the order is: humid zone = nonacid savanna > wetlands > desert fringe > acid savanna > steeplands.

The information and knowledge base

86 Soil, water, and nutrient management technologies only succeed if they are transferred to the farmers. In many countries, the significance of indigenous knowledge has yet to be appreciated. Sometimes the reluctance of farmers to accept technologies may be related to conflicts with this knowledge. The second kind of knowledge is scientific or technological knowledge. Transferring germplasm (seed) is easier than transferring knowledge involving traditions, values, and complexity.

87 The absence of resource information is a major deterrent to appropriate land-use policies in most developing countries (Eswaran, 1992). Discriminatory use of land, targeting research and development activities, and assisting farmers in the management of farms all require information on the soil resources.

88 The need for a better information base on SWNM was widely recognized in the responses to the questionnaire (Annex II). We believe it to be essential to the better prioritization of SWNM research, as well as essential to governments endeavouring to improve their management of natural resources.

89 We see a need for high priority to be given to establishing a better data base on current land use, allied to a geographic information system (GIS), that will enable changes in land, agricultural, and socioeconomic conditions to be more effectively monitored than at present. Such a data base would enable apropriate priority for the most serious land problems facing the national programmes to be identified, and for support to be given to the programmes accordingly.

90 Very high priority should also be given to support for an SWNM information network to share information between the national programmes, and to facilitate the sharing of results between users of land and water and those engaged in research related to land and water use.

Soil resilience - reversing degradation

91 Much is known about the causes of soil degradation and the negative impacts of degraded systems. However, information on rates of degradation, a quantified assessment

of the state of degradation, and the resilience capacity of the system is less well established, and provides a new avenue for research in the quest for sustainability. Resilience is the ability of the soil or system to revert to its original or near-original performance level subsequent to stress (Eswaran, 1994). Soils differ in their rates of degradation under stress and their resilience capability, as illustrated in Figure III.2.

92 According to this conceptualization, there is a point of degradation beyond which the process is almost irreversible. The patterns of degradation (rate functions) and the ability to revert to the near-original state are criteria which differentiate resistant, resilient, fragile and marginal soils. The continued application of stress is usually due to cultivation, since crop and residue removal can move fragile and marginal soils to a point of no return - although resistant or resilient soils will normally be able to return to previous performance conditions.

93 Resistant soils occupy about 10% of the total global arable land surface, and occur mostly in temperate areas. There are no good estimates of other kinds of soils, and a reasonable estimate would suggest that about 50% of soils belong to the resilient type, about 25% are fragile, and the remaining 15% are marginal. Fragile and marginal soils occur predominantly in the tropics. Many have reached a state of irreversible degradation through mismanagement. The downward spiral resulting from increased populations in the finite land resource base is increasing the proportion of marginal and fragile soils which are close to the point of no return, and this is the warning signal highlighted by Agenda 21.

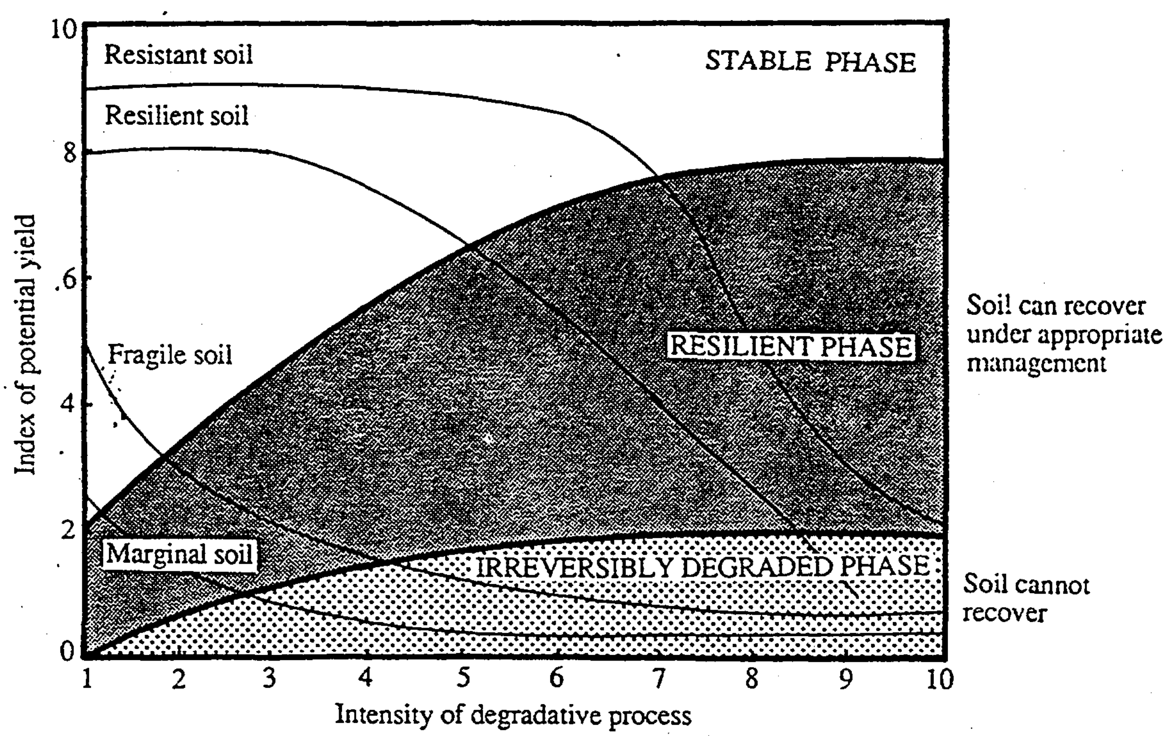


Figure III.2 Response of resistant, resilient, fragile, and marginal soils to stress (adapted from Lal, Hall, and Miller, 1989).

94 An SWNM strategy must ensure:

- high productivity from soils in the stable phase where degradation is unlikely;
- careful management of resilient soils to avoid degradation or to reverse degradation when it has occurred; and
- a conservation reserve programme for soils which are irreversibly degraded, and for fragile and marginal soils which can easily become irreversibly degraded.

95 These are remedial measures, best implemented on a communal basis. An equally important task is to develop early warning indicators and appropriate monitoring systems to alert land users of the impending degradation of systems. At a recent workshop on Soil Resilience and Sustainable Land Use held in Budapest in 1992, the following recommendations (Greenland and Szabolcs, 1994) were made:

- The global data base of human induced soil degradation developed by UNEP, ISSS, and ISRIC, in collaboration with various countries, should be complemented by a similar assessment of:
  - areas with sustainable land management systems;
  - areas where degraded lands have been rehabilitated; and
  - the resilience of the land resource base in different ecosystems.
- To implement some of the recommendations of Agenda 21 in the area of land resource planning and management, an assessment of current land use should be made at national and global levels.

96 This will require that:

- existing long-term trend-monitoring programmes, data collection, and experiments are maintained and documented, and that new ones are supported in key agroecological zones in developing countries;
- key species, biotic assemblages, and processes contributing to soil resilience are identified;
- quantitative indicators and threshold values of those attributes which determine soil resilience and sustainable land management are determined; and
- appropriate practices for different soils are identified to ensure land management is conducted on a sustainable basis.

97 It was also indicated in the workshop that any research should:

- be developed in association with local communities and social scientists;
- be built on past experience;
- use interdisciplinary teams;
- be targeted at specific agroecosystems; and
- obtain better information on land-use systems and changes in key soil properties related to resilience.

Biophysical solutions: the holistic approach

98 Biophysical solutions to most SWNM problems related to crop production exist, but the challenge facing scientists is to find solutions which are environmentally sound, economically viable, and socially acceptable. Fortunately, there are a number of approaches, some requiring a modicum of further strategic research, but many requiring only

applied and adaptive studies which could be integrated with existing production systems by joint efforts from farmers and scientists. The need is of course for a whole farm approach, but as argued previously, the effects of changes also have to be considered on a wider basis, and on a longer time scale than a single crop season. The effects on successive crops and associated animal systems also have to be considered, as well as the relationship to the landscape and ecosystem - considerations usually missing from the farming systems approach.

99 We are dealing not merely with soil systems, but with soil-water-plant-animal-forestry systems. Range management specialists, foresters, and hydrologists may need to be involved as well as soil scientists. The interdisciplinary approach will often need to be wider than that of soil scientists with plant breeders and physiologists, and involve ecologists and socioeconomists, and sometimes others. Not everyone can be involved at every stage, as teams become unmanageable, but the breadth of expertise needed for sustainability studies has to be recognized. We have focused on changes at the farm level, for it is here that most of the decisions affecting resource use are made. It is a challenge to scientists to evaluate the various advances in strategic and applied research - not only at the farm level but also at the landscape level - and to consider a time scale not of a crop season but of decades.

100 A questionnaire was also sent to those whom we believed had sufficient specialist knowledge to make an assessment of the problems of SWNM (Annex VI). The answers have been collated to simplify presentation. The important problems of SWNM as seen by our correspondents are given in Figure III.3.

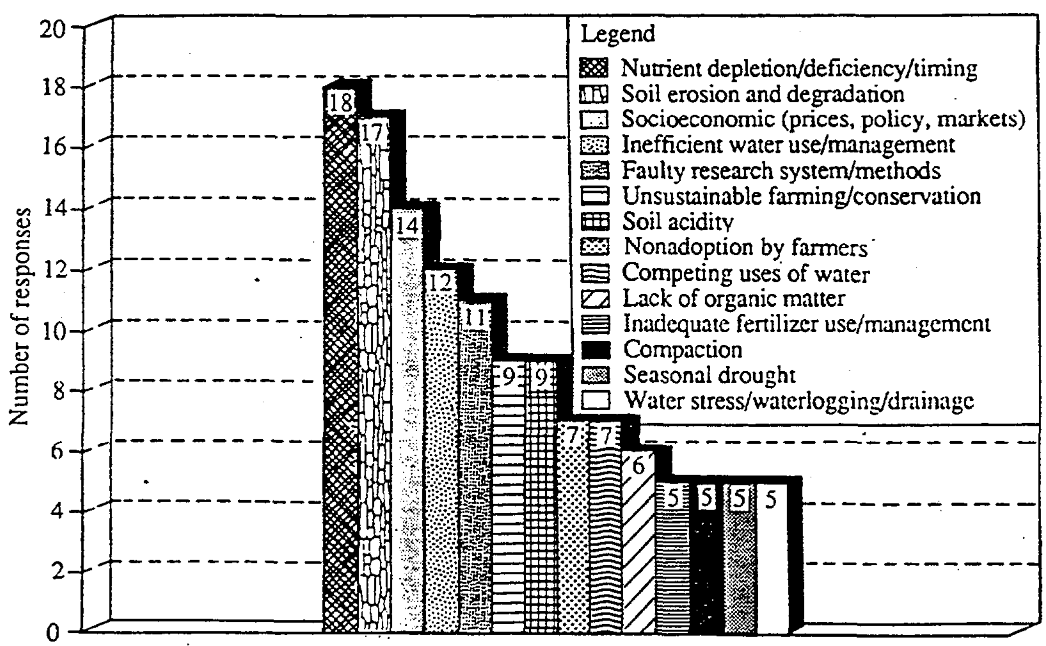


Figure III.3 Perception of major SWNM problems.

IV RESEARCH PRIORITIES

Overview

101 From the issues raised previously in this paper, it will be apparent that increases in global agricultural productive capacity must go hand-in-hand with the conservation of the resource base, and at the same time some provision must be made for other uses of the land. The downhill spiral of unsustainability, which results from mismanagement and the fact that many regions of the world are already at the lower end of the spiral, justifies a sense of urgency. If developing countries are to be helped to meet these challenges, long-range concerns about food security, income generation, and the condition of natural resources must be addressed in planning future economic and social development. The supporting research must be holistic and integrated, and always have the structure and the function of the broader agroecosystem in mind, be conducted on a landscape (catchment) basis. Though research on soil, water, and nutrient management is essential to this task, there needs to be recognition of the fact that there is a cost attached to sustainability - a cost which farmers must be aware of, which scientists must address, and which society must be willing to pay for.

