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The role and function of organic matter in tropical soils

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Abstract

Soil organic matter (SOM) has many functions, the relative importance of which differ with soil type, climate, and land use. Commonly the most important function of OM in soil is as a reserve of the nitrogen and other nutrients required by plants, and ultimately by the human population. Other important functions include: the formation of stable aggregates and soil surface protection; maintenance of the vast array of biological functions, including the immobilization and release of nutrients; provision of ion exchange capacity; and storage of terrestrial carbon (C). This paper considers the quantity and quality of SOM of soils in the tropics, which are estimated to contain one quarter of the C in the global pool in terrestrial soils, and supports strongly the use of analytical methods to characterizing labile SOM to develop valuable insights into C dynamics. As in other regions, the transformation of tropical lands for agriculture exploits SOM, and in particular nutrient reserves. The process of exploitation is accelerated in the tropics by the necessity to increase agricultural production, largely through agricultural intensification, to overcome inadequate nutrition, to satisfy population growth, and to cope with the limited reserves of arable land. Poverty has an overriding influence on the exploitation and degradation processes. Areas at greatest risk of land degradation are the infertile acid soils of the tropics, which, invariably, are cultivated by the poor. Soil organic matter has a central role in sustainable land management, but perspectives on the roles of SOM differ widely between farmers, consumers, scientists and policy-makers. Some consider SOM as a source of nutrients to be exploited, whereas others can afford to utilize it as a key component in the management of the chemical, biological, and physical fertility of soils. Still others see SOM as a dumping ground for excess nutrients and toxins, or as a convenient store for fossil fuel emissions, particularly CO_2. Farmers need sustainable land management systems that maintain OM and nutrient reserves. Nevertheless, many available practices, whether based on indigenous or scientific knowledge, do not meet social and economic criteria that govern farmer behaviour. Much scientific knowledge about the various roles of SOM does not reach farmers and other decision-makers in a form that can be used easily. The biggest challenge to researchers is to engage with clients to pinpoint gaps in knowledge and utilize new and existing information to devise decision support Systems tailored to their needs.

Introduction

''*In nature nothing dies. From each sad remnant of decay, some forms of life arise . . .*'' (Charles Mackay, 1814–1889)

In terrestrial ecosystems, soil organic matter (SOM) is an essential reservoir of carbon, nutrients, and energy in the cycle of life (Jenkinson 1988). Without SOM, the Earth's surface would be a sterile mixture of weathering minerals. Appreciating the importance of SOM and understanding its role in sustaining life are fundamental issues challenging scientists and, increasingly, groups outside the scientific community. Scientists have generated much knowledge of the fundamental ecological, biological, and physicochemical processes governing the behaviour of OM, but much remains to be understood. Although scientific studies may be limited, there is a wealth of indigenous knowledge in the tropics about soils and their management that has been tapped only recently (Pongsapich 1998). The role and functions of SOM are multifarious and the priorities assigned to the different roles depend on the particular biophysical conditions and the perspective of the user group.

Human population growth and increased demand for food have necessitated the transformation of large areas of land for agriculture, particularly in tropical regions (Buringh and Dudal 1987). Much of the increased agricultural output has relied on the exploitation of reserves of SOM that occurs as land is bought into production.

In areas with high production potential, nutrient inputs through fertilization may help counterbalance the decline in SOM. This is not the case in areas that are marginal because of soil acidity, salinity, drought or steep slopes. In these soils, the rates of erosion and nutrient export in harvested products further accelerate the decline in SOM (Dalal and Mayer 1986). The mismatch between fertilizer needs and use in areas of low production potential perpetuates the poverty of millions of people in the tropics (Craswell et al. 1998a). The required increase in crop production in many tropical areas depends on expanded cultivation of marginal lands (Greenland et al. 1997). This is particularly critical where average yields are declining in current production systems. Fertilizers are important in maintaining production in many high potential areas and increasing production on marginal areas. For both current and new agricultural lands, it was estimated that the global use of nutrients in fertilizers must double by 2020 to meet projected food demand (Vlek et al. 1997). Meeting the growth in demand for food without accelerating land degradation, including the continued decline in SOM, must be one of the greatest challenges facing the human race in the 21st century.

