Sustainable Land Management for Crop Production

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Abstract

Recent evidence confirms the view that land degradation is having a significant impact on crop production in developing regions. The major cause of the degradation is agricultural intensification using practices that damage the land and water resources base. The whole process is driven largely by widespread poverty and population pressure. Adverse impacts occur both on-and off-site, due to detrimental flows of soil, water, and nutrients. The goal for crop production systems should be sustainable land management (SLM), that maintains or enhances production and services, reduces production risks, protects the natural resources base and the environment, and is economically viable and socially acceptable. In practice farmers must cope with many biophysical and socio-economic constraints that operate on differing scales and work against SLM.

In the tropics, much of past research had focused on the high potential areas where intensive systems for the production of cereal crops dominate, and from which enormous yield gains have been made to feed the world. With the urbanization of many societies and increased demand for vegetables, fruit, and meat, peri-urban areas are now also important intensive production systems. Sustainable land management in these systems is under threat from a range of major constraints, including unbalanced fertilization, salinity, poor soil health, and shortages of water. Adverse environmental impacts include groundwater and soil pollution by agro-chemicals. More diversity in cropping and judicious management of inputs are the key to the achievement of SLM in many of these high potential areas.

In the low potential areas, millions of poor farmers must contend with major threats such as low and declining soil fertility, drought, soil acidity, erosion, salinity, and soil structural deterioration. Consequent off-site impacts of erosion on water systems and broad-scale negative nutrient balances present intractable problems to the communities and governments of many developing countries. More encouraging are some of the examples of successful SLM such as the oil palm production systems by smallholders in acid soil areas of the Asian warm, humid tropics, and the widespread adoption of minimum tillage in Brazil.

Many technological solutions to SLM constraints have been developed but few are adopted widely. The reasons include: the complex and knowledge-intensive nature of the technologies, the lack of farmer participation in the development of the technologies, the lack of involvement of social scientists and economists in research teams, and the absence of an enabling policy environment. An innovative research paradigm to overcome these problems is gaining widespread acceptance. Combined with the new information technology, the paradigm holds promise to accelerate the scaling up and use of research results that ensure sustainable land management.

Introduction

The 20^{th} century saw global food crop production keep pace with rapid population growth. In the

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developing countries, the area of cultivated land expanded, but most importantly, cereal yields in irrigated and other high potential areas increased dramatically due to the widespread adoption of modern varieties and improved crop management practices. The increase in crop production and population growth expanded human domination of the Earth's ecosystems to the point that between one-third and one-half of the land surface have been transformed (Vitousek *et al.*, 1997). Attention must now turn to assessing the ecological and economic costs incurred. For example, Vitousek *et al.* (1997) estimate that more than half of all accessible surface fresh water is put to use by humanity and that more atmospheric nitrogen is fixed through human influence than through natural terrestrial sources. Massive human impacts on biodiversity and on carbon dioxide levels in the atmosphere are also being documented.

The agricultural intensification to double global food production in the 20^{th} century required a 6.9-fold increase in nitrogen fertilizer use and a 3.5-fold increase in phosphorus fertilization (Tilman, 1999). These nutrients were largely applied to rice, wheat, and maize grown in high potential areas. Resulting accumulations of nutrients on-site, and in feed-lot and urban areas due to domestic and international trade, have created serious environmental problems in densely populated areas (Miwa, 1990; Faerge *et al.*, 2000). At the other end of the spectrum, nutrient depletion due to inadequate input use in marginal lands looms as a major economic problem in many African countries (Drechsel and Gyiele, 1999) and in the marginal uplands of Asia (Wijnhoud *et al.*, 2000).

Globally, land degradation affects two-thirds of agricultural land (WRI, 2000). The most widespread cause of land degradation due to intensification of cropping is soil erosion by water. Water erosion has serious off-site as well as on-site economic and environmental impacts. Penning de Vries (2000) estimated that, based on current trends, land degradation, loss of agricultural land to urban infrastructure, and non-food crop expansion will reduce the global carrying capacity by 10-35% in the coming decades. Asia and Africa will be most affected. Resolving these seemingly intractable problems requires action by land managers and farm communities at the local level and by policy-makers at the national and global levels.