102 To reverse or reduce unsustainability trends, omnipresent in most developing countries, every attempt should be made to ensure fullest land-user participation in each phase of the research process - planning, technology development, and dissemination. The above analysis has clearly established that the implementation of technology has minimal impact at the farm level if the social, political, and institutional context of on-farm and off-farm activities are not considered. It is essential to capitalize on the opportunities to be reinforced and to identify the constraints which need to be overcome in order to approach sustainability. Applied soil, water, and nutrient management research that does not address issues of gender, social structure, indigenous knowledge, and the functioning of different local institutions, is unlikely to have permanent application.

103 To develop priorities, the following points must be borne in mind:

- Athough soil-related research has a high element of site-specificity, there are common threads among the target zones.
- Any target zone may have many constraints, and it is necessary to recognize the relative importance of the individual constraints and their interactions with other constraints, and then to prioritize research activities as a function of the constraints and objectives.
- A number of problems have a common cause - for example, depletion of soil organic matter will seriously affect several soil physical, chemical, and biological properties.
- There is an urgent need to develop indicators or early warning signs of resource degradation. Cause and effect is generally complex, and may be misleading. A good example is erosion in some environments which may be triggered by chemical or physical constraints to vegetation establishment, a lack of which promotes erosion; addressing erosion is only a partial solution, and the larger cause must be understood and rectified.

- Though it is easier to resolve components of problems, a holistic approach on a farming system or watershed basis has a longer-term impact with residual benefits.
- Though soils are subject to improvement, the soil-water-plant-animal-human-environment linkages are so overriding that if the system is not addressed as a whole, the solutions may be temporary.
- Finally, the key to moving upwards in the sustainability spiral is income generation, and to a lesser extent reduction of risks. These two issues are the prerequisites for sustainability.

Setting priorities

104 The rationale for developing priorities in soil, water, and nutrient management involves many different considerations. For national agricultural research systems (NARS), the considerations include the availability of stress-free land, population distribution, in-house capability to undertake the task, the availability of funds, and even the importance attached to SWNM research by national decision-makers. For resource-poor farmers, the primary consideration is income generation, with subsidiary considerations of equity. For the international community, the main objective is to enhance the ability of a finite resource base to support the burgeoning population. Thus the emphasis varies with the population under consideration. It is important to establish some kind of rationale specifically for donor-supported research and to prioritize the activities in a generic fashion so that donors can select areas depending on their customer requirements and the global relevance of the problem. We have noted elsewhere the inadequacy of available data bases for the presentation of the problems.

105 The following are some considerations that have been taken into account in our assessment of the relative significance of the problem areas:

- the likelihood that the problem will be solved by research, and if solved that the results of the research will be acceptable to the land user and implemented to bring about the desired change;
- the relative importance of the problem with respect to attaining sustainable development;
- the number of people who will benefit by a resolution of the problem or the number of people impacted by the problem;
- the relative magnitude of the gains in production that will result through resolution of the problem;
- the significance of the environmental implications of the problem;
- the gains in production in terms of cost-effectiveness and/or a shorter time frame from amelioration of the resource base rather than modification of the plant;
- the generation of increased labour use and a reduction in the seasonality of labour use, together with an increase in production;
- increased production, with the capacity to promote small-scale associated agrobased industries;
- the involvement of institutions currently involved in aspects of basic research diffusion activities, and their linkage with other more applied research institutions and NARS to facilitate technology development; and

- the relative magnitude of other benefits to society.

High-priority research components

106 On the basis of the discussions in the preceding sections, and the responses to the questionnaire that was distributed (Annex VI), we have integrated the specific problems of SWNM research into ten principal problems where we believe research has a major contribution to make. They are, in no particular order:

- **nutrient losses and soil acidity due to the export of nutrients via crop harvests, leaching, and soil erosion;**
- **land degradation and alienation, by erosion, pollution, and urbanization;**
- **the low level of application of knowledge already available from research;**
- **the lack of long-term experiments which can be used to monitor changes in soils due to land-use changes, and as a basis for validating indicators of sustainability and developing simulation models to predict the effects of land-use changes;**
- **the distortion of farmers' decisions on sustainable land management methods by markets or policy decisions affecting costs and prices;**
- **the impermeabilization and loss of soil structure (architecture) due to inappropriate land-clearing and cultivation techniques;**
- **the loss of soil organic matter by excessive cultivation, and the inadequate return of organic materials to the soil;**
- **inadequate methods for the diagnosis of SWNM problems;**
- **inappropriate methods of water management, in both irrigated and nonirrigated areas; and**
- **The inadequacy of the information base on which decisions about land use, crop production, and grazing management must be based.**

107 All of these problems occur in one or more of the target zones. Their significance differs between zones. In relation to most of the problems, there is a substantial data base of information which can be used for adaptive research on location-specific problems, but there is also a need for further strategic and applied research.

108 We have included as a principal problem the **lack of an adequate information base.** We believe it to be essential to the better prioritization of SWNM research, as well as essential to governments endeavouring to improve their management of natural resources. In Agenda 21, the inadequate information base on which action has to be initiated is recognized in the call for "an action programme on land resources planning

information and education for agriculture [to] be developed to systematically identify sustainable land uses, and production systems for each land and climate zone, to control inappropriate land use and to take into account the actual potential carrying capacities, and limitation of land resources".

High-priority research areas

109 Addressing the research problems identified becomes an academic or even a futile exercise if the problem is addressed in isolation, and not in the context of the socio-economic limitations. The driving force in defining the priority areas should be the ability to move upwards in the unsustainability spiral.

110 The research areas that should be given priority attention are those where there are many sites near or at the bottom of the spiral, and those where factor productivity is falling most rapidly. A rational prioritization of needed research requires information about where different communities are operating on the spiral of unsustainability. This information needs to be supported by knowledge about the resilience of the soils on which the communities depend. Such information has not yet been assembled in usable form, and we believe that high priority needs to be given to assembling this information. In the meantime, there are areas where acute problems are already apparent, as in mountain areas and other steeplands, at the desert margins and the drier savannas where desertification is occurring, in irrigation schemes where siltation of reservoirs and salinization is reducing productivity, and in more populous areas, particularly on marginal lands, where shifting cultivation has been the traditional land management system. Thus we see that priority should be accorded to:-

- **land and water management in the mountainous areas and steeplands;**
- **land and water management in desert margins;**
- **land and water management in irrigated areas;**
- **management of acid soils;**
- **factor productivity in wetlands;**
- **integrated inorganic/organic farming methods for savannas;**
- **alternatives to shifting cultivation for humid forests.**

111 All of these are under study or under consideration for development as major projects. There are also many activities which do not form a part of current projects related to these priority areas, but are very relevant to them. These include many activities managed by NARS, many research projects based in developed countries, such as the USAID-funded Soils CRSP and the soils projects of ORSTOM. There are also many development projects conducted by NGOs, in which there is a major component of adaptive research, but which have only weak linkages with organizations conducting the strategic and applied research on which the adaptive work is based.

112 We agree with the views expressed most clearly in the responses to the questionnaire (Figure IV.1) that the most urgent need is for adaptive research to apply and adapt what is already known to specific situations.

113 We believe a mistake of the past has been to see strategic and applied research as the starting point, producing new knowledge which users are expected to evaluate. A harmonious partnership needs to be established, in which the starting point is the problem as it exists in the field, and the highest priority is given to finding a solution. Resolution of the problems may require strategic and applied research. However, most farmers are already finding their own solutions by trial and error. They need to be brought into a system in which adaptive research to solve their problems is conducted, and linked to centres with the necessary strengths in applied and strategic research.

114 Thus we believe very high priority must be given to creating a mechanism - rather than a structure or strategy - for SWNM that will facilitate the interactions between the many participants. The mechanism has to enable real linkages between those involved in all aspects of relevant research to be formed and maintained, with a flow of information from the adaptive to the applied and strategic work, and equally in the other direction.

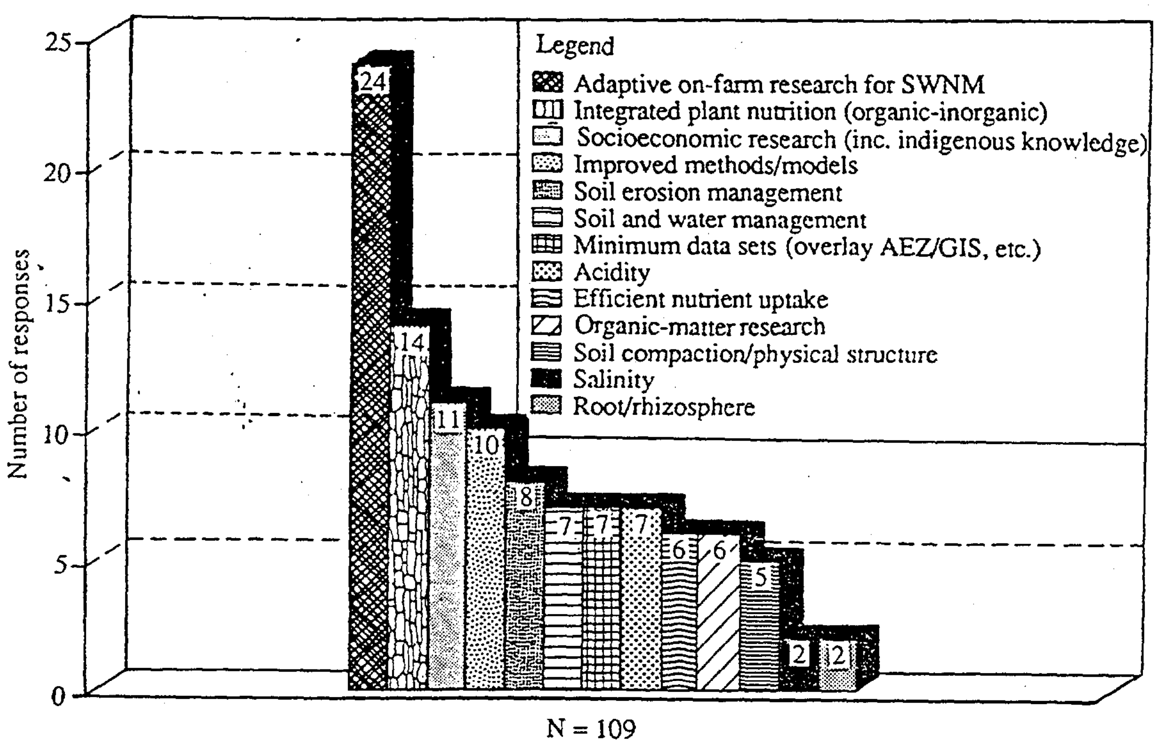


Figure IV.1 Perceptions of major research priorities.

115 The biophysical problems of SWNM may be of dominant importance to any one of the target zones, but several are also generic. There will be an advantage in concentrating strategic research efforts in one or in relatively few centres, if the mechanism exists to ensure that all can benefit from the results.

V HARMONIZING ACTIVITIES - AND A SUGGESTION FOR IMPLEMENTATION

The need for harmonization

116 It would seem particularly important to harmonize the activities of the different organizations involved in tackling the problems of SWNM research to ensure the most efficient use of resources. The growing awareness among the donor community of the significance of SWNM research, and the fact that national programmes need support for their applied and adaptive research, as well as strategic research, has led to the establishment of several international initiatives in addition to those of the CG system, such as IFDC, IBSRAM, ICIMOD, and TSBF, each of which was established to provide essential support to national SWNM-related activities. As a result, there is now a considerable but fragmented and poorly coordinated international programme of activities on SWNM research.

117 When discussing the expansion of the CGIAR system and the establishment of a number of centres with ecoregional mandates, TAC (1991a) suggested that "there could be a series of agroecologically focused institutes or ecoregional mechanisms linked by a global council". We certainly see a need for better linkages between the many organizations now involved, but believe that this might best be achieved by establishing some form of 'clearing house' which would be responsible for facilitating and catalyzing information exchange between consortia working on priority problem areas, and harmonizing the activities of the wide range of other organizations involved in related SWNM research.