The objectives of this paper are to highlight some specific issues on the role and function of OM in the tropics and the prospects for organic matter management to contribute to sustainable land management, and to indicate some priority areas for further research and knowledge synthesis. Soils of the tropics support the livelihood of millions of poor farmers whose perspectives differ from other clients for this knowledge; their requirements must be paramount in prioritising research on SOM and sustainable production systems.

The functions of soil organic matter

Soil organic matter encompasses the soil biota, and plant and animal tissues at varying stages of decomposition. Arguably the most important component is humus, the well-decomposed, dark-coloured organic material in soil. Despite extensive research, our understanding of the basic chemistry and microbiology of humus, and of SOM in general, is incomplete (Oades 1995). The major constraints are the complexity of the physicochemical processes of decomposition and humification and the difficulty of separating the organic components from the soil mineral complex.

There is no doubting the importance of SOM in the fertility, productivity, and sustainability of agricultural and non-agricultural ecosystems. Soil organic matter is a critical component of the soil resource base, which affects the biological, chemical, and physical processes of the soil and, through the effect on these processes, fulfils a very wide range of functions (Wild 1995). Soil organic matter is the driving force for biological activity as the primary source of energy and nutrients for many soil organisms. A direct effect of this biological activity is seen in the macro structure of soils, through the formation of soil pores as a consequence of faunal activity and root and fungal growth. Larger, but less direct effects of biological activity are the resultant changes in the organic compounds of SOM that result from biological breakdown, and the concomitant mineralization and immobilization of nutrients (Zech et al. 1997).

The relative importance of these different functions varies with soil type, climate, and farming system (Tiessen and Shang 1998). In many situations, the most important function of OM in soil is as a reserve of the nutrients required by plants, and ultimately by the human population. Soil organic matter has a less direct, but nonetheless important effect on nutrient supply through its influence on cation exchange capacity and on the capacity to adsorb anions; and these functions have additional important implications for the impact of toxic ions and biocidal agrochemicals (Woomer et al. 1994).

The role of SOM in the formation of stable soil aggregates has major implications for soil structure and, therefore, on water infiltration, water holding capacity, aeration, soil strength and resistance to root growth, and surface crusting (Scholes et al. 1994). In situations where soil moisture or soil strength are major limitations to plant growth, the greatest impact of SOM can be on these physical components of soil fertility.

Increasingly, it is being recognized that another important role for SOM is as a critical component of the global C balance, being a much larger C pool than the atmosphere and the biota, but less than that in fossil fuels and the predominant marine C pool (Lal et al. 1995). Management of SOM can have significant implications on the global C balance, and thus the impact of increased atmospheric CO_2 on climate change.

The quantity of soil organic matter

Understanding the role of soil biota in the breakdown and decomposition of organic residues is increasing, as is appreciation of soil biodiversity, although much of this work is being done in the temperate regions where there is greater scientific capacity to undertake such research (Zech et al. 1997). While there is no evidence that these fundamental processes differ in the tropics, the dynamics can differ (Jenkinson 1988), and so more studies on SOM in the tropics are required. The lack of data from the tropics was evident in a recent attempt to use the scientific knowledge base to assess the potential for carbon sequestration (Paustian et al. 1997).

Tropical soils are not necessarily lower in OM content than temperate soils but, with the exception of wetland rice soils, agricultural intensification, through clearing and clean cultivation of soils for annual cropping almost universally causes a decline in soil organic content (Greenland et al. 1992). The extent of the decline depends on the balance of inputs of organic and inorganic nutrients that affect plant growth and residue return, along with other management practices that affect SOM dynamics.

Recognition of the importance of SOM in the global C balance has spurred many recent attempts to estimate the global SOM pool (Paustian et al. 1997). Increasingly, there is agreement about estimates of the global SOM pool (Batjes 1996) at approximately 1500 Pg of organic C in the top 1 m of soil, of which approximately one-quarter is in tropical soils. Such estimates must be treated with due reservation as there are a number of problems in estimating the global SOM pool (Batjes and Sombroek 1997). Firstly, estimates are based on relatively limited data, which may be unrepresentative of geographical zones, major soil types, and critical management histories. Secondly, these estimates are restricted to the top 1 m of soil, even though it is known that soils can contain significant amounts of C at greater depths. It is likely that problems of uneven distribution and overall data scarcity are greater in the tropics, where more ecological research is needed (Paustian et al. 1997).