This paper reviews developments in research on soil and crop management with an emphasis on sustainability. As a starting point, the goal of sustainable land management (SLM) is defined and a typology of cropping systems is presented. Requirements for SLM in high and low potential cropping areas are then discussed, giving examples of recent research results. Finally, the track record of research to develop crop management technologies is reviewed in the context of the need for a paradigm shift to improve the adoption rates and expand the impact of scientific knowledge.

Sustainable land management — the goal

Much past research on crop management has been productivity-oriented and has largely ignored the negative impacts of intensification on the natural capital, particularly the land and water resources base. Furthermore, the social and long-term economic impacts of unsustainable practices have been neglected. A holistic tool for SLM assessment is needed that can be applied to diverse agricultural ecosystems or crop management technologies. To meet this need, FAO and IBSRAM developed the Framework for Evaluating Sustainable Land Management (FESLM) (Smyth and Dumanski, 1993). The FESLM sets the SLM goal as a system that combines technologies, policies, and activities aimed at integrating socio-economic principles with environmental concerns so as simultaneously to: maintain or enhance production/service; reduce the level of production risk; protect the potential of the resource base/natural capital; be economically viable and be socially acceptable. These objectives (productivity, security, protection, viability, and acceptability) constitute the five pillars of the FESLM. It is important to note that all five pillars are required to achieve SLM. Furthermore, effective use of the FESLM requires an interdisciplinary approach.

Intensification and cropping systems

Constraints on SLM vary considerably amongst cropping systems with different levels of intensity. Shifting cultivation with long (10- to 20-year) periods of fallow meets the FESLM test for sustainability, but is now relatively rare because of the large land area needed per capita. Shifting cultivation with long fallow periods can be seen as one end of a spectrum of cropping systems with different degrees of intensification (Fig. 1). When shifting cultivation intensifies to the point that marginal land is cropped annually, the soil is subjected to erosion and soil organic matter levels decline. To reduce this land degradation, alleviate poverty, and curb out-migration to the cities, require a shift from subsistence cropping to some form of mixed cash cropping with improved soil and fertilizer management. In high potential areas with assured water supplies, the cultivation of two or even three crops per year is possible, but environmental problems commonly arise if agrochemical inputs are managed poorly. These problems become more acute in continuous vegetable production systems in peri-urban areas, where localized environmental problems are potentially most serious. In the ensuing sections I will deal with challenges to SLM in some of these systems.

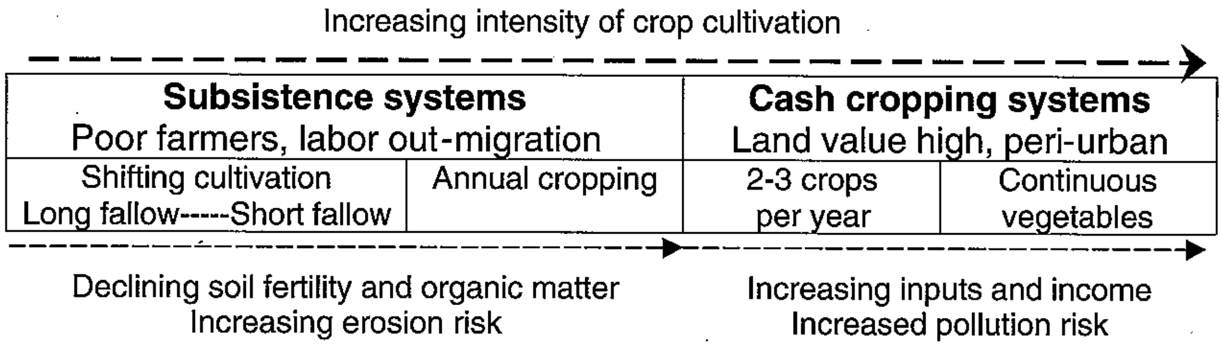

Fig. 1 Some characteristics of cropping systems with different degrees of intensity