118 One area in which we see the need for better linkages to be particularly important is in relation to assisting various international organizations in coordinating their relations with different NARS. In this respect we believe the views and interests of the NARS must be paramount.

Assessing comparative advantages

119 The principal international organizations involved in SWNM research are listed in Table V.1. While the activities of the UN organizations have been given little specific attention in earlier sections, their vitally important work in supporting NARS - in the development of the *World Soil Map*, and in establishing global monitoring systems of land use and other factors related to environmental change - is fully recognized. All national governments are also involved in SWNM. Normally several government departments undertake related aspects of research and other activities involving SWNM. Universities, NGOs, and others are also involved. The important contribution made by research organizations in developed countries to SWNM research in developing countries has also to be recognized. These national and nongovernmental organizations are too numerous to list here. NGOs are gaining much experience in handling location-specific problems, but the full value of their successful projects is often not obtained because there is no mechanism for linking their work to that of others. Each of the different organizations is playing an important role in SWNM research. A discussion of their 'comparative advantage' in basic, strategic, applied, and adaptive research is given in Annex VII.

120 Following the TAC's recognition of the increased importance to be given to problems relating to resource management, several of the CGIAR IARCs were asked to assume 'ecoregional mandates' (TAC, 1991a.) In the paper addressing this issue, TAC states: "The ecoregional entities will take primary responsibility for the bulk of the CGIAR research on resource conservation and management, which is absolutely critical to the sustainability of production systems. The primary focus will be on strategic research, but a key question for the CGIAR is the portion of the adaptive, applied, and strategic research for which an international system has comparative advantage."

121 We see the last statement as a key question, although not for the CGIAR alone. It is also important for all of the international organizations involved in SWNM. In a paper issued shortly after that which addressed the ecoregional focus, TAC (1991b) considered the relations between the CGIAR centres and the national agricultural research systems (NARS). They rightly state that: "Another problem is the need to avoid placing too great a burden on national systems through independent approaches made to the same institution by several centres." The problem involves not only the CG centres but also most of the other organizations listed in Table V.1 that are likely to be approaching the same national organizations to invite them to participate in their activities.

Table V.1 Some organizations involved in SWNM activities.

CG IARCs	Other IARCs	NARS in developing and developed countries	UN agencies	Others
CIAT	IBSRAM	Including government	FAO	ISSS/CIP
CIFOR	IFDC	organizations concerned	UNEP	IGBP/GCTE
CIMMYT	ICIMOD	with agriculture, forestry	UNESCO	IUCN
CIP	ISRIC	irrigation, environment	IAEA	TSBF
ICARDA	CABI	natural resources,	WMO	WRI
ICRAF	AVRDC	land development, land reform,	WHO	NGO's
ICRISAT		land conservation, and		
IFPRI		research in the above areas,		
IIMI		universities, NGO's		
IITA				
ILCA				
IRRI				
ISNAR				
WARDA				

122 The TAC suggested that a way forward for the NARS and CG centres would be by networking arrangements, and indicated that the networks formed might involve some organizations other than the NARS and CG centres. We agree that some form of networking arrangements are needed. To avoid a 'top-down' approach to network management, the route taken by IRRI, in which its networks were redeveloped as 'consortia', has advantages. In a consortium (defined by IRRI as "a limited number of national and international institutions formally organized to collaborate in research, training, and technology generation designed to meet mutually agreed objectives") the partners are expected to play equal roles. It may remain desirable for the management of a consortium to be with an international body seen to be independent of the interests of any

one country, or as having an interest in extending the results of any one research organization.

123 The comment of TAC on this problem was (TAC 1991b): "As far as cooperative networks are concerned, if they are to be successful and sustainable there is no viable alternative to a demand-driven system in which the countries themselves define the problems and determine the priorities." We would agree with this statement provided that "countries" allow the voice of the farmers and other users to be heard, and that a mechanism is in place to facilitate the sharing of results and information. We see that an equal partnership needs to be established in consortia in which all those with relevant interests and expertise are involved. We also believe that an international organization has a considerable comparative advantage in the management of a consortium provided that it is not generating results which the partners in the consortium are expected to embrace.

124 International centres are seen by many NARS as models for the research process. Divorcing the IARCs from adaptive research, where we see the most immediate needs for SWNM research, is likely to lead to neglect of adaptive research by the NARS. Thus we believe that an international effort focused on the methodologies of adaptive research is essential. An international body independent of particular interests should be most influential in promoting the sharing of results and information.

A suggested mechanism for SWMN research

125 At present there is no global strategy for research on the problems of sustainable land management, or on the major components of land management, namely soil, water, and nutrient management. There are many organizations concerned with various aspects of sustainable land management. Many of these attempt to deal with local problems where an immediate answer is needed, as in the control of soil erosion on an economic basis or in the rights to land tenure. Others contribute to the already substantial knowledge of soil characteristics and behaviour, and the factors determining soil productivity. Most internationally supported research has been directed to problems of yield improvement on a plot basis rather than a catchment basis. Concern is sometimes expressed that the focus on yield draws attention away from the problems of long-term sustainability and the need to address production and sustainability problems on the basis of the whole catchment or a larger area.

126 For developing countries, and particularly the poorer of them, only through greater productivity can the threat of environmental damage be reduced - by giving attention to reducing the pressure on marginal lands, and by taking the necessary measures to avoid environmental damage. There is no conflict between measures to increase productivity and yield and measures to improve the quality of the environment and conserve natural resources. There is rather a considerable degree of complementarity between them. There are varieties of most crops available with yield potential greatly in excess of current yield levels. The potential of these improved varieties will not be realized without improvements in SWNM. The long-term sustainability of cropping systems and the avoidance of environmental degradation are also dependent on the development of better methods of land management. Many of the problems need to be solved in the immediate future if

irreversible damage to the productive capacity of the land, the availability of water supplies, and the quality of the environment is not to occur.

127 We know how to make most soils yield more than they do at present. What we do not know is whether the changes needed to make them more productive are sustainable in all instances, nor how to make changes which are adapted to the social, economic, and political conditions in which most of the land threatened by unsustainability is used. Nor do we have sufficient information to know how important the off-site effects of land-use changes are.

128 The organizations needed to conduct the necessary research already exist. But the research is too fragmented, with inadequate focus on major problems; there is too little coordination of the work between the different international organizations, between the international and national organizations, and between governmental and nongovernmental organizations. Too little account is taken of indigenous knowledge, and socioeconomic problems. Within some national and international organizations there is too little interaction between crop and soil scientists, between the agriculturists and the foresters, and between the biophysical scientists and the socioeconomists.

129 To manage the activities related to specific SWNM research problems, we suggest that research consortia (or some formalized linkages) be formed, some of which might evolve from existing research networks. The consortia would need to be focused on the priority research areas identified previously, and would need to be representative of the range of disciplines that need to be involved and of the national and international organizations with a significant interest and expertise related to the problem.

130 The consortia would have responsibilities to ensure that not only an effectively coordinated, demand driven, user-based, interdisciplinary research programme is developed, but that an appropriate training programme is also implemented. To support the work of the consortia we suggest that an information system, including a GIS data base on land use and land-use changes be established, and an information network created. For the NARS we would see an advantage in that linkages would be to the consortia rather than to competing international centres with related interests.

131 To harmonize the work of the consortia, and to serve as an information centre for the consortia and governmental and nongovernmental organizations conducting development projects attempting to establish productive and sustainable land management systems, we suggest that what, for want of a better name, we have termed a 'clearing house' should be established.

132 The 'clearing house' should provide the necessary mechanisms by which the involvement of scientists, policy-makers, and farmers in the consortia and in its own operations are ensured, and appropriate leadership provided for the consortia in their activities in technology generation and adoption.

133 The first challenge is to link and harmonize the presently fragmented research efforts, so that:

- results and problems can be shared;
- duplication, which is expensive, is reduced;

- priority-setting is organized;
- research relevance is established; and
- accountability is promoted.

134 Finally, it is reemphasized that technical research and developmental efforts in soil, water, and nutrient management will only have long-lasting impact if:

- local community control of resources and environment is promoted;
- income generation and reduction of risk is encouraged;
- intergenerational equity is sought;
- national policies do not conflict with sustainability efforts;
- the land-user has an integral role in the research and development effort; and
- appropriate attention is given to spatial and temporal issues.

"We have now the technical capability to build enduring national and global nutrition security systems based on sound principles where the short and long-term goals of development are in harmony with each other. What we often lack is the requisite blend of political will, professional skill, and farmers' participation. We live in this world as guests of green plants and of the farmers who cultivate them. If farmers are helped to produce more, agriculture will not go wrong. If agriculture goes right, everything else will have a chance for success." (Swaminathan, 1986)

Annex I

The symptoms of unsustainability

Yields changes. Globally, yields of the major cereals have been increasing on a per hectare basis for the past 50 years, and continue to increase (Figure A1.1.) Yields are still well below established maxima so that there should be scope for further, and in most cases substantial, increases. Why then the concern? The first problem relates to the return per unit of input, where areas of intensive rice monoculture and high yield levels, stagnant yields, and declining trends in factor productivities are now observed (Pingali and Rosegrant, 1993.) The second problem relates to areas where low or zero inputs are used, as in many parts of Africa, where sorghum, millet, and cassava yields have been declining or static at very low levels for two or three decades (Table A1.1). The reason for falling per hectare yields is declining soil fertility, associated with more frequent land cultivation and the need to cultivate marginal land which was previously considered to be unsuitable.

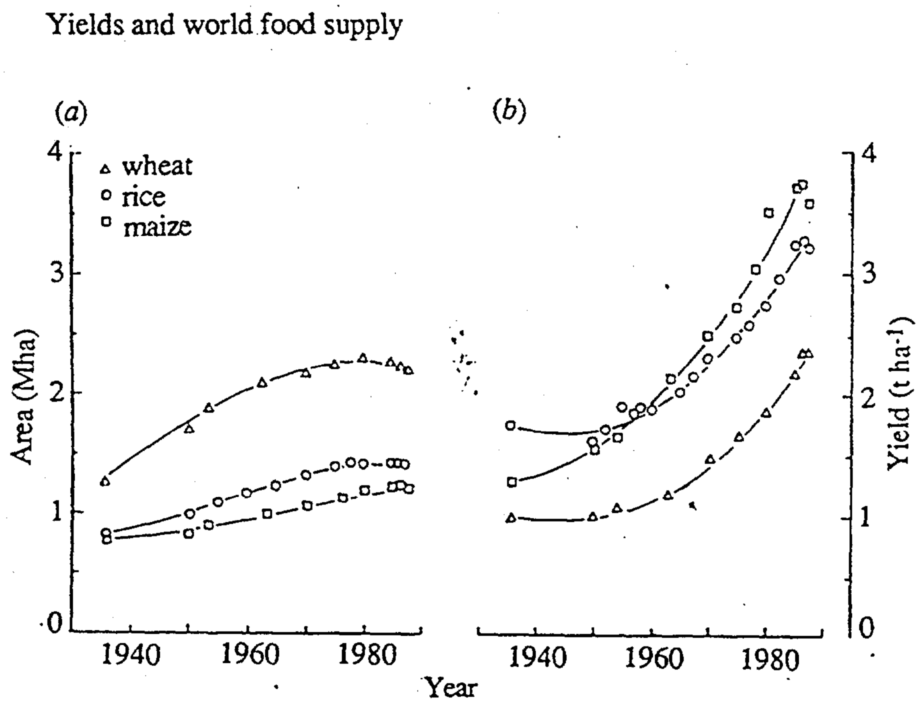


Figure A I.1 Trends in total area (a) and average world yield (b) of the three major cereals (data from *FAO Production Yearbooks*, collated by Evans, 1983).