Another problem, which affects both global estimates and measurements made for the purpose of understanding C dynamics at the farm scale, is the measurement of soil C. Many measurements of SOM are from oxidation of soil C with methods based on the Walkley-Black method (Walkley and Black 1934). These methods are known to result in incomplete recovery of soil C, which is acknowledged in the use of a range of factors to convert measured C to total organic C. Resistant or inert forms of C, such as charcoal (Skjemstad et al. 1990), can contribute significant amounts to the total organic soil C pool, as can carbonates to total soil C. The increasing use of methods that result in more complete oxidation of organic C (Heanes 1984) and the move to catalytic combustion methods, which measure total soil C, including carbonates unless they are removed prior to analysis, should result in more accurate measures of total soil C. The move to catalytic combustion may be accelerated by the need to reduce the use of chromium-based oxidation methods on environmental grounds and the possible adoption of catalytic combustion as the prescribed method of SOM measurement under the United Nations Framework Convention on Climate Change and the subsequent Kyoto Protocol.

Better measurements of total soil C are only part way to improving our understanding of soil C dynamics. In their study of kinetics of organic C loss from different soils subjected to different periods of cultivation, Dalal and Mayer (1986) provided examples of the large range in pre-cultivation amounts of C, the patterns and rates of decline with cultivation, and the equilibrium values of soil C after long-term cultivation. Clearly, SOM includes a wide range of C compounds with very different breakdown dynamics.

These differences between soils illustrate why multicompartment C models are needed to simulate accurately the changes in soil C (Parton et al. 1988; Jenkinson 1990). At a minimum, these models require an active or labile C pool, and a less active or inert pool, and commonly they have an inert pool and a number of pools with differing activity. The use of stable and radioisotopes of C was important in developing a greater appreciation of the different turnover rates of some of these C pools e.g. (Jenkinson 1964; Balesdent et al. 1987), although only a limited number of studies have been done with radioisotopes in the tropics (Scharpenseel et al. 1992).

The quality of soil organic matter

Concomitant with increased interest in modelling C pools, has been increased interest in measuring the size of different C pools. These measurements have employed a wide range of techniques (Lefroy et al. 1995a). Early measurement of very broad, non-specific chemical groups, such as humic and fulvic acids and humins, on the basis of solubibty, developed into separation on the basis of more functional chemical groups, for example with ^{13}C NMR (Oades et al. 1988), and, increasingly, on the basis of relative bioavailability. Measurements related to bioavailability include detection of the small but active microbial pool by fumigation techniques (Jenkinson and Powison 1976) to measurement of labile C with high potential for biological oxidation. High potential for biological oxidation has been related to surrogate measurements on the basis of physical fractionation such as the light fraction of C by density fractionation (Christensen 1992), and on the basis of chemical oxidation (Blair et al. 1995). The move from very broad chemical groups, to more functional chemical groups and to pools that are more closely related to soil biological activity, increases the potential to better understand soil C dynamics.

These various measurements of labile soil C need to be used more widely and, most importantly, they must be related to important aspects of soil chemical, physical, and biological fertility, to productivity, and to the broader aspects of system sustainability. For instance, the measurement of labile C by oxidation with potassium permanganate (Blair et al. 2001) has been shown to be related to cultivation (Lefroy et al. 1993; Conteh et al. 1997; 1998), residue incorporation (Blair et al. 1998; Conteh and Blair 1998; Konboon et al. 1998), aggregate stability (Bell et al. 1998; 1999; Whitbread et al. 1998) and infiltration (Bell et al. 1998), and some concomitant links to productivity and sustainability. Much of this research concludes that residue, fertility, tillage, and other management practices that maximize C inputs and increase soil C, particularly the labile C fraction, are critical for the development of sustainable cropping systems. Such measurements need to be used across a wider range of soils, farming systems, and research groups. In addition, these measured C pools need to be used in soil C models, rather than relying on more theoretical separation into pools. For instance, with a three-pool model that uses labile, less labile, and resistant or intractable C, based on differences between potassium permanganate oxidizable C, a modified Walkley-Black measurement, and total C (Blair et al. 1997; Armstrong et al. 1999).

