Managing soils for long-term productivity

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SUMMARY

Meeting the goal of long-term agricultural productivity requires that soil degradation be halted and reversed. Soil fertility decline is a key factor in soil degradation and is probably the major cause of declining crop yields. There is evidence that the contribution of declining soil fertility to soil degradation has been underestimated.

Sensitivity to soil degradation is implicit in the assessment of the sustainability of land management practices, with wide recognition of the fact that soils vary in their ability to resist change and recover subsequent to stress. The concept of resilience in relation to sustainability requires further elaboration and evaluation.

In the context of soil degradation, a decline in soil fertility is primarily interpreted as the depletion of organic matter and plant nutrients. Despite a higher turnover rate of organic matter in the tropics there is no intrinsic difference between the organic matter content of soils from tropical and temperate regions. The level of organic matter in a soil is closely related to the above and below ground inputs. In the absence of adequate organic material inputs and where cultivation is continuous, soil organic matter declines progressively. Maintaining the quantity and quality of soil organic matter should be a guiding principle in developing management practices

Soil microbial biomass serves as an important reservoir of nitrogen (N), phosphorus (P) and sulphur (S), and regulates the cycling of organic matter and nutrients. Because of its high turnover rate, microbial biomass reacts quickly to changes in management and is a sensitive indicator for monitoring and predicting changes in soil organic matter. Modelling techniques have been reasonably successful in predicting changes in soil organic matter with different organic material inputs, but there is little information from the tropics.

Nutrient depletion through harvested crop components and residue removal, and by leaching and soil erosion accentuates the often very low inherent fertility of many soils in the tropics. An integrated approach involving inorganic and organic inputs is required where animal and plant residues are returned, as far as practicable. Chemical fertilizers alone cannot achieve long-term productivity on many soils and organic material inputs are required to maintain soil organic matter levels and crop productivity. A major research effort is required to develop improved strategies for halting and reversing soil degradation if long-term productivity is to be secured.

1. BACKGROUND

There is considerable speculation as to how the demand for food for an increasing global population can be met. Most observers agree that increased food production must come from a more productive use of land resources and that this must occur without further degradation. For most of the world a major expansion in cropland area is no longer a feasible option (Pinstrup-Andersen 1994). However, Crosson (1995) has emphasized the potential for increasing not only the quality of the land supply, by improving soil characteristics which increase plant production per hectare, but also its quantity by bringing more land area into crop production, without necessarily increasing quality, or by some combination of both. However, to realize the potential supply of land at acceptable economic and environmental costs in developing countries would still not meet the required production increases over the next 20 years.

In many situations, agricultural systems have responded to population pressure as agriculture based on slash and burn (up to a 20–25 year rotation) has progressively moved to bush fallow (up to a 6–10 year rotation), to short fallow (with only a 1–2 year rotation), to annual cropping, and, to multicropping with irrigation (Boserup 1965). Here, population growth drives intensification.

The hypothesis which frames this paper is that the goal of long-term productivity can only be met if soil degradation is halted and reversed. In this regard the underlying philosophy is consistent with that advanced by Lal & Stewart (1992) who emphasized the need to reverse the trend of soil degradation through restorative measures of soil and crop management. This requires detailed understanding of the causes of soil degradation so that effective and appropriate management strategies can be developed and implemented. It is increasingly recognized that the underlying reasons for soil degradation are essentially social and economic in nature (Greenland *et al*. 1994) and driven by pressures on land-using households. But just why some farmers degrade their soils and others do not is still poorly understood. Also, the reasons for the lack of farmer uptake of modern technologies are similarly complex.

In this paper soil fertility decline is highlighted as the key factor in soil degradation. The reasons for focusing on soil fertility and its management are (i) declining soil fertility is probably the most important reason why crop yields per hectare are falling; (ii) the contribution of soil fertility decline to soil degradation appears to have been underestimated; and (iii) given that soil fertility depletion is a major constraint to productivity, then investing in soil fertility enhancement is likely to give a quick and large return, even in the longer term, particularly when financial resources are scarce.

2. CROP PRODUCTIVITY AND THE SOIL

Genetic improvement of plants and improving the suitability of the physical environment for plant growth are two key ways of enhancing crop yields. With regard to the latter, it is well established that in the absence of disease and freedom from pests, six external factors contribute to the growth of plants (Brady 1974). These are (i) light, (ii) mechanical support, (iii) air, (iv) heat, (v) water, and (vi) nutrients. With the exception of light, the soil plays a total or partial role in supplying each of these external factors. Thus, in developing soil management strategies for long-term productivity it is essential to have an understanding of those soil properties and processes which determine the supply of the five external factors. It then becomes necessary to maintain and/or improve soil conditions so that the supply of these factors is adequate for optimum plant growth. That the most limiting of the essential plant growth factors will determine the level of crop production remains as valid today as when the concept was developed by Liebig in 1843 (Wild 1988). Any decrease in the supply of these soil factors potentially contributes to soil degradation.

3. SOIL DEGRADATION

Soil degradation may be defined as the temporary or permanent lowering of the soils productive capacity. It is an insidious process which undermines food production and threatens food security. In spite of the fact that soil degradation is widely recognized as being a major global problem, its geographical distribution and the areas affected are not well understood. The *World map of the status of human-induced soil degradation*, published in 1990 (Oldeman *et al*. 1990) was the major output from the UNEP project—Global Assessment of Soil Degradation (GLASOD). Although rather subjective, this was an important step in providing a regional assessment of the extent and severity of the different soil degradation processes. However, as emphasized by Crosson (1995), there is some difficulty in predicting the likely contribution of land restoration to increasing global agricultural land supplies using the meaning of degradation and the degree of degradation used in the GLASOD study. The rate at which soil degradation occurs is very important in relation to long-term productivity but this is much less well established.