Declining quantity and quality of land resources. The effects of increasing population pressure on land resources are illustrated by the data (Figure A1.2), which show that land for further development will have almost disappeared by the year 2025, except for a few countries in Africa and Latin America. Future development must depend on increased productivity and intensified land use. Only about 11% of arable land is resistant to degradation, or strongly resilient (Figure III.2). All of this land is currently intensively cultivated. Other soils are being degraded. They differ greatly in their ability to recover from stress, but most soils have the ability to recover if the stress is not extreme. Fragile and marginal soils degrade easily and have limited resilience.

Table A I.1 Mean annual yields and production of some major staples.
(a) Some countries with declining or stagnating yields,
(b) Some countries with increasing yields (data from FAO production yearbooks).

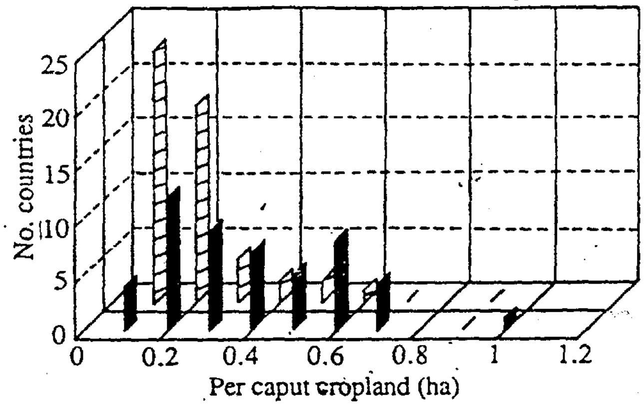
Crop	Country	Yield (kg ha^{-1})				Production ('000 t)		
		61/65	69/71	79/81	89/91	69/71	79/81	89/91
(a) Stagnating and declining yields								
Wheat	Bangladesh		854	1869	1665	103	803	972
	Kenya		1678	2011	1747	223	212	210
Rice	Pakistan		2246	2465	2309	3431	4884	4862
	Côte d'Ivoire		1168	1171	1174	335	448	661
Maize	Angola		864	506	301	467	303	228
	Côte d'Ivoire		773	684	728	257	352	497
	Mozambique		1003	569	367	364	383	370
	Haiti		1058	868	807	245	179	168
Millet	Niger		422	435	383	975	1311	1422
	Sudan		567	397	166	423	436	185
Sorghum	Niger		445	422	280	262	347	423
	Sudan		808	744	534	1525	2273	2085
Roots and tubers	Ghana	7100	6383	6721	6609		3183	5159
	Zaire	12100	6795	6901	7562	10752	13595	18528

Crop	Country	Yield (kg ha^{-1})			Production ('000 t)		
		69/71	79/81	89/91	69/71	79/81	89/91
(b) Increasing yields							
Wheat	Pakistan	1110	1567	1844	6796	10760	14433
	China	1168	2047	3129	29687	59196	94682
Rice	Bangladesh	1681	1952	2593	16540	20215	26935
	Indonesia	2346	3262	4298	19136	29570	44864
	China	3295	4244	5622	109853	145665	187036
	Korea, Rep.	4628	5513	6282	5574	6780	7770

Apart from the pressures for more land for cultivation, the need for more land for nonagricultural uses is increasing - for forestry, biodiversity reserves, and for urban development, which is mostly on areas of the best land where centres of population have developed. Also large areas of steeplands and wetlands demand protection and conservation.

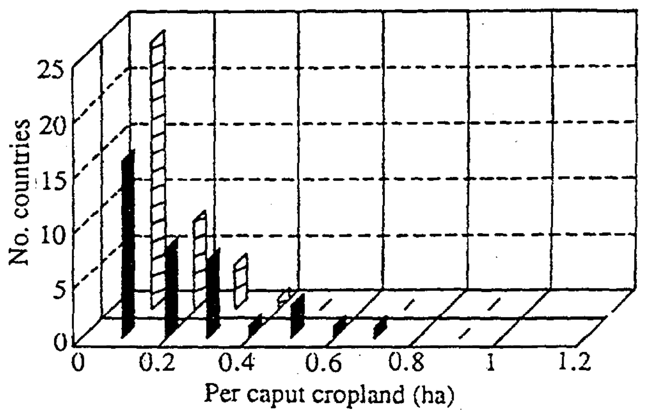
The relatively poor quality of many soils in the tropics has received much attention. While many of the myths about the difficulties of cultivating soils in the tropics have now been exploded (Sanchez and Lal, 1992), there is no doubt about their greater fragility and susceptibility to degradation, often due as much to the higher temperatures and more intensive rainfall to which most are subject as to inherent soil limitations.

(a) Per caput cropland in year 1990 and 2025
AFRICA



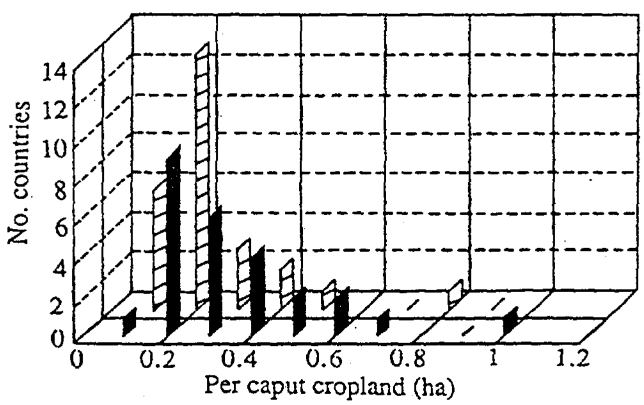
Source: WRI (1992)

(b) Per caput cropland in year 1990 and 2025
ASIA



Source: WRI (1992)

(c) Per caput cropland in year 1990 and 2025
CENTRAL AND SOUTH AMERICA



Source: WRI (1992)

Figure A1.2 Predicted reductions of per caput cropland, 1990-2025.

Subsistence farmers have of course been ingenious in finding ways to manage soils. This has usually meant that they have had to find new land to cultivate or new sources of organic manures. An active trade in animal manure has been a feature of the Kano market in Nigeria for many years, enabling farms in a large area around Kano to be cultivated continuously and productively. In Nepal, farmers have carried branches from the forest areas to their cultivated plots to use as mulch or for composting, a practice which has enabled them to manage steeply sloping lands on a sustainable basis for centuries. This system is now breaking down, as the damage to the forest causes erosion of the watersheds, and as the distances the women have to walk to find suitable trees as a source of their mulch and compost continues to increase.

Better ways to manage production from such areas have to be found. There has, of course, been considerable research conducted to find ways to increase and sustain yields while avoiding soil and other environmental degradation. These studies have established that the most important factor is proper nutrient management, but physical and biological factors are also involved. The problems of soil and environmental degradation are usually due to a combination of factors, and their effects may be both on-site and off-site. Soil erosion is generally considered to be the most common cause of land degradation (Oldeman *et al.*, 1990) It usually leads to slowly declining yields and reduced productive potential of the cultivated land, while causing equally insidious and sometimes more devastating effects off-site. Both farmer and researcher seeking ways to make farming systems more productive and sustainable must focus on the problems of maintaining organic-matter levels. The problems are currently dominated by social and economic issues, connected with the direct and indirect costs of finding or growing the organic material, and incorporating it in the cultivated area.

Declining water resources. Water, like land, is becoming a scarce resource. Over the past three decades 30 to 40% of the food supplies of the world have been grown under irrigation, and 50 to 60% of the extra food produced in the period between 1960 and 1980 was produced from irrigated land. Unfortunately the rapid expansion of the irrigated areas that occurred in that period is not continuing, and the demands on existing supplies for urban and rural drinking water, sanitation, and health are competing increasingly with the needs for irrigation. It is becoming more and more difficult to identify new opportunities to develop water-storage facilities. The construction of large dams is now generally recognized as uneconomic when based on a realistic estimate of the costs, which include the need for erosion control in the catchment area and drainage facilities in the command area. Opportunities to develop water-harvesting methods and to develop microcatchment storage systems appear to merit much more attention than they have so far received. However, for crop production the most important problem is to improve water-use efficiency. This requires efficiency in the supply of water to the field, and efficiency in the use of water by the crop to increase economic yield. Many irrigation systems are known to be functioning at very low efficiencies. The expected life of many irrigation systems has also had to be drastically reduced because of soil erosion problems in the catchment area of the reservoir, causing excessively rapid siltation (Shahin, 1993, and Table A1.2).

Table A1.2 Siltation of reservoirs in India (Narayana and Ram Babu, 1983).

Reservoir	Catchment area 1000 km^2	Sedimentation rate ha m/100 km^2	
		Predicted	Observed
Hirakud	83	2.5	3.6
Tungabhadra	26	4.3	6.6
Mahi	25	1.3	9.0
Rana Pratap	23	3.6	5.3
Nizamnagar	19	0.3	6.4
Pong	13	4.3	17.3
Pamchet	10	2.5	10.1
Tawa	6	3.6	8.1
Kaulagarh	2	4.3	18.3
Mayurakshi	2	3.6	20.9

A further problem of major significance in the drier irrigated areas is salinity, caused by rising water tables in the command area, and in all areas waterlogging. Widely different estimates of the extent and rate of increase in saline areas have been made, but there can be no doubt of the importance of the problem.

Water quality problems have also been stated to be a concern. The problem is probably greatest in relation to disease organisms associated with water supplies (Obeng, 1992), although vigilance is certainly necessary in relation to chemical contamination. However, in most developing countries where a food problem exists, the dangers to health are more likely to arise from malnutrition than from chemical contamination of water. Water quality in relation to potential use for agricultural purposes has received wide study. With improved irrigation methods, opportunities to use water of relatively high salt content are increasing. India for instance is currently using large volumes of poor-quality water for summer irrigation in areas where the winter monsoon will wash out accumulated salt.

Declining soil nutrient reserves. Soils of the tropics present special nutrient management problems. Not only are the majority inherently low in nutrient content, but the dominance of low-activity clays means that nutrient retention is poor, and often primarily dependent on organic-matter content. In addition, many of the soils in areas which have been cultivated for long periods have been mined of their nutrients. Recent studies of nutrient balances on a country scale have shown that nutrient mining in sub-Saharan Africa is widespread (Figure III.1, and Stoorvogel and Smaling, 1990.) Productivity is low because there are insufficient nutrients to support economic yields of crops. Once nutrients have been taken from a soil, recycling of residues can do little to help, as it will only recycle poverty.

To raise productivity and stop further degradation it is essential that nutrients are brought to cultivated areas from outside. Where land is plentiful it is possible to do this by transfer of nutrients in manure or tree prunings. Once land availability is restricted, it has to be done by bringing in inorganic fertilizers. For this to be possible, it is necessary for them to be available at economic prices. Hence much effort has gone into the identification of cheap sources of fertilizer for the tropics and improvement of the efficiency of fertilizer use. Such work remains essential.

Nitrogen is a special case. It is the only major nutrient that can be fixed from the air. Many studies have been devoted to methods to maximize the recovery of nitrogen from the air by biological nitrogen fixation in farming systems of the tropics. Finding better methods to exploit the potential of biological nitrogen fixation will remain an important research priority for many years to come. In many of the areas where nutrient availability is a serious constraint to crop production, fertilizers are not readily available - and when they are, the costs are greater than the value of the extra yield produced. Hence the problem of establishing a productive, sustainable system depends on factors beyond the farm gate. Most important is the need to identify and develop cheaper sources of organic manures and plant nutrients, preferably those which are locally available.

Annex II

The farmer-back-to-farmer approach

Figure II.2 illustrates the farmer-back-to-farmer paradigm as one model for an integrated approach to applied and adaptive SWNM research (Rhoades and Booth, 1982). The research process begins with a joint participatory diagnosis of the problem (farmers and scientists may not see the same problem.) Instead of scientists defining the problem and generating technologies as a result of strategic and applied research in laboratories and experiment stations, the research process begins with the farmer. Traditional and local knowledge (ethnoscience) is given its rightful place in the research design and diagnosis stages. (Although now regarded as a new approach, it is worth noting that the fertilizer industry was established on the basis of the shared knowledge of a farmer [John Gilbert Lawes] working with a chemist [Henry Gilbert] at Rothamsted manor in England in the last century).