Factors affecting SOM quality

The amount and dynamics of soil C differ with soil type, particularly mineralogy, with climate, and with management. Although the myths of lower quantity and quality SOM in tropical soils compared to temperate soils have been countered (Sanchez 1976; Greenland et al. 1992), there are some broad differences in the soil C dynamics between tropical and temperate zones, as there are between agricultural and non-agricultural systems. The breakdown rate of OM can be significantly faster in the tropics, although there are no major differences in the pattern and products of breakdown (Jenkinson and Ayanaba 1977). Correspondingly, the inputs of C to tropical systems can be much greater, which may explain the lack of a general difference in total organic C between temperate and tropical areas.

Similarly, the change from a natural ecosystem to an agroecosystem can involve significant changes in C inputs and turnover rates. Many undisturbed forest and grassland systems have large total C pools, comprising C pools with a wide range of activities, and relatively continuous inputs of C of different quality. Frequently, the move to agricultural systems involves more discrete, event-driven inputs of fairly uniform quality C. Even if there are minimal changes in total C inputs, changes in management and C quality, which in turn affect breakdown rates, can have very large effects on C dynamics in different systems.

Incorporation of residues with tillage operations reduces the size of residue particles and increases the contact with soil particles and biota, thus producing increased breakdown of recently added organic C.

Similarly, evidence from stable isotope (^{13}C) measurements (Lefroy, unpublished) and oxidizable C pools (Armstrong et al. 1999) suggest increased tillage can significantly increase the breakdown of apparently recalcitrant C, presumably through the exposure of new surfaces for decomposition. Reductions in C inputs, through product removal, plus increased losses in erosion and runoff with agricultural practices can further change the C dynamics.

The breakdown of added residues and of SOM are affected by their physical and chemical characteristics, as well as by temperature, moisture, nutrition, and other factors that affect biological activity directly. C compounds can be physically protected from breakdown by the physical integrity of the organic material and by organic or mineral coatings, such as humified substances and clay particles, respectively (Oades 1995). Disruption of these physical barriers during tillage can increase breakdown. Similarly, the resistant chemical nature of C compounds such as lignins, polyphenols, and various humified substances constitute chemical barriers to breakdown (Tian et al. 1995). With the importance of physical and chemical barriers to breakdown, methods for assessing soil C pools must include both components. This is why care must be taken in sample preparation for the measurement of labile C pools by density measurements and oxidizing agents as the degree of aggregate/particle disruption, with sonication or grinding, may affect these measurements significantly.

Understanding the controlling factors in the breakdown of organic residues is likely to become an important factor in developing more sustainable farming systems. The importance of lignins, polyphenols, nutrients, particularly N, and other factors in controlling the breakdown of residues is acknowledged (Tian et al. 1995), although more work is required to elucidate the controlling mechanisms and the most appropriate parameters (Palm and Rowland 1997). In the meantime, a relatively simple empirical laboratory technique for measuring breakdown of residues has been found to correlate with plant growth responses to residue additions and measurement of chemical characteristics of residues (Lefroy et al. 1995b). The selection of residues on the basis of quality, and thus breakdown rate, may become an important tool in developing more sustainable systems by increasing soil C and maintaining a good balance between labile, less labile, and intractable C pools.

Selection of plant species and management practices may have significant effects on soil C through inputs from roots and aboveground plant parts. Fisher et al. (1994) showed large accumulation of soil C from roots in deep soil profiles under improved grasslands in Brazil. Measurement of root decomposition indicates that significant proportions of root C can be considered highly recalcitrant and that the short- and long-term rates of decomposition have significant impact on the short- and long-term availability of soil N as well as the overall soil C dynamics (Urquiaga et al. 1998).

Areas at risk

Exploitation of SOM reserves and soil degradation is accelerated by agricultural intensification caused by the combination of population growth, the requirement for improved nutrition, and the limited reserves of land (Scherr 1999). Scherr points out that the nature and impact of intensification depends on the land type, e.g. irrigated, high-quality rainfed, marginal or peri-urban. Past research and development activities and investment have concentrated on the irrigated and high-quality rainfed lands, leading to the success of the so-called ‘‘green revolution’’.