The major types of soil degradation which occur (Oldeman 1994) include water and wind erosion, which displace soil material, and a range of *in situ* chemical degradation processes (including depletion of organic matter and loss of nutrients, salinization, acidification and pollution) and physical degradation processes (including compaction, crusting and sealing, and waterlogging). The regional and global extent of the four major types of degradation are shown in table 1.

Table 1. *Area of land (million ha), on a regional basis, which is moderately to excessively affected by the four major types of soil degradation and their major causes*

(Food and Agriculture Organization (1993), adapted from ISRIC/UNEP 1991.)

	area (million ha) affected by				
	water erosion	wind erosion	chemical degradation	physical degradation	total
region					
Africa	170	98	36	17	321
Asia	315	90	41	6	452
South America	77	16	44	1	138
North and Central America	90	37	7	5	139
Europe	93	39	18	8	158
Australasia	3	—	1	2	6
total	748	280	147	39	1214
major causes (%)					
deforestation	43	8	26	2	384
overgrazing	29	60	6	16	398
mismanagement	24	16	58	80	339
other	4	16	12	2	93
total	100	100	100	100	1214

[a] Percentage of each major cause of total.

Table 2. *Area of land (million ha), on a regional basis, which is affected by chemical soil degradation (all categories)*

(Taken from Oldeman (1994.))

region	loss of nutrients	acidification	salinization	pollution	total
Africa	45	1	15	+	62
Asia	15	4	53	2	74
South America	68	–	2	–	70
North and Central America	4	+	2	+	7
Europe	3	+	4	19	26
Oceania	+	–	1	–	1
total	136	6	77	21	240

Water erosion is considered to be the most important type of soil degradation affecting 748 million ha to a moderate to excessive extent (table 1) and a further 343 million ha to a light degree of degradation. One of the most important consequences of soil erosion is the loss of soil fertility because of the loss of more fertile topsoil.

Except for salinization in the semi-arid areas of Asia, loss of nutrients (and this includes organic matter depletion) is the key contributor to chemical soil degradation (table 2). Nutrient loss is particularly important in South America, with acidification being of comparatively little importance on a global scale. It is also particularly important to distinguish between inherently low soil fertility and a decline in soil fertility brought about by poor land management. The prospects for enhanced productivity are likely to be better where soil fertility decline is responsible for low crop yields.

Results of a recent study in Asia (Food and Agriculture Organization 1994) suggest that soil fertility decline, which was previously not as widely recognized as other types of degradation, is a substantial and widespread problem in the region. Reductions in soil organic matter levels and depletion of nutrients are apparent from soil and plant analyses, nutrient input data, secondary and micronutrient deficiencies, and lower responses to fertilizers. As a result, estimates for fertility decline have been revised for India and Pakistan.

A major difficulty in evaluating the impact of soil degradation on crop productivity is that several factors may be responsible for a decline in yield. The challenge is to identify the major limitations for which management practices are available, or can be developed, to minimize and reverse soil degradation so that sustainably increased crop yields are achieved. This requires enhancing soil quality and its productive capacity beyond the *status quo* implicit in preservation and conservation (Lal & Stewart 1992).

4. SUSTAINABILITY AND RESILIENCE IN THE CONTEXT OF SOIL DEGRADATION

According to Greenland *et al*. (1994), a land use system can be regarded as unsustainable if it leads to irreversible biophysical changes in the ability of the land to continue to produce equally well in future cycles of similar land use, or if there are prohibitive costs in reversing the changes. Sensitivity to soil degradation is implicit in this approach to sustainability; recognition of the biophysical and economic dimensions of unsustainability is explicit.

Soil degradation is identified directly as a key component in the definition of sustainable land management developed by an International Working Group and formalized in the Framework for Evaluating Sustainable Land Management (Smyth & Dumanski 1993), which is as follows. 'Sustainable land management combines technologies, policies, and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously: 1. maintain or enhance production and services; 2. reduce the level of production risk; 3. protect the potential of natural resources and prevent degradation of soil and water quality; 4. be economically viable; 5. be socially acceptable.'

Shifting the focus from increased agricultural productivity, *per se*, to the development of sustainable production systems has a history of only some ten years. Although preventing degradation of the soil and water resource base has become the new paradigm, increased food production still remains a key issue in much of the developing world, provided these increases are sustainable.

The relationship between soil degradation and sustainability is shown in figure 1 for three contrasting soils (Eswaran & Virmani 1990). In Oxisols, inherent productivity is low and this declines rapidly with the onset of degradation. In Alfisols, there is an initial period of buffering but after a threshold period productivity declines rapidly and continuously. For Vertisols, particularly those with deep profiles, there are usually several threshold situations where the soil may recover in the face of degradation processes, but productivity eventually drops rapidly, particularly if the profile is medium or shallow, but following a longer period of time.