In the diagnosis stage three general questions have to be asked:

1. We need an understanding of how and why resources such as manure, crop residues, and trees are utilized before recommending any changes. What resources are available, what are the alternative uses, what are the alternative values? This information must be matched with the information the scientist has on the value of resources in terms of their potential contribution to the livelihood of the farmer and the farm family, the alternative values of the resources (e.g., the nutritive value of crop residues as livestock feeds), and the environmental and long-term consequences of one sort of action or another. Decisions may also be influenced by family and social obligations, which in turn may depend upon the economic status or gender of the farmer.

2. Why are these practices followed? Too often too much effort has been expended attacking the 'problems' without first having understood why they develop. Perhaps a seemingly negative practice has to do with differences in access to resources, social status, land tenure, or poverty. In the case of gender, women normally have access to fewer resources than men because they lack the necessary labour, have many household responsibilities, or are excluded from credit. While recognizing that the nature and risk of soil degradation will be determined by biophysical conditions, decisions as to what the land is used for, how it is used, and what practices will be followed will be determined by the socioeconomic circumstances.

3. How do farmers perceive their problems, and how do their perceptions differ from those of SWNM scientists? The major factors which influence the decision-making of a household are their livelihood objectives, and their perception of their physical environment and the options for change open to them. Farmers' knowledge and perceptions of soil constraints, and their broader production objectives and ideas concerning production potential and limitations, together with environmental, cultural, and economic considerations are all used in making decisions on a particular farming practice. The degrading effects of a particular practice may not in fact be perceived by the farmer (Swift *et al.*, 1994.)

The farmer-back-to-farmer diagnosis method proceeds through successive phases to define the problem more clearly and to seek potential solutions. Each step involves farmer and scientist, culminating in the on-farm evaluation and testing of the supposedly improved technology. The process should greatly enhance the chances of success. The model provides practical targets that translate research results into adoptable land-use practices. It also provides an interdisciplinary forum in which the different perceptions and aspirations of policy-maker, land user, and scientist can be reconciled.

By changing the role of the scientist and extension agent from one where he or she brings precepts, messages, and packages to the farmer, to one where each brings principles, methods, and baskets of choices, diffusion of the results of the research are greatly simplified. The farmer is now part-owner of the research, and he becomes the extension agent. And what is diffusing becomes principles, concepts, skills, forms of organization, and ways of experimenting.

Annex III

Biophysical problems of SWNM research

As in any dynamic system, the topics treated below are interrelated. For example, poor plant growth due to nutrient deficiency will have important consequences for ground cover and erosion control, for soil organic matter, nutrient and water relations, for soil physical factors affecting succeeding crops, and for the impact of root diseases. Research needs in the target zones identified by Sanchez and Nicholaides (1981) are in Table A3.1.

Table A3.1 Priority rankings of research components by agroecological zones: 0 = none, 1 = low, 22 = medium, 3 = high (Sanchez and Nicholaides, 1981).

Research and development components	Humid tropics	Semiarid tropics	Acid savannas	Wetlands	Steeplands
A. RESOURCE APPRAISAL					
1. Soil characterization and classification	3	3	3	3	3
2. Soil classification for plant nutrition	3	3	3	3	3
3. Soil fertility evaluation	3	3	3	2	3
4. Fertilizer marketing, distribution and use	2	2	2	2	2
5. Fertilizer manufacturing technology	2	1	2	2	1
B. STRESS FACTORS					
1. Selection of germplasm tolerant to soil stress	3	2	3	3	2
2. Management of soil acidity	3	1	3	0	1
3. Salinity	0	2	0	2	0
C. NUTRITIONAL CONSTRAINTS					
1. Nitrogen fertilizer efficiency	3	1	2	3	1
2. Phosphorus fertilizer management	3	1	3	0	2
3. Nutrient balance	2	1	2	1	1
4. Sulphur	2	1	3	2	2
5. Micronutrients	2	1	3	2	2
D. BIOLOGICAL CONSTRAINTS					
1. Biological nitrogen fixation (BNF)	3	3	3	3	3
2. Organic residue utilization	2	2	1	1	2
3. Photosynthetic efficiency	1	1	1	1	1
4. Rhizosphere effects	1	1	1	1	0
5. Basic stress physiology and genetics	1	1	1	1	0
E. PHYSICAL SOIL CONSTRAINTS					
1. Water management in rainfed system	1	3	2	0	3
2. Erosion prevention and control	2	3	2	0	3
3. Mechanical impedances	2	3	1	0	2
4. Land clearing methods	3	1	1	0	2
F. IMPROVED FARMING SYSTEMS					
1. Sustained production in Oxisols/Ultisols	3	0	3	0	0
2. Multiple cropping	2	2	1	1	3
3. Agroforestry	3	3	1	0	3
4. Intensive fertilization of high value crops	0	0	0	0	0
5. Management of irrigated farming systems in arid areas	0	1	0	0	1
6. Low input farming systems	3	3	3	3	3
G. TECHNOLOGY TRANSFER					
1. Validation and adaptation of research results	3	3	3	3	3
2. Training	3	3	3	2	3
3. Developing fertilizer recommendations	3	2	3	2	2
4. Information services	3	3	3	3	3

Nutrient deficiencies. The problem of restoring nutrients lost by harvests or erosion is how to do it economically. Despite the considerable work by groups such as FAO and IFDC, there is further scope in a GIS framework embracing soil type and climatic factors to identify the responsiveness of various crops to fertilizers, and particularly to enhance fertilizer-use efficiency by studies on application placement and timing. Some developing countries have appreciable deposits of rock phosphates, and it is desirable that the usefulness of these to plant species be further studied. In a farming-system context, the residual values of applied fertilizer in a cropping sequence, and nutrient losses (including micronutrient losses), from a site by harvest removal, leaching, and denitrification need to be identified. These are important adaptive research areas.

Recent strategic research approaches which hold great promise for increasing the efficiency of applied fertilizer are: (i) an improvement of seasonal weather forecasting integrated into decision-making on the likely return from fertilizing, and (ii) the selection/breeding of genotypes for high efficiency in the uptake and use of soil nutrients and applied fertilizer. There are an increasing number of instances of 50-200% differences between genotypes within species of grain crops, and between tree species, in response to added fertilizer. Such a low-input technology should be easy to integrate into many existing farming systems: additional studies on root biology and nutrient uptake, together with heritability studies on root characteristics (there is often medium to high heritability), and on nutritional physiology would also be useful.

Biological nitrogen fixation. One major area almost certain to enhance productivity with low input and high acceptability is the enhancement of biological nitrogen fixation by legumes and some nonlegumes. Restoring soil nitrogen is a major priority - not only to sustained productivity but also in the rehabilitation of eroded and damaged soils such as mining sites. In a great many, if not most, systems biological nitrogen fixation is not being optimized. In many cases inoculation with selected bacteria is not being used, and in other cases responses to inoculation are often disappointing, due either to poor inoculum quality or to competition from less-effective indigenous strains.

Applied research needs include the development of an inoculum with extended longevity under local storage conditions in developing countries (and an improvement in the logistics of inoculum supply) and the selection of bacterial strains which are not only effective but also can compete successfully with indigenous strains and survive and spread. Important areas of strategic research include the selection of genotypes of grain legumes and of nitrogen-fixing trees for high nitrogen fixation (up to fourfold differences have been recorded) and optimization of nitrogen fixation by tree species used in agroforestry by genotype selection and appropriate management.

Nitrogen fixation by the *Azolla/Anabaena* symbiosis in wetland rice is frequently limited by low phosphate, high temperatures, and insect attack. Amelioration of these constraints by hybridization and by gene transfer is showing some success.

There is a good case for strategic studies on nitrogen fixation. Above all, there is a need for adaptive research evaluating the benefit of increased nitrogen fixation on the growth of succeeding crops and on soil organic matter.

The increase of nutrient uptake by the management of mycorrhiza needs further study: soils/plants likely to be responsive need to be defined, and methods need to be devised for introducing effective strains (where they do not already exist) and for managing their population and spread.

Soil physical constraints. Many soils suffer from physical constraints. Highly compacted subsoils (occurring naturally or by poor management of stock and machinery), surface crusting, and loss of structure associated with loss of organic matter can induce these constraints. Compaction decreases root penetration and access to water, and surface crusting increases runoff and erosion and decreases the emergence of seedlings. The absence of subsoil root penetration is part of the problem, and soil compaction is often a major limitation in rehabilitating tin-mine sites. Crust formation is particularly serious in parts of West Africa and India.

There is certainly more work needed on characterizing soils at risk from such factors, and for management practices inducing/ameliorating them. However, costs of amelioration of deleterious physical conditions, e.g. by deep ripping (impedance) or tillage (crusting) are usually prohibitive in developing countries. A key factor in reducing compaction and surface crusting is the management of soil organic matter (see below), which is of great importance in restoring soil structure and water harvesting. In solonized soils, the growth of Kallar grass and some tree species often increases subsoil permeability.

Soil water management. Management of soil water and of nutrition are the two major factors in sustained productivity. Water is inextricably involved in many phenomena, e.g. nutrient uptake and soil erosion. Some 28% of arable land has drought as the major constraint to production (World Bank, 1990) and periodic water deficiency probably affects as much again. Ensuring adequate rainfall harvesting is a first requisite, and this is closely related to soil structure and affected by soil organic matter and by tillage methods. Rainfall-harvesting efficiency can also be enhanced physically by leading water into depressions around trees and along planting rows.

Management of the plant factor holds great hope for increasing water-use efficiency: the selection/breeding of genotypes with deep rooting systems, the possible breeding of genotypes which are conservative of soil water early in the season, the selection of short-season genotypes, and (more recently) the selection of genotypes with high physiological efficiency in water use. Management of the temporal and spatial use of soil water is of special importance in mixed-cropping systems and in agroforestry (adaptive/applied research).

Irrigation systems. Irrigated systems have accounted for many of the increases in food productivity over the last 30 years. While there is still scope for increased areas to come under irrigation (there are often economic constraints), much of the irrigation water is currently being used only at 10-20% efficiency, whereas some 80% efficiency could be obtained with sprinkler and drip irrigation. Increasing the efficiency of use of irrigation water by methods of delivery and better scheduling is obviously a high priority (applied/adaptive research). There is also scope for studies defining the periods of plant growth where withholding of water is critical (or not).

Catchment considerations. The catchment of surface water in a landscape (for irrigation or human use) will be largely governed by runoff patterns, and this needs to be monitored with different cropping/land-use systems, together with modelling of the consequences of different land uses. Eventually, however, decisions on overall land-use planning are at a community or administration level, not at the individual farm level. Nevertheless, runoff is inextricably bound up with cropping practices on individual farms, and the poorer practices also lead to erosion.

There is an important need for a definition of aquifers and their behaviour in relation to farming/land-use systems. A definition of aquifer quality and abundance is essential in forward planning for irrigation and its sustainability. Tree clearing in some areas has resulted in changes to underground waterflow, with consequent development of dryland salinity over large areas. This calls for administrative action to minimize tree clearing and for social studies to define alternative sources of income from the land.

Erosion. Water erosion accounts for extreme losses of productive land each year. Desertification, closely associated with wind erosion, is about 200,000 km^2 per year. Both types of erosion are symptomatic of poor and unsustainable land management practices, the start of the downward spiral.

As well as having severe on-farm effects, water erosion involves lowered water storage of soil, increased runoff, and increased siltation of dams. Although there is a need for basic study on soil characteristics leading to high erosivity, the most urgent need is to study soil loss (and water runoff) as a function of plant growth (affected by many factors) and cover (spacing) during a season, management (e.g., tillage), and soil permeability (affected by organic matter) in different farming systems - a multifactor adaptive research approach. In the rehabilitation of eroded soils, the first priority is to replace some of the lost nutrients. It is here that the optimization of nitrogen fixation by appropriately selected legumes (see above) is an important strategy. Perennial legumes, such as trees (and nitrogen-fixing nonlegumes such as *Casuarina*) have an important role to play in the control of both water and wind erosion, which is exacerbated by overstocking.