Governments and development agencies must turn their attention and investment strategies to the problems of the marginal soils of the tropics and subtropics, particularly those areas that are densely populated. Increasing agricultural production in these areas will not only alleviate the increased demand for food as population grows, but will improve the livelihoods of the rural poor (Scherr 1999). With appropriate development strategies and a suitable policy environment, increased production can be coupled with improved management of the resource base. In this way, reduced resource exploitation, through reductions in nutrient mining, soil erosion, and SOM decline, can be coupled with improved incomes. If the correct policies are not in place, the quality of the resource base, in terms of SOM, nutrients, etc., may pass the ecological threshold beyond which land rehabilitation is irreversible, or at least not economic (Figure 1).

The marginal areas of the tropics and sub-tropics are limited by both biophysical and socioeconomic factors. Biophysically, they are marginal due to inherent infertility, particularly on the highly leached acid soils, and induced infertility, due to mismanagement by resource-poor farmers that results in high runoff and erosion. Socioeconomically, these areas are marginal as the farmers have limited resources for

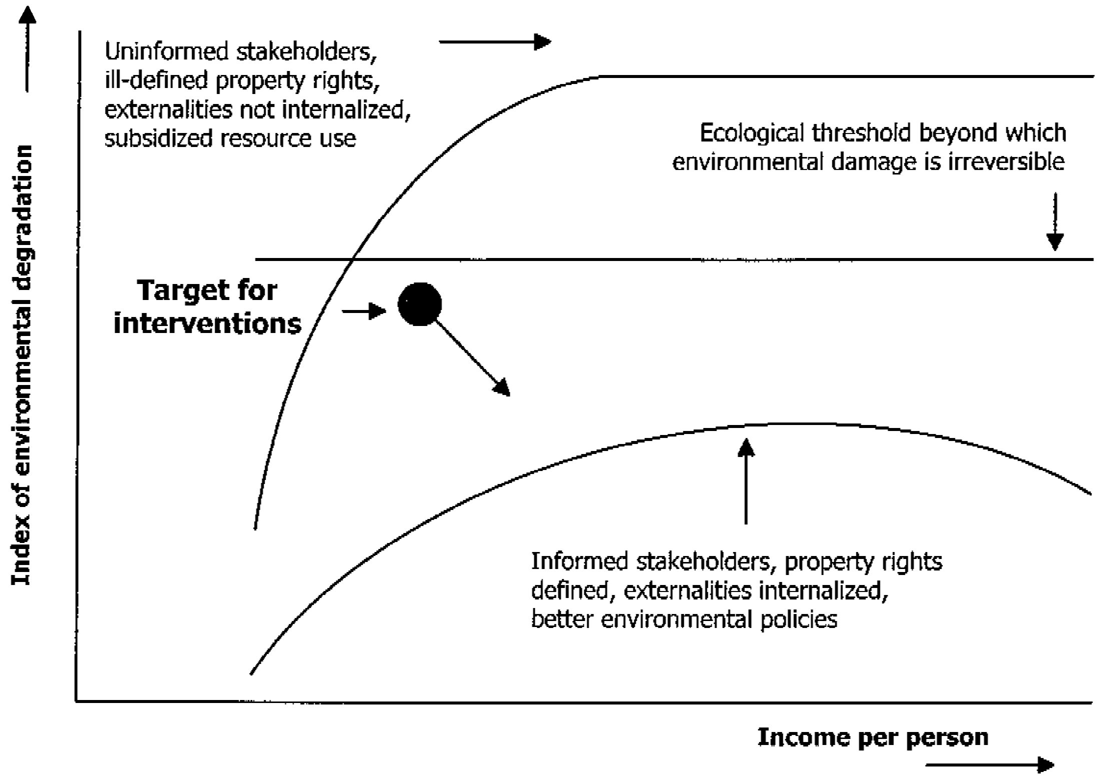

Figure 1. Environmental damage associated with different development paths leading to increased incomes (adapted from ADB (Asian Development Bank) (1997)).

improved management, frequently they have unfavourable tenurial status, and they have very poor infrastructure and services (Figure 1).

Developing farming systems that maintain good soil fertility through improved management of soil C is a major challenge at the biophysical level. The poor socioeconomic conditions under which these developments must be made increase the challenge significantly. Novel methods for supporting improvements in the farming systems of the poor need to be developed through provision of credit and other schemes that foster investment in land improvement (Scherr 1999).