That soils vary in their ability to resist change, such as by the processes of degradation, has tacitly been understood for many years. Brinkman (1990) used the term resilience of soils, in the context of climate change, to indicate resistance to changes in rainfall variability or increasing aridity. However, for systems which have already changed, the definition and conceptualization given by Eswaran (1994) is preferred. Here resilience is considered as the ability of the soil or system to revert

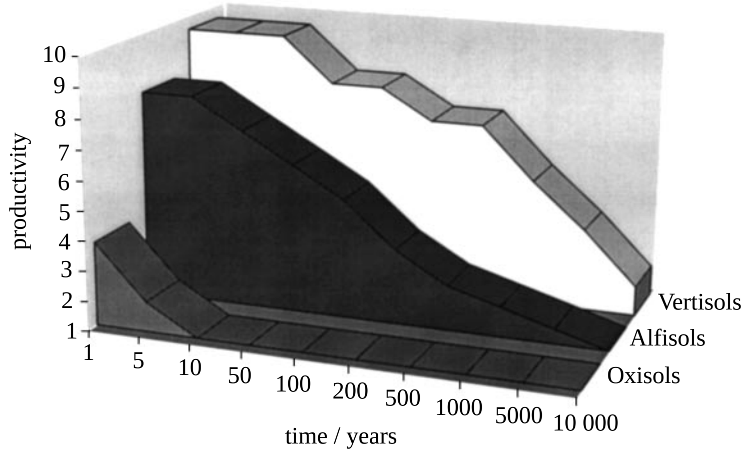


Figure 1. The concept of sustainability illustrated by the productivity–time relationship for three contrasting soils. Adapted from Eswaran and Virmani (1990).

to its original or near original performance subsequent to stress; the emphasis is on recovery ability with appropriate inputs rather than on the ability to resist change. Just as soils show a varying productivity decline related to the ease with which they are degraded (figure 1) they also vary in their resilience capacity. Characterizing the resilience capacity allows a differentiation of resistant, resilient, fragile and marginal soils, and a delineation of their response to stress (Lal *et al*. 1989). Information on resilience capacity is sparse and as emphasized by Greenland *et al*. (1994), this provides a new area of research in the pursuit of sustainability. It is essential to identify areas of resistant soils, where high productivity can easily be maintained, and of resilient soils where management practices can be developed and implemented to minimize and reverse degradation. The development of quantitative indicators and threshold values of the chemical, physical and biological attributes which determine soil resilience and sustainable land use is of high priority (Greenland & Szabolcs 1994).

5. MANAGING SOIL FERTILITY

In the context of soil degradation, a decline in soil fertility is usually taken to mean organic matter and nutrient depletion, although a deterioration in soil physical properties is often involved. The first two have been singled out for detailed consideration in this paper.

(*a*) *Soil organic matter*

Soils vary appreciably in the amounts of organic matter which they contain. But in spite of the higher turnover rate of organic matter in the tropics, there is no intrinsic difference between the organic matter content of soils from tropical and temperate regions (Sanchez 1976). The myths of a lower quantity and a poorer quality of humus (the well-decomposed, dark-coloured organic matter in soil) in tropical soils (Greenland *et al*. 1992) are gradually being deflated. What has changed little is recognition of the importance of organic matter in soil fertility. Because soil organic matter acts as a significant reserve of plant nutrients and improves soil structure and water-holding capacity, organic matter depletion results in a decrease in crop productivity.

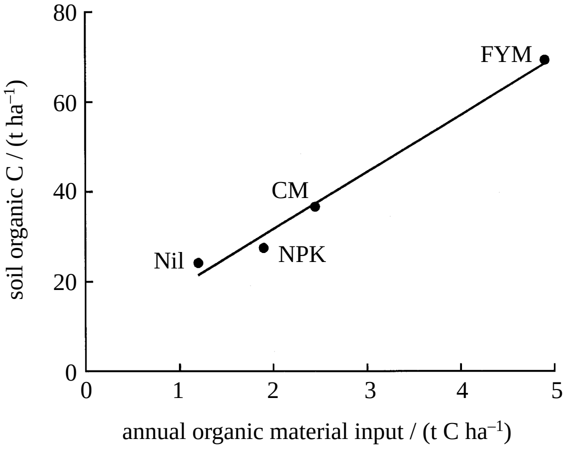


Figure 2. Relationship between soil organic carbon content of the topsoil (0–23 cm) and annual inputs of organic material for four plots on Broadbalk (Rothamsted Experimental Station): nil = no fertilizer since 1843; NPK = 96 kg N, 35 kg P and 90 kg K ha^{-1} yr^{-1} since 1843, CM = castor meal cake at 2 t ha^{-1} yr^{-1}; and FYM = 35 t ha^{-1} yr^{-1} of farmyard manure. Data from Wu (1991).

The level of organic matter in a soil is closely related to the amount of above and below ground organic matter inputs from plants growing in the soil or from the addition of animal manure added directly during grazing or brought in as an external input. This is well illustrated by data reported by Wu (1991) for selected plots on Broadbalk, at Rothamsted Experimental Station, where there is a very close relationship between the amount of soil organic carbon (C) in the topsoil and annual inputs of organic matter (figure 2).

In the absence of significant organic material inputs and where cultivation is continuous, soil organic matter declines progressively, as shown by the work of Siband (1974) in Senegal. In this study soil organic matter in the topsoil decreased from an initial value of 2.85% under native forest to 0.84% after 90 years (figure 3). In an evaluation of these data, Pieri (1989) reported that an equilibrium had not been reached even after 90 years.