Soil organic matter. The management of soil organic matter is also a top priority in sustainable agriculture. Decline in soil fertility is invariably associated with a decline in soil organic matter, which correlates with a loss of soil structure, lowered water infiltration, increasing soil compactibility, soil crusting, increasing erodibility and leaching, a decrease in the nutrient store, lower detoxification effects, and a poorer environment for faunal activity.

A good number of studies have been carried out on the effects of crop residues on soil organic matter and the supplies of nitrogen and phosphorus to the soil, but such research tends to be site-specific and short term, whereas soil organic-matter changes tend to be long term. There are now relatively good but simple models describing organic-matter changes over time under a range of conditions. The potential of these models is very great for predicting the effects of different rotations, tillage methods, and the timing of residue additions on nitrogen release, and they need to be tested on tropical/subtropical systems, incorporating the effects of trees and of annuals where appropriate.

Soil biology. Although the effects of soil fauna, e.g. earthworms and sometimes termites, on soil physical factors are well documented, there has been relatively little study on their management, except for the recognition that their activity is closely related to soil organic matter. The selection of appropriate soil fauna for introduction and management is at present in the strategic research phase, but its potential importance should not be overlooked.

One of the most important missing links in our knowledge of soil fertility is the extent of productivity loss due to unsuspected soil pests/diseases. These are likely to be much more common than was suspected, and may frequently be of the order of 30%.

Soil toxicities. These include salinity, high acidity, pollution by pesticides, and mining effluent (heavy metals). In many cases 'toxic' soils are the result of, or their extent is increased by, poor management. Deforestation in catchment areas with a consequent change in water balance has affected groundwater flows and caused dryland salinity, often remote from the deforested area. Extreme soil acidity can affect the productivity of many agricultural soils in the perhumid tropics. This situation is exacerbated by clearing and fertilization, and by the associated leaching of cations and the loss of organic matter.

Genotypic selection for salinity tolerance and for tolerance to acidity or associated aluminium or manganese toxicity has been achieved with a number of plant species, and it is possible that genetic engineering has a role to play in developing such genotypes in other species. The genetic approach is likely to be a much a more acceptable solution to acid soil problems than the costly application of lime. An associated problem of acid soils is the unavailability of phosphate due to phosphate adsorption, a problem that has largely defied solution by all but soil amendments.

Although there is a role for strategic/applied research in the amelioration of/prevention of toxic soils, e.g. in defining salt movement as a function of water and salt flow in soil and of plant transpiration, there is an important role for adaptive research because of the site-specificity involved. Site amelioration and its consequences for crop sequences and long-term changes calls for adaptive research.

Annex IV

Characteristics of the target zones

The desert fringe. The desert fringe has a mean annual rainfall of 100-400 mm, and the length of the growing period is 1-75 days. The zone encompasses arid regions, which are cool to hot. Precipitation is very low and highly variable in space and time. Upland soils are predominantly shallow, sandy or gravelly, with active clays which are often easily dispersed (sodic). Examples of the desert fringe can be found in the northern Sahel and in western Asia.

The major crops of the fringe are sorghum, millet, and barley. The farming systems are animal-based and often nomadic.

The nonacid savannas. These areas have a mean annual rainfall of 400 - 600 mm. The length of the growing period is 75-120 days. They have a relatively short rainy season characterized by high temporal and spatial variability of precipitation, albeit not as high as in the desert fringe. Whilst most of the soils are sandy or gravelly and shallow, the zone also includes large areas of Vertisols - swelling clay soils which are potentially productive but difficult to manage. Examples can be found in the southern Sahel and in peninsular India.

The major crops in nonacid savannas are sorghum and millet. The farming systems are animal-based with shifting cultivation.

The acid savannas. These areas have a mean annual rainfall of 600 - 1800 mm. The length of the growing period is 120-180 days. This zone is characterized by a single intense rainy season, when the soil is severely leached, and therefore has a low inherent fertility. The Cerrados area of Brazil is one example.

The major crops are maize, sorghum, and upland rice. The farming systems are in transition from traditional shifting cultivation to continuous improved pasture, or involve cropping with fertilizers and other inputs in the humid forests.

The humid forests. The mean annual rainfall is >1500mm. The length of the growing period is >180 days. The drier parts of this region are characterized by a bimodal rainfall pattern, and the wetter parts by a single prolonged wet season. The soils are mostly of low inherent fertility with low-activity clays. Those of the drier parts are very easily eroded. Examples can be found in the West African coastal region, the Brazilian shield, and the Zaire basin.

The major crops are cassava, maize, and perennial tree crops. The farming systems are tree-based shifting cultivation.

The wetlands. These are regions which are flooded for at least part of the year. They can occur in any climate. They include many small and large river deltas, tidal and other swamps, floodplains, inland streams, and river valleys. The soils are mostly inherently fertile, nutrients being washed into them rather than out of them. More than half of the irrigated areas in the world are used for flooded rice production, and occur in natural or artificially created wetlands. Example of wetlands occur in the floodplains and deltas of the Ganges, Brahmaputra, and the Yellow rivers.

The major crop in these regions is rice, with production based on continuous cultivation with fertilizers and other inputs.

The steeplands. These are hilly and mountainous regions where the dominant slope exceeds 15%. The characteristics of the soils and the climate differ widely, but the slopes result in a common problem of water erosion. Examples of such steeplands can be found in the Himalayan foothills, the Andean Altiplano, and the hill areas of northern Thailand.

The major crops in the steepland regions are maize, millet, root crops, and tuber crops. Farming systems employ mixed pasture and tree-crops with minimal inputs.

Annex V

SWNM problems of the target zones

SWNM problems of the desert fringe. Farming systems in the more arid areas have been traditionally based on nomadic herding. This is an appropriate response to the space and time variability of the rains. Unsustainability arises from resource degradation, due to the low carrying capacity of the land and increasing numbers of people and animals. In favourable periods, the number of animals increases, in a drought period all vegetation is rapidly eaten and the soils are exposed to wind, and when rain does fall to water erosion.

Nomadic pastoralism may be complemented by traditional rainfed agricultural production. Such production is at high risk because of the uncertain rainfall. When the soils are cultivated, the soil structure deteriorates rapidly, and the normally low levels of organic matter in the soil are further depleted. The net result is that the soils tend to form surface crusts which further impede entry of rain into the soil.

There are many examples of the response of farmers to these problems by water harvesting and water spreading, in which water running into gullies is diverted onto cultivated fields. These methods enable some yields to be obtained, but they are almost always low or very low. Where water is adequate, it has been shown that responses to fertilizers are common (Pieri, 1992). However, the use of fertilizers is rarely economical. It has been difficult to establish more productive animal-based systems unless water supplies can be improved, and better systems of herd management to avoid overgrazing are introduced. Vetiver grass has been shown to be remarkably resistant to drought, and very effective in reducing erosion. It is largely unpalatable, so it remains as a soil cover even during droughts, but its unpalatability makes it unpopular with some pastoralists.

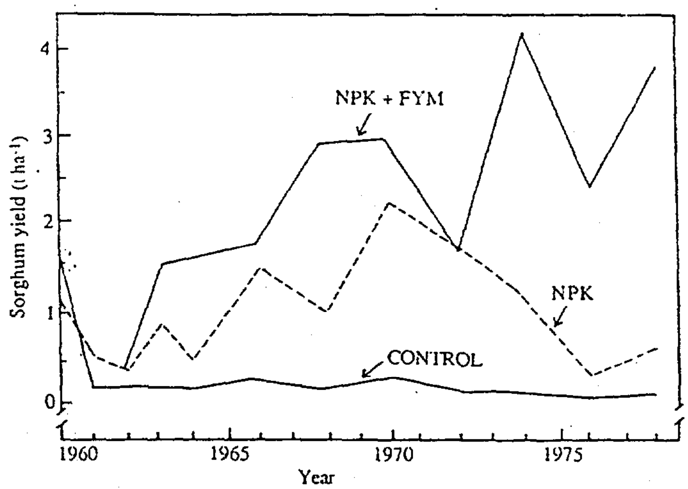
SWNM problems of the nonacid savannas. Population density in this zone is often relatively high. Consequently severe degradation occurs on account of drought recurrence, overgrazing, overcultivation, and deforestation (for fuelwood). In spite of the improvements which have been made in the plant type and yield potential of sorghum and millet, yields in Sudan and Niger have fallen consistently from 1960/65 to 1992 (Table A1.1) - even during the recent succession of favourable seasons. Production has been increased by cultivating larger areas, including much marginal land, and by more frequent cultivation of grazing land.

The deterioration of land in this zone has been referred to as desertification, or in Africa as Sahelization. The process is associated with soil deterioration due to a loss of organic matter, erosion, crust formation, and structural decline, and sometimes salinity. Together they may be more significant than postulated changes in rainfall. While farmers are aware of the need to return organic material to the soil, it is difficult to find material to use against the competing demands for fuel, animal fodder, and bedding and roofing material. Fertilizers can increase production from these areas for a decade or more, but they cannot do so indefinitely (Figure A5.1).

The erratic character of the rainfall is intensified by the effects of overgrazing and cultivation, which damage the natural vegetation and promote the formation of impermeable crusts on the soil surface (Albergel, 1987). Sustainability depends on the availability both of animal manures, or an alternative source of organic material, and of fertilizers. Under present conditions, sources of organic material are becoming increasingly difficult to find, and fertilizers are not economically available. In spite of the resilience of these areas (Rozanov, 1994), they are on a downward spiral of degradation. The deterioration is most pronounced on light-textured soils, which are the most common.

Areas covered by Vertisols present their own special problems. While these soils have a high water-retention capacity, they are almost always too hard or too sticky to be tilled. Management of these soils is particularly difficult when only human or animal power is available (Steiner *et al.*, 1988). Where these soils have high contents of sodium, they are liable to become severely compacted under continuous cropping, and the soil may become barren, as has happened in northern Cameroon. However, many

Vertisols can be highly productive when they are put under proper management, as has been demonstrated at ICRISAT and in IBSRAM's Vertisol network (IBSRAM, 1989a,b).



FYM = Farmyard manure

Figure A5.1 Effect of fertilizer and manure on sorghum at Saria, Burkina Faso, 1960-1980. (Pieri, 1992)

SWNM problems of the acid savannas. In savanna areas, where rainfall is higher and more consistent, the problem of water management is less serious than the problem of soil acidity. The soils have low organic-matter and nutrient levels, which are further reduced by cultivation. Tillage of these soils, especially when mechanized methods are used (Lal, 1991; Steiner *et al.*, 1988), can also lead to surface crusting, creating water-availability problems.

In Latin America these areas are often used for pastures, but they need lime and fertilizers if they are to be productive (Sanchez and Salinas, 1981; IBSRAM, 1987a,c.) The productivity could be greatly enhanced if suitable pasture legumes could be identified. Under cultivation, organic-matter maintenance is the most critical factor, as by complexing toxic aluminium it ameliorates the acidity problem as well as modifying soil structure and contributing to the nutritional status of the soil. It should be possible to identify sustainable alternate pasture-crop or tree-crop systems for these areas, but to date there has been limited success; most tree and pasture legumes are not adapted to the high acidity and low phosphate status of acid savannas. When a tolerant species has been introduced, serious pest problems have arisen.

SWNM problems of the humid forest regions. The major causes of unsustainability in this zone are low inherent soil fertility, with the result that yields rapidly fall to near zero, and the high erosivity of the rainfall, which means that unprotected soils are subject to severe erosion. Under forest cover, nutrients are efficiently recycled, and the soil is fully protected. The most adapted land-use systems are those which mimic the initial rainforest, conservative agroforestry and tree-based farming systems with perennial crops, such as rubber, oil palm, and cocoa. A leguminous cover crop can complement the protection afforded by the canopy of the perennial, and with good management it may be possible to grow annual food crops under the canopy. Such systems are sustainable only when they are economically viable, a condition strongly controlled by external markets. This severely limits the area which can be used in this way.