Intensive cropping systems

The key to sustainable intensification of crop production is ample water availability. The 250 million ha of irrigated land worldwide represent only 17% of the cultivated area but produce 40% of the agricultural outputs (Shady, 2000). In developing Asia, irrigated rice and wheat crops are the major source of food for hundreds of millions of people. The sustainability of rice production in these areas is under threat from water scarcity, salinity, waterlogging, and declining soil quality as a result of cereal mono-cropping (Greenland, 1997). These problems are a cause for particular concern in the Indo-Gangetic plain where rice-wheat systems occupy 13.5 million ha and where sustainability problems are the focus of a major research program involving national research institutions and centers of the Consultative Group on International Agricultural Research (Ladha *et al.*, 2000). Research has concentrated on problems with the cultivation of wheat in soils that have been puddled for rice, the build-up of nematodes and other plant pathogens that contribute to yield decline in some areas, and the efficient management of nutrients.

Nutrient management in intensive systems is a key component of SLM on a number of scales. At the farm level, unbalanced fertilization over the long term may, at high input rates, lead to depletion of soil reserves of nutrients such as potassium as shown in Table 1. Some intensive cropping systems are also prone to induced deficiencies of secondary nutrients, such as sulfur, and micronutrients, such as zinc. Increasing labor costs cause many farmers to turn away from traditional labor-intensive practices of composting and green manuring; instead they remove crop residues from the field for other uses, or burn them. As a consequence, soil organic matter and potassium levels decline, and in some soils physical conditions deteriorate (Kumazawa, 1984). In terms of trade-offs between FESLM pillars, intensive cropping without organic inputs does not satisfy the long-term requirements of the productivity and resources protection pillars, but does meet the short-term criteria of economic viability and social acceptability.

Gaseous losses of nitrogen applied to rice average 87 kg N ha^{-1} $crop^{-1}$ (Table 1), but generally go unrecognized as a sustainability problem at the farm level. However, at the national and global levels, the economic and environmental costs due to the wasted fossil fuel and the greenhouse gas emissions should be a major cause for concern. The seriousness of the problem is underscored by the recent increases in the price of oil and nitrogen fertilizers. The losses are due to ammonia volatilization and nitrification-denitrification processes promoted by surface broadcasting of urea into the unique ecosystem formed by flooding and puddling of soil. On the other hand, it has been known for many years that deep placement of urea in the paddy, made practical by the development of the supergranule, modelled on the Japanese mudball, significantly improves urea uptake efficiency in rice production (Craswell *et al.*, 1981). The major constraint on the adoption of this technology has been the lack of a practical delivery system and the high costs of deep placement. Only recently has a major extension effort, catalyzed in Bangladesh by the International Fertilizer Development Center, enabled the construction of village-level briquetting facilities and the deep application of urea briquettes to 100,000 ha of boro rice in 1999 (Ladha *et al.*, 2000).

An efficient alternative to deep placement technology is to split the doses of broadcast urea and adjust the timing and the rates based on a crop monitoring system such as leaf chlorophyll analysis or leaf color charts. Such systems of crop and fertilizer management have been characterized as knowledge-intensive (Dobermann and White, 1999). Farmers and policy-makers need appropriate decision support systems to improve fertilizer efficiency and avoid the significant economic costs due to nitrogen losses and unbalanced fertilization. New information technologies have a great potential to help in this endeavour, but the outcome will depend on the successful practical interpretation of the accumulated scientific knowledge, combining it with farmer knowledge, and precise targeting on an appropriate scale. The last /step will benefit from the resource management domain[1] (RMD) concept which combines social and economic dimensions with biophysical characteristics to contributes to appropriate targeting of information.

Table 1 Average nutrient balance for rice crop yielding 5 t ha-1 (Dobermann and White, 1999)

Inputs and outputs	N	P	K
	kg ha^{-1} $crop^{-1}$		
Inputs			
Fertilizer	117	18	17
Farmyard manure	5	2	5
BNF	50	-	-
Outputs			
Gaseous loss	87	-	-
Net removal in grain	58	12	13
Net removal in straw	20	2	35
Input-output balance	+7	+6	-26

Low potential areas

Major constraints on productivity in low potential areas include soil acidity, salinity, sodicity, steep slopes, drought, shallow soil depth, and low inherent soil fertility. The marginal uplands in the humid tropics present particular problems for intensification of agriculture due to their low phosphorus availability. Intensification without the addition of the external inputs, that many poor farmers cannot afford, leads to increased export of soil nutrients in harvested products. New tools for calculating nutrient balances provide important insights into soil fertility decline at the farm level or even at the national level (Drechsel and Gyiele, 2000).