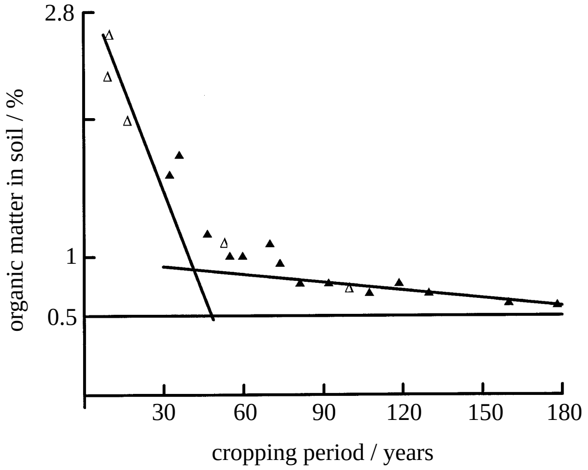


Figure 3. Relationship between soil organic matter content and cropping period following land clearing. Redrawn from Siband (1974).

Given the importance of soil organic matter, maintenance of an adequate level should be a guiding principle in developing management practices. But as emphasized by Greenland (1988), just what constitutes an adequate level is likely to vary according to soil type, environmental conditions and farming systems. Relatedly, although soil organic matter has been identified as a useful indicator of sustainable land management (Dumanski 1994), there is remarkably little information available on threshold values—defined as the level of an indicator beyond which a system undergoes significant change—which can be used as baselines against which sustainability can be assessed. Establishing target levels and threshold values for organic matter for different soils should be given priority.

Plant material composition is important in influencing soil organic matter content and crop yield, and there is now increasing interest in the concept of residue quality. Results from a long-term mulching experiment in Lopburi, central Thailand (Petchawee & Chaitep 1995) indicate that maize yield was increased almost two-fold, compared to the no mulch treatment, after receiving legume mulches, such as rice bean and mimosa, for five years (table 3) with associated increases in soil organic matter content.

Very recent work at the International Rice Research Institute has implicated organic matter quality as a key factor in nitrogen availability which appears to contribute to yield stagnation and decline in irrigated lowland rice (Cassman *et al.* 1995). There is almost no correlation between soil organic carbon content and the effective soil nitrogen supply capacity of lowland rice soils. In a survey of farmer's fields in Central Luzon (Philippines) there was a large range in the effective soil nitrogen supply capacity but no relationship between nitrogen uptake and soil organic carbon or total soil nitrogen (Cassman *et al.* 1996). Soil organic carbon and total nitrogen can increase without an increase in soil nitrogen supply capacity. It appears that incorporation of fresh organic matter under mostly anaerobic conditions results in an incomplete degradation of phenolic subunits and that these are able to form stable complexes with amino acids and other labile organic nitrogen compounds, in addition to rendering the mobile humic acids more recalcitrant to subsequent mineralization (Olk *et al.* 1996). The development of improved management practices which maintain the quality of soil organic matter and optimize nitrogen efficiency is important for halting and reversing the emerging concern about productivity decline in irrigated lowland rice systems of the tropics.

The balance between additions and losses due largely to decomposition determines the organic matter content of a soil. Decomposition is a continuous process, the rate at which it occurs and the activity of the soil biomass involved fluctuate in response to changes in the levels of substrate and in the environmental conditions, particularly moisture and temperature.

Two fairly recent developments in studying soil organic matter offer promise in underpinning the development of improved soil management practices; these are (i) soil microbial biomass and particularly its role in nutrient cycling, and (ii) modelling changes in soil organic matter. Each will be considered briefly.

(*b*) *Soil microbial biomass*

Soil microbial biomass not only serves as an important reservoir of available nutrients, particularly nitrogen, phosphorus and sulphur, but it regulates the cycling of organic matter and nutrients, and has a major control on the plant availability of nutrients in soils. Because of the rapid turnover of soil microbial biomass, with a turnover time of one to two years, the nutrients present are much more labile than those incorporated into soil organic matter, where mineralization takes much more time, with a turnover time generally in excess of ten years (Jenkinson 1990). For these reasons, an increase in the size of the microbial biomass is essential for the improvement of soil fertility.

Table 3. *Maize yield and soil organic matter content (shown in parentheses) under long-term mulching with plant residues at Lopburi, Thailand*

(Data from Petchawee & Chaitep (1995.))

	maize yield (t ha^{-1}) in			
	1980		1985	
treatment	−fert.	+fert.[b]	−fert.	+fert.
no mulch	2.5 (0.83)	3.2 (0.91)	2.8 (1.10)	4.2 (1.33)
rice straw mulch	2.9 (1.15)	4.0 (1.09)	4.3 (1.63)	7.6 (1.86)
sunhemp mulch (*Crotalarea juncea*)	2.6 (0.92)	3.0 (1.11)	3.9 (1.51)	5.5 (1.52)
rice bean mulch (*Vigna umbellata*)	2.2 (0.87)	3.5 (1.05)	5.9 (1.64)	7.6 (1.80)
mimosa mulch (*Mimosa invisa*)	1.9 (1.05)	3.9 (1.02)	7.5 (2.83)	7.6 (2.45)
compost[a]	3.3 (1.10)	3.9 (1.14)	5.9 (2.57)	8.2 (2.91)

[a] 20 t ha^{-1} of municipal compost.

[b] 62.5 kg N ha^{-1} and 27.3 kg P ha^{-1}.

Table 4. *Amounts of microbial biomass carbon, phosphorus and sulphur in topsoils* (0–15 cm) *from selected treatments in the Palace Leas hay meadow experiment* (*Pawson 1960*) *at Cockle Park Farm, Northumberland*

	microbial mass (mg kg^{-1})		
treatment	C[a]	P[a]	S[b]
control	1320	15	13
N	1710	13	27
P	1770	45	20
NPK	1040	20	20
FYM	1670	56	15
FYM + NPK	1880	66	12

[a] Data from Wu *et al.* (1997*a*).
[b] Data from Wu *et al.* (1994).