Alley cropping and other agroforestry systems mimic the protection of the forest, but their management demands and the advantages offered over traditional shifting-cultivation systems, even where these are deteriorating, have not been particularly attractive to small farmers.

If the vegetative cover of the soil in this zone is removed, heavy rainfall induces the collapse of the structure of the surface soil. This process can be dramatically enhanced if inappropriate mechanized methods of land clearing are used (IBSRAM, 1987b). As a result, runoff and consequent erosion increase. The failure to return organic matter to the soil as forest litter leads to a sharp decline in biological activity in the soil, and as a result the aggregation of the soil is lost and it becomes compacted. Under cultivation, nutrients are removed in harvested products - and moreover they are leached because they are no longer intercepted by the tree roots. This leads not only to nutrient deficiency, but also to acidification. Hence cultivation of these soils is inherently unsustainable. Long-term experiments at IITA and in Ghana confirm the rapid loss of fertility and the need to replenish nutrients and correct acidity. They have also shown that systems without protection of the soil with a mulch or cover crop are unsustainable, even if fertilizers and lime are used. Systems based on no-tillage and residue mulches allow a satisfactory soil conservation level, but have not been widely adopted because of the difficulties of weed control without the use of herbicides.

The traditional system of shifting cultivation in the humid zone was successful as long as there was sufficient land for farmers to leave the soil to rest under naturally regenerating forest for periods in excess of a decade (Robison and McKean, 1992). As demographic pressure has increased and more and more people have been forced to seek land in the forest areas, traditional systems have been replaced by crude slash-and-burn, in which the cultivation period is prolonged and the forest regeneration is endangered and is inadequate to maintain fertility. The net result is deforestation with its various undesirable consequences.

Combinations of tree crops with arable cropping systems, and rotations of forest plantations with arable production can be sustainable if the efficiency of the tree crop in recycling nutrients and controlling acidity is maintained. Productivity may be retained by careful management of nutrient levels, including those of trace elements, and acidity can be controlled with fertilizers and lime; but it has yet to be demonstrated that such systems are economically sustainable. After reviewing the extensive literature on shifting cultivation published since 1960, Robison and McKean (1992) concluded that "the problem is worse today in degree and scale, and much of the problem lies with social aspects. Farmers' perceptions and decisions, economic trends, and government policy all effect the problem, and will have to be reconciled in order for the problem to significantly, reverse overall trends of degradation".

SWNM problems of the wetlands. The rice-based farming systems of the wetlands of Asia are probably the longest sustained production systems that exist. In parts of China, rice appears to have been grown continuously for seven thousand years, and the main pillars on which such sustainability rests are replenishment of nutrients in deposited sediments and from high nitrogen fixation, no erosion from bunded fields, no acidification, relatively low weed problems, high phosphate availability, and no nitrate pollution of ground waters. These wetland areas have also been the centre of major successes of the green revolution. Rice yields have been increasing for the past twenty-five years and continue to increase.

National average yields in China and Indonesia now exceed 5 t ha^{-1}, and the concern about sustainability is not, as it is elsewhere, about raising very low yield levels, but of maintaining and increasing high levels. Long-term experiments at IRRI have shown a disconcerting downward trend for more than two decades, and long-term rice-wheat systems in India and Nepal also reveal a downward trend. Rice yields in Pakistan have stagnated for some time. Scientists at IRRI and CIAT have drawn attention to the serious problems arising in the Philippines and Colombia because of stagnating rice yields (Cassman and Pingali, 1993; Cuevas-Perez and Fischer, 1993).

Economic factors are one cause, as the responses to inputs are falling as yields increase, so that against a falling world rice price the system becomes economically unsustainable. Problems in the maintenance of the water-supply systems are another. Where rainfall is supplemented by irrigation, as it is in most of the more productive rice areas, there are serious problems of waterlogging and salinization. In areas which are naturally flooded, deteriorating conditions in the catchment areas, leading to greater depth of floods and more frequent and persistent submergence of the crop, are another cause.

Longer-term sources of unsustainability are associated with climate change, itself promoted by the emission of methane from rice paddies. Most important will be the effects of any rise in sea level, which is likely to have serious consequences for the cultivation of coastal wetlands such as those of the Gulf of Bengal, the Mekong Delta, and the Guyanas. These effects will further aggravate the problems which are already arising from human activities, such as embanking rivers to channel flood flows directly to the sea, thus depriving basin areas of the sediments which formerly offset land subsidence.

Although the use of organic manures for flooded rice production has been widely advocated, their use is declining, most dramatically in China. The major reason is the increasing value of land and labour, and the decreasing cost and increasing availability of inorganic fertilizers. It should also be taken into account that the advantages to be obtained from increased organic-matter levels are much less in flooded soils, where it is necessary to disaggregate the soil by puddling to enable it to retain water, and where the aggregating effects of the soil fauna are undesirable. The addition of organic materials is also undesirable because of the formation of phytotoxins in the anaerobic decomposition process, and the production of methane, a much more active greenhouse gas than carbon dioxide.

Crop intensification in the wetlands has resulted in an increased prevalence of pests, including those responsible for the propagation of vector-borne human diseases such as bilharzia, trypanosomiasis, and onchocerciasis (IRRI, 1989).

Most attempts to utilize the peaty and acid-sulphate soils of the wetlands have been unsuccessful. The peats suffer from severe nutritional problems which are difficult to manage, and the rapid oxidation of the iron pyrites of the acid-sulfate soils lead to the presence of free sulphuric acid in the soil and its consequent sterility.

SWNM problems of the steeplands. The major cause of unsustainability in the steeplands is the water runoff and consequent erosion which occurs whenever steep slopes are cultivated. Traditional methods for sustaining farming in these areas include the construction of terraces, and the maintenance of a cover on the soil of a perennial pasture or an organic mulch of materials taken from the forests growing on adjacent, and usually more steeply sloping, parts of the mountain or hillside. These traditional methods have broken down as population has increased and forests and pastures have been destroyed by overexploitation. The pressures on the steeplands have often been temporarily relieved by outward migration to the lowlands; but without continuing economic development in the adjacent lowlands, such migration may create as many problems as are solved.

Erosion in these areas is not necessarily man-induced. It often involves mass movement of soils and landslides as well as loss of topsoil, and the results are often easily observable. Steeplands are typically zones where the effects of unsustainability must be viewed on a variety of space scales, from field plots to subcontinental watersheds. Erosion in the Himalayas may be responsible for the siltation of reservoirs and canal systems in the northern plains of India, and also the source of sediments which are the basis of sustainability in farming systems in Bangladesh. While the effects of unsustainability are most pronounced and easily observed in mountain areas such as the Himalayas and Andes and the highlands of East and Central Africa, the problems are common to most areas where slopes exceed 15% (IBSRAM, 1988.)

SWNM problems of irrigated systems. Traditional smallholder irrigation based on simple technology has long been practiced in the rice areas of Asia, and in the dry areas of north and northeast Africa, western Asia, and Latin America. The rapid expansion of irrigation has been a major factor in the successes of the past 25 years in increasing production not only of food crops but of cash crops, such as cotton, on which much of Third World development has depended. Any threat to the sustainability of irrigation systems is a serious threat to development. Thus it is a matter of some concern that a serious threat does in fact exist. The threat arises from waterlogging and salinization in irrigated command areas, and from erosion in the catchment areas of reservoirs leading to siltation, and reduction of the capacity of storages, and choking of the distribution systems.

Problems in many traditional as well as modern irrigation systems arise from inadequate drainage of the irrigated area. Concentration of water in an inadequately drained area leads to waterlogging or a rising water table. If the underlying water table contains saline water, as it often does in arid and semiarid areas, the soil will be salinized and productivity will be severely reduced. More than half of the present irrigated areas have been affected by salinization, and every year several million hectares are abandoned because of salinization (Ahmad, 1991). A recent study in India has shown the economic importance of salinization problems to small farmers in different areas within a major irrigation system (Joshi and Jha, 1991), even when the salinity problem is not particularly severe and the land is unlikely to be abandoned.

The problems of reservoir sedimentation are probably as serious as those of salinization if sustainability is considered in terms of decades. Most irrigation systems are designed on the basis of a life of a century or more, the limitation being the rate at which the storage capacity is reduced by sedimentation. In fact most of the major storage systems constructed in developing countries in the recent past are now known to be suffering from siltation rates which will reduce their capacity far more rapidly than estimated when they were constructed (White, 1990; Shahin, 1993). For example the Kashm el-Girba reservoir in the Sudan will have lost 55% of its original capacity in 25 years, and the High Aswan Dam reservoir is now expected to have a life which will only be 50% of the design expectancy. A survey of reservoirs in major irrigation systems in India has produced similarly disturbing data (Table AI.2). In the Philippines, the loss of storage capacity in the major reservoirs from which the principal rice-producing areas are irrigated has meant that water is not always available to the rice farmers during the growing season. Future prospects for increased production to meet demand are therefore facing serious difficulties (Masicat *et al.*, 1990).

The source of the sedimentation problem is, of course, the increased intensity of cultivation and deforestation in the catchment areas, resulting in erosion rates above those assumed at the time the dams were designed. The situation might be improved by restrictions on slash-and-burn agriculture in the catchment areas, although where such regulations have been introduced they have been ineffective unless an alternative source of livelihood is offered to the cultivators.

As with soil management, much is known about how to improve water management. Great improvements in the efficiency of water use are possible, and the need to ensure adequate drainage at the time irrigation systems are constructed has been constantly emphasized by soil scientists and agronomists. The need to ensure proper erosion control and prevent deforestation in the catchments of major reservoirs has also been stressed. Again, the problem has been to find economically viable and socially acceptable ways to include these measures in the planning and development of irrigation schemes. In a report on the need for research on irrigation to improve food production, Pereira *et al.* (1979) noted that in the vast irrigated areas of the Gangetic plain, the Indus basin, and the valleys of the Nile, Tigris and Euphrates, crop production was less than a quarter of the potential created by the amounts of water available.

While the problems of large irrigation schemes are now well known, new schemes are still being undertaken with inadequate data, particularly where microdams are being constructed, as in the semiarid regions of northeast Brazil, northern Mexico, and the Sahel. The lack of appropriate complementary inputs, poor water control, the absence of double cropping, and inappropriate agronomic practices commonly result in production that is scarcely superior to that obtained from rainfed agriculture. If the external costs of loss of grazing and other land, fishing opportunities, and of moving people are also included, it often becomes difficult to justify the investment in irrigation (Matlon, 1987).

Unsustainability in many irrigation systems stems from the fact that for the last four decades international assistance for the development of irrigation resources has concentrated on provision for capital works designed by hydraulic engineers. Too little attention has been given to the warnings of soil scientists and agronomists, and often none to the problems seen by the farmers who will be using the water provided, and the effects of irrigation developments on the role of women in farm and household management. Although these issues are receiving increasing attention (FAO, 1987b; Samad *et al.*, 1992), much remains to be done.

Annex VI

Responses to the questionnaire

Synopsis of survey results. In an effort to gain a better appreciation of the perceptions of organizations and individuals working on SWNM problems in developing nations, a questionnaire was distributed widely by the consulting team. Four open-ended requests were asked:

- identify 5 major problems in SWNM;
- identify 5 most crucial knowledge gaps in SWNM;
- identify 5 priority research areas; and
- identify needed approaches to address SWNM problems.

Thirty-three organizations responded.

Type of organization	Number	Percent
1. NARS	11	33
2. Developed-country organizations	11	33
3. CGIAR institutions	8	24
4. Non-CGIAR (ICIMOD, IFDC)	2	6
5. Regional bodies (TSBF)	1	3

The survey results are depicted as histograms in the text (Figures III.2. and III.3.) and in Figures AVI.1 and AVI.2. Each respondent described problems in their own words, many listing less than five requested responses. The individual responses were then listed and grouped according to logical categories by the responses.