Recent research in rainfed areas of Northeast Thailand (Wijnhoud *et al.*, 2000) shows that the nutrient balance of rice-based cropping systems varies widely between farms and even from field to field (Fig. 2). They also showed that farmers with higher off-farm income choose to invest more in soil fertility improvement. This indicates the need for government policies to target support to the poorest farmers who appear to be running down their soil fertility most quickly.

At the aggregated national level, the economic costs of nutrient decline can be significant. Drechsel and Gyiele (2000) recently showed that on the average, the countries of sub-Saharan Africa would have to pay 7% of the Agricultural Gross Domestic Product (AGDP) to replace nutrients lost from arable land; in Niger the cost is as high as 20%. Consequently in terms of the FESLM criteria — economic viability, productivity, social acceptability, and resource protection — the low-input subsistence agriculture practiced widely in many African countries is clearly unsustainable. National aggregated nutrient budgets for Asian countries have not yet been calculated using the same economic model. In the Asian case, the nutrient deficits of the marginal uplands would probably be masked by the positive balances in the high potential areas, and the higher proportion of the AGDP from the high potential areas. The national and farm-level data on nutrient budgets provide invaluable backing for national policy-makers to pay greater attention to soil fertility problems.

The ultimate solution to the nutrient decline problem lies with the integrated use of chemical and organic

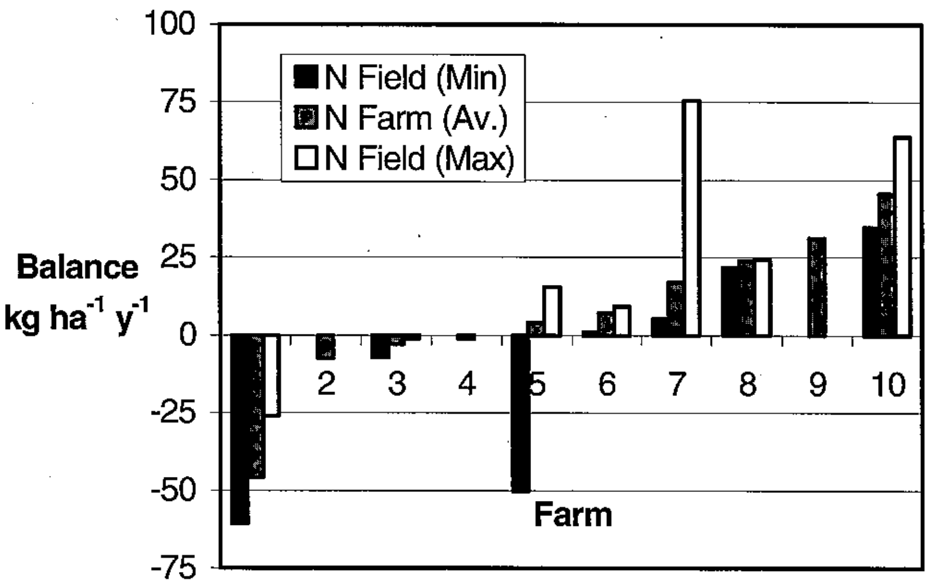

Fig. 2 The range and average nitrogen balance in the rainfed rice fields of 10 farms in Ubon, Northeast Thailand (Wijnhoud *et al.*, 2000)

[1] Dumanski and Craswell (1998) defined a resource management domain as a spatial unit encompassing the environmental and socio-economic characteristics of a recognizable unit of land including the natural variability which is inherently characteristic of the area. An RMD can be defined at field level if the purpose is to differentiate management practices employed by farmers, or on a broad scale if the purpose is to relate to management implications imposed through policies or programs, or at any level in between, provided that the linkages among the levels are illustrated.