Data from the literature indicate that the amounts of soil microbial biomass carbon, nitrogen, phosphorus and sulphur vary with soil type, crop species, climate and management. Under arable management in temperate regions, microbial biomass carbon generally comprises one to four per cent of organic carbon in the topsoil (Sparling 1992). The range is wider for grassland soils (and for nitrogen, phosphorus and sulphur) where one to ten per cent of the total nitrogen, phosphorus and sulphur can be maintained in the microbial biomass. The amounts of microbial biomass carbon, phosphorus and sulphur in topsoils from the long-term hay meadow experiment at Palace Leas, Northumberland, are shown in table 4. The quantities of phosphorus and sulphur present in the microbial biomass and the annual flux of phosphorus and sulphur through the biomass, calculated using a turnover time of 1.5 years as proposed by Jenkinson & Parry (1990) for UK conditions, were appreciably larger than those taken up by grass, which ranged from 2–11 kg P ha^{-1} and 2–8 kg S ha^{-1} in 1993.

Under comparable management, the amounts of microbial biomass, carbon, nitrogen, phosphorus and sulphur maintained under arable cropping in tropical soils are lower than those in temperate soils. The amounts of biomass carbon in low input cropped soils in the tropical regions are often lower than 200 kg ha^{-1}. However, the turnover rates of microbial biomass are expected to be much higher (less than one year) in tropical soils. Srivasava & Singh (1991) calculated that for Indian soils, the flux of nitrogen and phosphorus through the microbial biomass ranged from 27–64 kg ha^{-1} yr^{-1} and 13–26 kg ha^{-1} yr^{-1}, respectively. Although there is a shortage of data, it appears that in poorly managed tropical soils the amounts of nitrogen, phosphorus and sulphur retained are very limited (2–5 kg ha^{-1}), due to the small size of the microbial biomass.

Because of its high turnover rate, microbial biomass reacts much more quickly to changes in management than does soil organic matter content. Also, the larger proportional change in soil microbial biomass, makes microbial biomass carbon a more sensitive indicator of organic matter flux than changes in total or organic carbon. Powlson & Johnston (1994) reported substantial changes in microbial biomass carbon under different cultivation and cropping regimes when changes in soil organic carbon were small. Thus microbial biomass carbon appears to be a sensitive and useful indicator for monitoring and predicting changes in soil organic matter. Further evaluation is required with tropical soils because of the paucity of information.

6. MODELLING CHANGES IN SOIL ORGANIC MATTER

The dynamics of soil organic matter and the nutrients associated with it can be treated quantitatively, simplified and captured in mathematical models. In addition to providing a better understanding of decomposition and accumulation processes, such models can, within specified limits, be used to predict future conditions from previous experience. Models such as the Rothamsted carbon model (Jenkinson 1990) and the CENTURY model (Parton *et al.* 1988) have been developed for temperate regions and validated against data from long-term experiments. These models have been quite successful in predicting changes in soil organic matter for local soils, climatic conditions and agricultural practices. In particular, they can be used to simulate the changes in organic matter that occur in soils with different organic material inputs and to assist in determining which management practices are likely to lead to target organic matter levels.

In the tropics, there are very few data sets which can be used to demonstrate long-term changes in soil organic matter and related soil nutrient parameters. Thus model predictions are potentially valuable for improving management practices where experimental data are limited. An example of the use of the Rothamsted model to predict changes in soil organic carbon in upland sandy soils in north-east Thailand is shown in figure 4. Historical data are not available to validate the model in this situation although field data obtained over zero to three years fit well with the

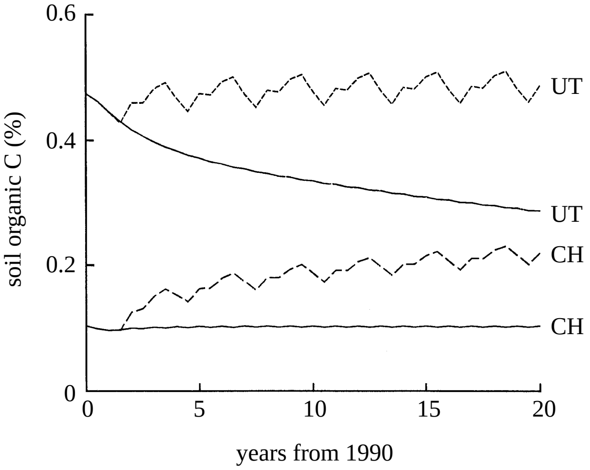


Figure 4. Predicted changes in soil organic carbon content of the topsoil in upland sandy soils at two sites in north-east Thailand under continuous cassava (solid lines) and ley-arable management (dashed lines) UT = Udon Thani, CH = Chaiyaphum. From Wu *et al.* (1997*b*).

model predictions (Wu *et al*. 1997*b*). Myers (1995) evaluated the CENTURY model using a 15-year data set from a crop residue management experiment, also involving green manuring, at Lopburi in central Thailand. In general, the model predicted the nature of the changes in crop yield and soil organic matter with time in response to crop residue and nitrogen and phosphorus fertilizer input. In most cases where soil organic matter was well simulated, crop yield was also well simulated. However, the model underestimated soil organic matter accumulation, particularly in the plots receiving nitrogen and phosphorus fertilizer, and in those receiving the highest organic inputs. The effect of higher temperatures on soil processes in the tropics can be accommodated by varying the rate factors in the model. However, rainfall and moisture regimes are very different and may require more careful consideration.