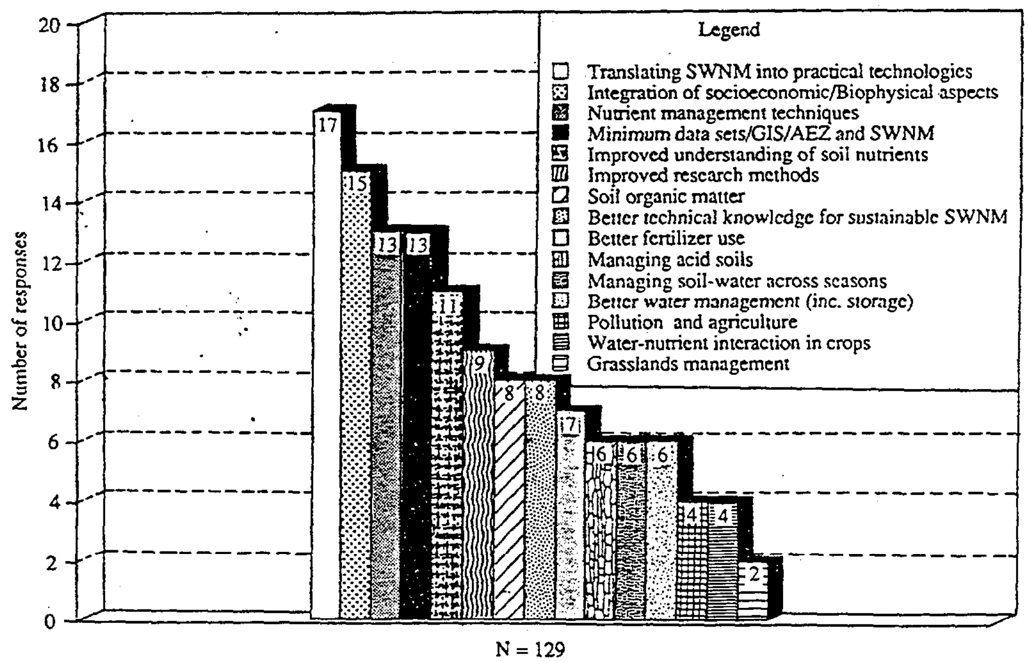


Figure AVI.1 Perceptions of major gaps in SWNM research.

In brief, the perceptions for each category can be summarized as:

- **Major problems.** On the technical side, nutrient recycling/timing, soil erosion/degradation, and water management were thought to be important. On the socioeconomic side, respondents saw prices/policy/markets along with faulty research systems as the main problems.
- **Major gaps.** The two most salient major research gaps identified were 'translating SWNM into practical technologies' and 'integrating socioeconomic and biophysical aspects'.
- **Major research priorities.** Overwhelmingly, the perception is that more adaptive on-farm research is needed.
- **Achieving results.** The primary suggestions called for interdisciplinary research, strengthening NARS capacity, better coordination, and long-term experiments.

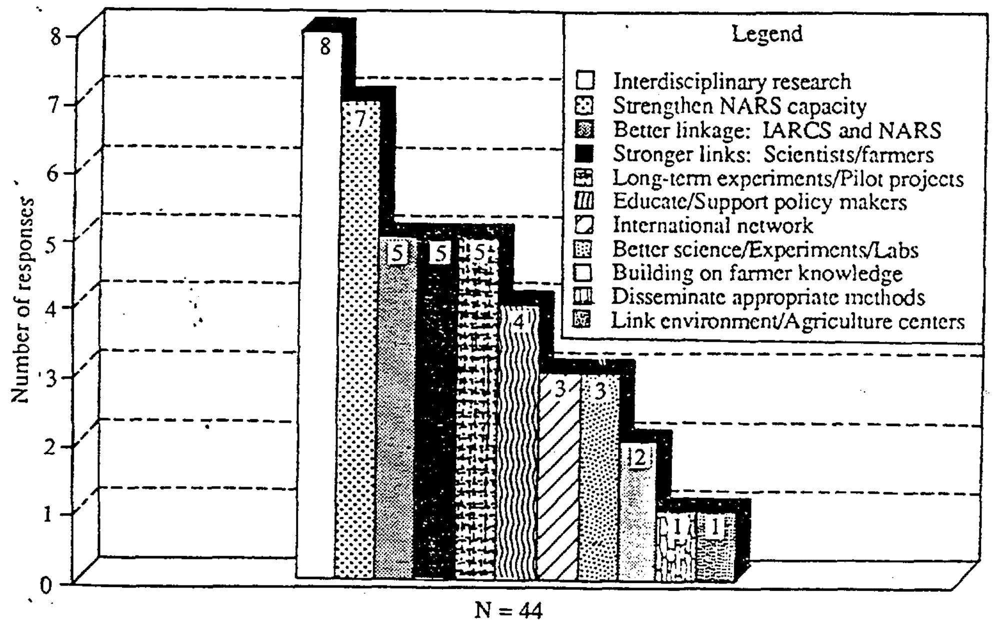


Figure AVI.2 Perceptions of linkages required to support SWNM research.

Annex VII

Comparative advantages in basic, strategic, applied, and adaptive research

If consortia on land management are to operate effectively, there needs to be a clear acceptance of roles, related to the comparative advantages of each participant. These differ considerably according to whether the research is basic, strategic, applied, or adaptive.

Basic research. In basic research we would not expect the international organizations to be heavily involved, other than the International Council of Scientific Unions (ICSU). In national terms most of the basic research will be conducted in universities and specialist research institutes. An example of an area where close linkage between the international centres and basic research organizations is highly desirable is in work on global climate change and the way in which changes in land use are effecting the release of carbon dioxide and other greenhouse gases. ICSU has established the International Geosphere-Biosphere Programme (IGBP), and within that a 'core project' on Global Change and Terrestrial Ecosystems (GCTE). There would seem to be a strong case for strengthening the linkages between the GCTE project and the CG and other centres involved with SWNM research. A linkage between IRRI and the GCTE project already exists, relating to the evolution of methane from rice paddies.

Strategic research. Strategic research is the great strength of the CGIAR centres. We would expect the CG centres to maintain a leadership role in strategic research, emphasizing even more strongly than in the past the linkages between crop improvement and natural-resource management, and including in this survey socioeconomic and policy studies related to natural resource use. The CG centres already have very strong linkages with many other strategic research organizations in developed and developing countries, and we would expect that these would continue, and that they would be further strengthened by involvement in SWNM research.

One example is in the development of an international data base on agricultural environments, in which several of the CG centres have worked closely with FAO and other organizations; another example is in the conduct and management of long-term experiments, intended to be continued for decades rather than years.

The latter issue merits further consideration. While there has been much recent interest in the indicators of sustainability, there is no way in which any certainty can be given to discussions of the sustainability of a particular land management system unless there is an experiment which measures the changes in the indicators over time. As discussed in Section IV, particularly important - but difficult and expensive to manage - are such experiments conducted on a catchment basis. Relatively few countries have the resources to maintain such experiments.

Nevertheless several such experiments need to be conducted as a reference for related sustainability studies, and should be managed as an international responsibility, with other trials on a plot rather than a catchment basis conducted by the NARS in a wider range of environments and directed to answering more specific questions. The NARS may often be supported by international projects in the conduct of such trials, as in IBSRAM networks, and in the trials which are being developed as part of the 'Alternatives to Slash-and-Burn' project being developed and managed by ICRAF. Both IBSRAM and ICRAF have established strong linkages between the organizations concerned with strategic research and those concerned with applied and adaptive research activities.

Several of the national programmes are also conducting important strategic research on aspects of SWNM, and are normally willing to share their results with others. To mention just one example, the Indian Salinity Research Institute is conducting vitally important work on the salinization of soils and their recovery for agricultural use.

Applied research. The distinction between strategic and applied research in relation to SWNM is very blurred. The TAC's definitions of the research categories (Figure II.2) distinguishes applied and strategic research on the basis that the purpose of applied research is to create new technology, whereas the purpose of strategic research is to solve specific research problems. Thus most of the CG centres are likely to be involved in both strategic and applied research, while national programmes may be more concerned with applied and adaptive research.

Adaptive research. The TAC defines adaptive research as the adjustment of research to meet the specific needs of a particular environment. The great diversity of land systems, and of the social, economic, and political conditions in which land is managed requires that responsibility for adaptive research must be accepted by national governments. Support for them is needed from various international endeavours. The support may best be arranged by networking between the various organizations involved on the basis of commonality of problems, enabling the experience of the different national programmes to be effectively shared, and avoiding the potential for considerable overlap in research activities.

There would seem to be a significant comparative advantage for national programmes in conducting land-use planning and development activities within their boundaries, but international organizations are likely to have a considerable comparative advantage in the organization of consortia to share experience and to link strategic and applied research. Such work may be greatly facilitated by giving greater emphasis to site characterization, and by developing a better system for information exchange. The linkage between strategic, applied, and adaptive research may be a considerably strengthened if all concerned work together in a consortium which is directed to the solution of one of the top-priority problems.

Annex VIII

About the authors

Dennis Greenland is a soil chemist, and currently visiting professor at the Department of Soil Science of the University of Reading, UK. He has previously held appointments at the Universities of Ghana and Adelaide, and was director of research at IITA, Nigeria, deputy director general (research) at IRRI (Philippines), and director of scientific services of CAB International, UK.

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Hari Eswaran is a soil scientist specialized in soil survey, classification, and conservation. He is currently national leader of World Soil Resources at the Soil Conservation Service, U.S. Department of Agriculture, where one of the projects he manages deals with enhancing the quality of soil resource information for sustainable agriculture in developing countries. He has worked in 75 countries. He was previously at the University of Ghent, Belgium, and at Cornell University, Ithaca, New York.

Robert E. Rhoades is an anthropologist with over two decades of experience in agricultural development projects. He spent 12 years at the International Potato Centre (CIP) in Lima, Peru, and is the founder of UPWARD (Users Perspective with Agricultural Research and Development). Presently he is head of the Department of Anthropology, University of Georgia, USA.

Christian Valentin is a soil physicist employed by ORSTOM, France, and working in Niger. His main field of expertise lies in small watershed management and related crust formation in the Sudano-Sahel areas. He presently leads a research unit in ORSTOM on the dynamics and rehabilitation of water resources in fragile and highly populated tropical ecosystems.

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Abbreviations and Acronyms List

ACIAR	Australian Centre for International Agricultural Research
AEZ	Agroecological zones
AVRDC	Aisan Vegetable Research and Development Centre
BNF	Biological nitrogen fixation
CABI	CAB International
CGIAR	Consultative Group for International Agricultural Research
CIMMYT	Centro Internacional de Majoramiento de Maiz y Trigo
CIP	Centro Internacional de la Papa
CRSP	Collaborative research support project
DANIDA	Danish International Development Agency
FAO	Food and Agriculture Organization of the United Nations
FSR	Farming systems research
GCTE	Global Change and Terrestrial Ecosystems
GIS	Geographical information systems
GLASOD	Global assessment of soil degradation
IAEA	International Atomic Energy Agency
IARCs	International agricultural research centres
IBSRAM	International Board for Soil Research and Management
ICARDA	International Centre for Agricultural Research in the Dry Areas
ICIMOD	International Centre for Integrated Mountain Development
ICRAF	International Council for Research in Agroforestry
ICRISAT	International Crop Research Institute for the Semi-Arid Tropics
ICSU	International Council of Scientific Unions
IFDC	International Fertilizer Development Centre
IFPRI	International Food Policy Research Institute
IGBP	International Geosphere-Biosphere Programme
IIMI	International Irrigation Management Institute
IITA	International Institute for Tropical Agriculture
ILCA	International Livestock Centre for Africa
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
ISRIC	International Soil Reference and Information Centre
ISSS/CIP	International Society of Soil Science/Committee on International Programs
IUCN	World Conservation Union
NARS	National agricultural research systems
NGO	Nongovernmental organization
NRMR	Natural resource management research
ORSTOM	Institut français de recherche scientifique pour le développment en coopération
SWNM	Soil, water, and nutrient management
TAC	Technical Advisory Committee to the CGIAR
TSBF	Tropical Soil Biology and Fertility programme
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
WHO	World Health Organization
WMO	World Meteorological Organization
WRI	World Resources Institute