inputs. For smallholders, cash crops can provide the income to purchase inputs. In addition to providing cash for investment in soil fertility, well-managed perennial crops such as rubber, oil palm and fruit trees, can be used to stabilize erosion-prone land. In Indonesia and Malaysia, smallholders have participated in the expansion of oil palm systems that represent one of the great success stories of the integrated management of nutrients, crop residues, and soil. Fairhurst and Mutert (1999) point out that the oil palms are widely grown on Ultisols which are naturally acid infertile soils, yet management practices such as the use of cover crop legumes, recycling of plant biomass residues and carefully planned fertilization strategies have led to average fruit bunch yields in Asia of 16-18 t ha^{-1} y^{-1}. In FESLM terms at the local level, the oil palm systems meet several criteria such as productivity and economic viability, as well as resources protection due to low soil erosion rates. At the global environment level, oil palm systems are predicted by Fairhurst and Mutert (1999) to become an important part of carbon offset management because oil palms sequester more carbon per unit area than tropical rain forests. Another success story in the tropics with implications for greenhouse gas concentrations is the large-scale adoption of direct-drill mulching systems by crop producers in Brazil (Seguy *et al.*, 1998).

A novel approach to overcoming nutrient constraints in resource-poor areas is the so-called recapitalization of soil fertility, achieved by the application of large doses of phosphate fertilizers. The phosphate applications increase yields and, with the use of legumes to fix nitrogen, provide a base for integrated nutrient management and recycling of crop residues (Fairhurst *et al.*, 1998). Work with farmers in Indonesia as part of the project SebarFos (which means to spread phosphorus) demonstrates that recapitalization through one-off applications of one ton of reactive rock phosphate has a potential to promote SLM (Fig. 3). The SebarFos program relies on the full involvement of farmer cooperators and illustrates the benefits of a participatory approach that also involves non-government organizations and the private sector.

In the steepland areas of the humid tropics, soil erosion by water is the major threat to SLM. The steepland population in the tropics currently accounts for 36% of the rural poor in the world. As an RMD,

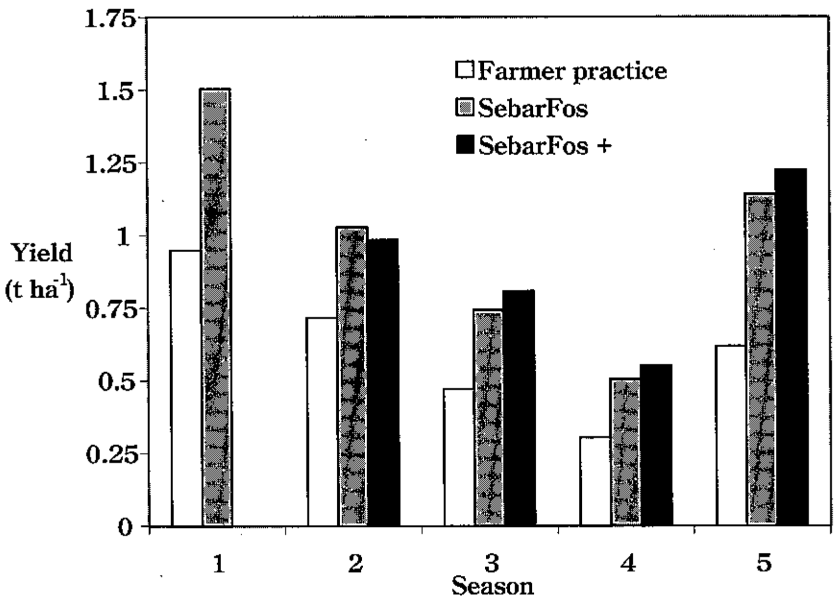

Fig. 3 Mean response of peanuts to the SebarFos treatment (1 t of reactive phosphate rock ha^{-1}) across farms for 5 seasons in Jambi Province, Indonesia (SebarFos meeting, unpublished data)
The SebarFos+ treatment involves RPR re-applied once in each year.

the Asian and Pacific steeplands have many biophysical and socio-economic characteristics in common (see Craswell *et al.*, 1997). The soils are generally acid with low inherent fertility; soil erosion is the major land degradation process and rain intensity is high; the native climax vegetation is commonly rain forest, but large areas have been logged, subjected to increasingly intensive shifting cultivation and covered with pernicious weeds like *Imperata cylindrica*; steepland areas are remote and have been bypassed by governments; the rural people are generally ethnic minorities, but increasingly include lowland people unable to find land to cultivate elsewhere; land tenure is a problem; and off-farm employment is a major source of income.