7. NUTRIENT DEPLETION

Nutrient depletion or nutrient mining is a characteristic feature of agriculture in most developing countries. This is compounded by the fact that many of the soils are of low or very low inherent fertility. Given the inability of resource-poor farmers to provide fertilizer inputs, it is inevitable that productivity will decline further. Yates & Kiss (1992) have suggested that recycling, by biological means, the currently low levels of nutrients in low-productivity subsistence agriculture in Africa can only condemn most of the continent to continuing poverty levels of productivity. An integrated approach to nutrient management involving inorganic and organic inputs is required.

Nutrient depletion occurs primarily through crop removal in harvested products and residues, and by leaching and soil erosion. Whereas the quantities of nitrogen, phosphorus and potassium (K) removed by crops can be estimated with reasonable reliability, those lost by leaching and soil erosion are more difficult to assess. Losses by leaching are important for nitrogen and potassium, whereas soil erosion is an important pathway of loss for all nutrients, but for phosphorus in particular. Gaseous loss is important for nitrogen.

In a comprehensive study of the nutrient balance in 38 countries in sub-Saharan Africa, Stoorvogel & Smaling (1990) concluded that nutrient mining was widespread, given that the sum of inputs minus the sum of outputs was negative for essentially all countries (figure 5). Further, when the rates of nutrient loss between 1983 and 2000 were estimated it was found that, with very few exceptions, nutrient balances were becoming increasingly negative. High rates of nutrient depletion were found in erosion-prone areas in east and southern Africa, where most of the soils are still relatively rich in nutrients. Low depletion rates were characteristic of semi-arid environments where the soils were usually already poor in nutrients. Further progressive loss of nutrients can only lead to further decreases in crop productivity in a region where per capita food production has declined over the past two decades.

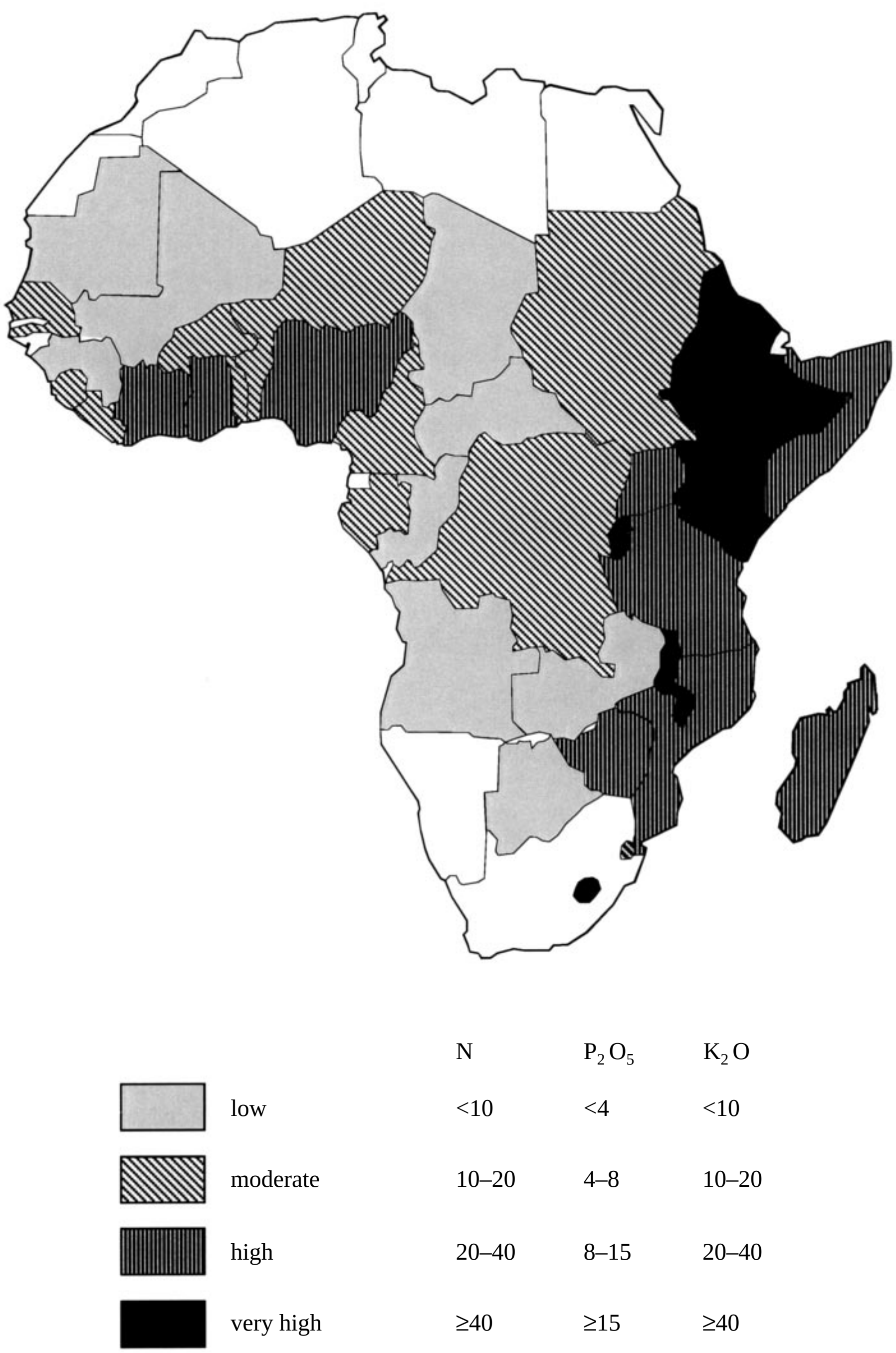
The construction of nutrient balances in southern Mali allowed van der Pol (1992) to calculate the economic cost of nutrient mining. It was estimated that up to 40% of the total income generated by farming was derived from soil mining. It was possible to identify cropping systems which offered higher cash returns and thus more potential for investment in soil fertility management. It was concluded that permanent traditional cereal cropping systems, with low returns, were unlikely to offer long-term sustainability and would continue to be dependent entirely on soil mining.

At the global scale, intercontinental exports of nutrients have major implications for national long-term productivity. A particular case in point is the export of potassium in cassava from Thailand. Cooke (1986) calculated that in 1982, the 7815 kt (kilotonnes) of tapioca products prepared from cassava which were exported would have removed 129.7 kt of potassium; this was 4.4 times as much potassium fertilizer as was used in Thailand in 1981–1982 when the cassava was produced. Much of this would have contributed to agricultural productivity in Europe, which received 94% of the total exported, particularly the Netherlands. In 1994, exports of tapioca products from Thailand were down by some 27% on the 1982 figure but this still represents a substantial drain on soil potassium reserves. In developing countries it appears that losses of nitrogen and potassium through exports are much larger than gains from imports. Nutrient balance studies are required to assist with setting national policies to maintain and enhance soil nutrient status in countries which export large quantities of agricultural products.

8. MANAGEMENT PRACTICES TO MAINTAIN SOIL ORGANIC MATTER AND PREVENT NUTRIENT DEPLETION

Preventing a decline in soil organic matter, and the nutrients (N, P and S) complexed by it, is a key issue in managing soils in the tropics. Although residue input is a vitally important component, little or no agricultural residues, plant or animal, are returned to the soil in many tropical cropping systems (Woomer *et al*. 1994). Leguminous species, used directly as a crop, as a green manure (as crop residues and tree prunings), or as a live mulch, are an important source of high-quality organic material; in addition they enhance soil nitrogen levels, through biological fixation of gaseous nitrogen, which is a priority for sustained productivity and for rehabilitating degraded soils. Legume residues have a low C/N ratio and a low lignin and polyphenol content, and are regarded as high quality (Swift *et al*. 1994). Because of the control on biological processes, residue (resource) composition can influence the quantity and quality of the soil organic matter formed, in addition to nutrient availability. Manipulation of resource quality, particularly nitrogen and polyphenol content, is a potentially important way of managing soil organic matter.

In much of the tropics, crop residue management is very much determined by the presence of livestock and other competing requirements, particularly alternative sources of fuelwood. Animal manure is an integral



		N	P_2O_5	K_2O
░	low	<10	<4	<10
▨	moderate	10–20	4–8	10–20
▥	high	20–40	8–15	20–40
■	very high	≥40	≥15	≥40

Figure 5. Rate of soil nutrient depletion in sub-Saharan Africa in 1983. Redrawn from Stoorvogel & Smaling (1990).

component of soil fertility management, particularly where the input of chemical fertilizers is low. As with crop residues, competing requirements for its use as a fuel often limit the amount available. The limitations posed by animal numbers and the availability of feed indicate that the quantity of animal manure is insufficient to sustain crop yields on a long-term basis, as shown by the work of Williams *et al.* (1995) in Niger. Even though reliance on manure is not a sustainable strategy, the efficient use of manure remains an important objective.

If long-term productivity is to be achieved, soil nutrient depletion should be halted; in situations where nutrient mining has caused soil degradation it must be reversed. This can potentially be achieved by (i) decreasing nutrient loss—by controlling soil erosion and recycling residues: it seems likely that the latter is best done in the form of manure in semi-arid areas and as a mulch cover in humid regions (Pieri 1995); and (ii) increasing nutrient input—by using the most economically and agronomically effective methods. Financial constraints usually limit the ability to purchase imported chemical fertilizers and where possible the use of indigenous resources, such as effective phosphate rock materials, should be promoted.

However, the limitation of supplying chemical fertilizers alone to achieve long-term productivity is now well established. The results of trials conducted over 20 years in west Africa and summarized by Pieri (1992) showed that chemical fertilizer input was able to reverse the decline in productivity initially during cultivation, but not indefinitely. It was concluded that

Table 5. *Yield of soybean seed (kg ha^{-1}) on a Paleustult in north-east Thailand as influenced by organic and inorganic nutrient inputs*

(Data from Wongwiwatanachai (1993.))

year	control	compost[a]	NPK[b]	compost + NPK
1	1160	1570	1830	1930
2	1030	1630	1500	2040
3	356	669	475	756
4	856	1640	2050	2090
5	869	1360	1690	1860
6	756	1070	1670	1930

[a] 20 t ha^{-1} annually for years 1–3.

[b] 38 kg N, 44 kg P and 63 kg K ha^{-1} yr^{-1}.

inputs of organic materials are required to maintain soil organic matter levels and crop productivity. Similarly, research conducted in north-east Thailand and summarized in table 5 demonstrates how the effectiveness of chemical fertilizers is increased substantially by the addition of organic materials. Conversely, work with low external input systems on acid soils in south-east Asia indicate that unless nutrient deficiencies are corrected, crop yields do not respond to inputs of organic residues (Siem *et al.* 1994).