A major on-site impact of soil erosion is the selective loss of the surface soil layer that contains much of the reserves of plant nutrients; its loss accelerates nutrient mining (Drechsel and Gyiele, 1999). Off-site impacts are complex and difficult to assess quantitatively. Cultivation of sloping lands significantly increases runoff (see Craswell *et al.*, 1997) and hence may affect the regularity and seasonality of stream flows. Steepland farmers are often targeted as scapegoats when flash flooding occurs, although it is difficult to find reliable data to answer the question of how much of the off-site damage is human-induced. IBSRAM and its partners in Asia established the Management of Soil Erosion Consortium (MSEC) to help answer some of these questions (Craswell and Niamskul, 1999). MSEC has conducted collaborative experimental catchments studies at sites in seven Asian countries. The effects of land management on runoff and soil loss measured at weirs established in catchments in Vietnam are shown in Fig. 4 (Bricquet *et al.*, 2000). Cultivation for cassava

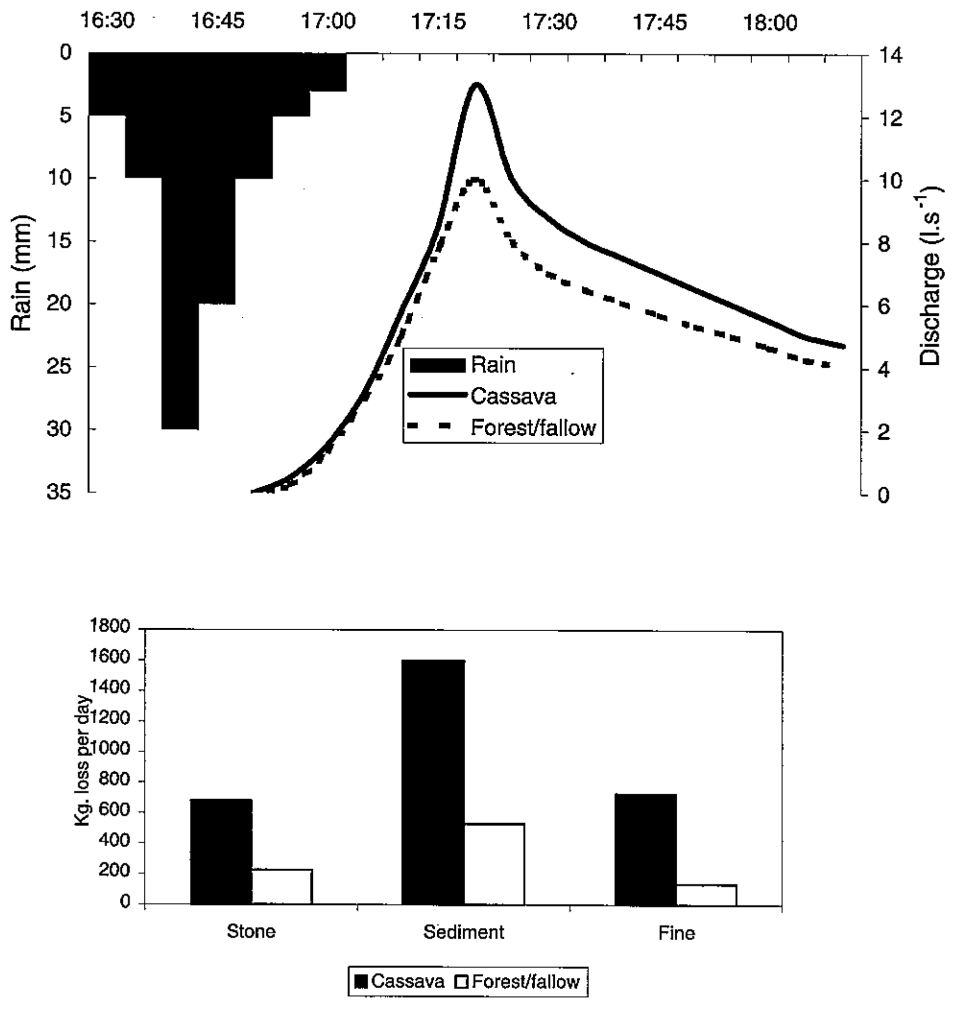

Fig. 4 Impact of a storm on rainfall, weir discharge rates and sediment flows from micro-catchments cropped to cassava or in forest/fallow in Vietnam (Bricquet *et al.*, 2000)

cropping increased soil loss tenfold and peak discharge by 40% compared with forest/fallow. The results suggest that localized runoff and sedimentation impacts will be serious if cropping continues. However, cropping systems to promote SLM are available. Steepland farmers who have participated in on-farm research have modified hedgerow systems to include cash crops such as teak, pineapple, day lily, banana, and coffee (Craswell *et al.*, 1997). The systems devised by the farmers with the scientists are attractive economically yet fulfil the requirement of the FESLM protection pillar to reduce soil erosion. IBSRAM's current on-farm work is designed to develop and enhance methods to scale up adoption to reach the millions of farmers in the steeplands.

The new paradigm

Notwithstanding the success stories quoted above, degradation and declining productivity continue almost unabated in many countries, despite the fact that knowledge of soils and their management abounds in the scientific literature. In contrast, indigenous knowledge about SLM has not been well documented. Research on improved crop management to enhance SLM is having too little impact in farmers' fields because researchers have ignored the needs of clients (Craswell and Niamskul, 1999). Poor communication is a problem at all levels — between land users and policy-makers on the one hand, and the scientific community on the other. Farmers may be blamed for land degradation because they did not adopt technologies advocated by researchers. However the technologies may not have been relevant to farmers' needs and resources endowment. In many countries, the top-down approach to extension by government agencies persists and is only slowly changing to incorporate the participatory approaches that have been so successful amongst non-government agencies. Policy-makers need better information about how to improve the policy and legislative environment in which farmers operate.

One significant underlying cause of these problems in the past was the reductionist training of many soil scientists. This has led to too much emphasis on small experimental plots and on strategic research into processes in isolation from the target farming systems. Furthermore, biophysical scientists have been slow to develop collaboration with colleagues in the fields of economics, sociology, and anthropology that hold the key to ensuring relevant and client-oriented research. They also need to recognize that indigenous knowledge has much to contribute to SLM.

The past failures of research on soil, water, and nutrient management require a new agenda based on innovative concepts about how to improve research effectiveness and impact (Greenland *et al.*, 1994). They proposed a new research paradigm based on an interdisciplinary, participatory approach and with the following characteristics, which encapsulate the lessons learnt at IBSRAM in recent years:

* *User orientation*-Participatory and community-based at all stages from planning to implementation
* *Policy* — Focused on policy and institutional issues that influence farmer and community decisions
* *Equity* — concerned with equity, including gender issues, in research planning and implementation
* *Landscape* — Integration of people, land, and water at every stage from plot to catchment
* *Research intensity* — Linking strategic, applied, and adaptive research with technology development and participatory dissemination
* *Knowledge* — Reliance on both indigenous and scientific information
* *Goals* — Linking increased productivity with natural resources conservation

Conclusions

Improved crop management to promote SLM remains a major challenge in the 21st century. Much progress has been made in our understanding of the ecological and biophysical principles of crop management. Integrating that understanding with social and economic information in a range of scales and locations should now be emphasized. We need to convert our data and information more effectively into knowledge that can be used by our clients. We also need more effective methods of targeting that knowledge for particular groups of farmers and policy-makers. The work of researchers will not be complete until our scientific knowledge is used effectively so that food crop production and income generation meet the needs of the current generation without damaging the prospects for future generations.

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