Monitoring has an important role to play in refining and evaluating the impact of management practices aimed at maintaining and enhancing soil fertility, particularly in controlling nutrient balances. The methodology for doing this at the farm level is already well advanced (Guiking *et al.* 1994), but there is a need for further development and testing.

9. RESEARCH NEEDS AND OPPORTUNITIES

Recent research on soil organic matter and nutrient dynamics is providing a sounder basis for the development of appropriate management practices to secure long-term productivity. In particular, the more sensitive measure of organic matter changes provided by soil microbial biomass carbon can now be incorporated into models and used to good effect in evaluating and predicting the effect of changes in cultivation and cropping practices on crop productivity. Further work is required to better understand the interactions of microbial biomass carbon and other nutrients (N, P and S), particularly where longer-term data are being collected. This is important for tropical soils where little information is available. Studies of organic matter dynamics, water use and nutrient flow associated with changes in soil, water and nutrient management should be given priority. The increasing use of stable isotopes (^{13}C and ^{15}N) is providing good opportunities for valuable underpinning research.

The research and extension effort required to pursue the development and implementation of improved soil management technologies and strategies is substantial. An effective collaboration between National Agricultural Research and Extension Systems, International Agricultural Research Centres, Advanced Research Organizations and Non-Governmental Organizations is required to achieve this. It will also require a more coordinated funding mechanism than presently exists. The developing World Bank initiative on recapitalizing soil fertility in sub-Saharan Africa provides a potentially useful blue print for achieving this undertaking.

Nutrient budgets provide an effective way of establishing and monitoring the rate and extent of nutrient depletion at different scales. There is an urgent need for more case studies at the farm, district, provincial and national level to provide information for decision makers with regard to fertilizer recommendations and policies. Where sufficiently detailed information is available, this can feed into developing improved management practices to combat soil fertility depletion and enhance productivity.

Improved soil management technologies and strategies will increasingly require a more holistic and integrated approach. They must be assessed in terms of economic viability, and environmental and social acceptability. There is a new paradigm for research in soil, water and nutrient management (Greenland *et al.* 1994) to which work on the soil fertility components outlined in this paper can be a major contributor. If soil degradation is to be halted and reversed, and long term productivity secured, this must be pursued vigorously.

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Discussion

D. S. Powlson (*Institute for Arable Crop Research, Rothamsted, Harpenden, UK*). First a comment, effort could usefully be given to applying one or more soil carbon models which do exist to tropical sites in order to evaluate different management options. This is a natural extension of the GCTE SOMNET exercise, started for temperate sites. Second, a question. Professor Syers made the point that cycling of nutrients, particularly P, through the soil microbial biomass is advantageous. To capitalize on this, larger inputs of organic C to soils are required. How great a limitation to achieving this are the competing uses of crop and animal residues? Which zones are likely to be the most critical in this respect?

J. K. Syers. I fully support the suggestion that soil carbon models developed for temperate regions should be tested with tropical data. We have in fact been using the Rothamsted carbon model with our data from Thailand. However, it is possible that such models may require some modification for use in the semi-arid tropics, in particular. The availability of suitable organic materials will limit the ability to cycle substantial amounts of P through the microbial biomass. In areas where crop residues are used for animal feed and where crop and animal residues are used for fuel, this will be particularly serious. However residues could be used more effectively than at present in some regions.

I. Rappaport (*London, UK*). You cited two main factors causing soil degradation—social and economic—but went on to observe that they are both poorly understood. You also stated that for soil management regimes to be sustainable they must be socially and environmentally acceptable. In view of these causes and requirements and the fact that land managers are beginning to recognize that 'land management is 99% people management', should research into the maintenance of soil fertility be refocused so as to address these fundamental and essentially human issues?

J. K. Syers. It may be more appropriate to consider land management as being 99% management by people; I am not sure that one can always manage farmers. I suggest that the key to halting and reversing land degradation lies at the interface between soil fertility and those social and economic factors which determine farmer attitudes, to nutrient management.

P. A. Sanchez (*ICRAF, Kenya*). I support the positive emphasis which Rattan Lal places on soil restoration versus degradation. Are the processes reversible? Are there hysteresis effects in soil organic matter and soil biology restoration?

J. K. Syers. I agree with the positive emphasis. It is not sufficient to minimize degradation; we must aim to reverse it. To a large extent and given adequate time, degradation is largely reversible but it would be surprising if there were not some hysteresis effects.

R. Lal (*Ohio State University, USA*). There are three differences in soil organic matter in tropical and temperate regions: (i) the rate of decomposition is very high in the tropics, (ii) the rate of recovery of soil organic matter in the tropics is very slow, and (iii) biomass C and the quality of soil organic matter may be different.

D. J. Greenland (*University of Reading, UK*). There have been several conceptual models of the dynamics of change in soil properties in the tropics, but we lack long-term experiments which can be used to validate these models. What should be done to validate these models?

J. K. Syers. In the absence of adequate long-term data it is obviously difficult to validate conceptual models. However simulation modelling can be used 'with some success', provided the increasing body of available data is put to good use.

J. Ingram (*NERC Institute of Hydrology, Wallingford, UK*). In a plan for the need to restore degraded lands, Professor Syers called for moves to restore the soil's chemical and physical properties. Soil biological processes are important in maintaining many aspects of soil fertility and it is necessary to also restore the biological status of the soil.

J. K. Syers. I fully agree. It is important to recognize that many chemical and physical properties are influenced and largely driven by biological processes.