The role of soil organic matter in sustainability

In light of the many well-documented functions of SOM in tropical soils discussed above, we suggest that perceptions of its roles vary greatly across the wide range of concerned clients or stakeholders. In order to utilize existing knowledge and to plan research to be more relevant, a client-oriented approach built on an understanding of these perceptions should yield useful new insights. If sustainable land management of tropical soils is the agreed overarching goal, the Framework for Evaluating Sustainable Land Management (FESLM) (Smyth and Dumanski 1993) provides a convenient basis for assessing the role of SOM in relation to management. The FESLM sets the goal of a system that combines technologies, policies, and activities aimed at integrating socioeconomic principles with environmental concerns so as to simultaneously: maintain or enhance production/services, reduce the level of production risk, protect the potential of the resource base, be economically viable and socially acceptable. These objectives – productivity, security, protection, viability, and acceptability – constitute the five pillars of the FESLM, and form convenient factors under which the management of SOM can be considered.

Productivity

Productivity, not SOM, lies at the heart of most farmers' perceptions of soil management. Many resource-poor farmers are forced by their circumstances to consider SOM as a source of nutrients to be exploited. In south and central Ghana, farmers were found to be aware of differences in SOM in terms of changes in colour and, to a lesser extent, soil structure (Quansah and Drechsel 2000). The major role they perceive for SOM is in terms of nutrient supply, although they are aware of other roles for SOM, including soil structure and water-holding capacity, and indicated the value of OM in improving structure, and thus making weeding easier. Resource-rich farmers can afford to use SOM as a key component in the management of the chemical and physical fertility of soils. As such, they may be prepared to undergo short-term reductions in productivity for longer-term gains; poor farmers cannot consider such approaches. Farmers, both rich and poor, may consider OM a source of pathogens. When this is likely, alternative methods for SOM management, with no pathogenic threat, must be developed.

Security

Soil organic matter can play an especially important role in climatically risky environments (Probert et al. 1994). SOM represents a slow release source of nutrients that mineralizes nutrients after rain. By controlling nutrient release and crop demand, available moisture in the soil can improve the synchrony of nutrient supply and demand. Thus, in dry areas, integrated nutrient management, through the use of organic and inorganic inputs and the management of SOM, can reduce the risk associated with investment in fertilizers. Furthermore, OM addition as a mulch to the soil surface, reduces the range of soil temperature extremes and reduces soil water loss due to evaporation, while associated improvements in soil structure increase infiltration and water-holding capacity. In the humid tropics, slow release of nutrients by SOM reduces the risk of leaching losses, while surface protection and improved soil structure reduce runoff and erosion risk (Probert et al. 1994).

Protection

The role of SOM in the protection of the soil resource base and the environment invokes concerns from several different perspectives. Scientists, for example, recognize the central role of OM in soil quality and use measurements of soil organic C, particularly the labile C, as indicators of sustainability (Gomez et al. 1996; Blair et al. 1995). In contrast, the non-agricultural sector may view SOM as a dumping ground for excess nutrients and toxins, as having potential for bioremediation, or as a convenient store for fossil fuel emissions, particularly CO_2(Lefroy et al. 1997). These alternative roles for SOM can be implemented in such a way as to be in conflict with sustainable agriculture, however, with care, much greater compatibility can be achieved. For instance, prudent use of the waste products of non-agricultural activities, particularly nutrients and C sources, can be used to benefit agriculture, rather than to create problems (Lefroy et al. 1997; Drechsel and Quansah 1998).

Similarly, processes for increasing C sequestration in agricultural systems may be supported actively by industries generating large amounts of CO_2, particularly with the advent of C taxes. However, current methods being developed in the fuel industry to pump compressed CO_2 directly into depleted oil and gas fields may prove more economic and of more interest as it is an intra-industry activity.

Managing SOM to reduce the sensitivity of agricultural production to climatic and other risks results in increased protection of the land resource base so that the quality of land is maintained or enhanced. Ultimately, farmer adoption of such practices will depend on trade-offs between societal goals and the needs of farmers. In many situations, it is inevitable that the adoption of sustainable land management practices by resource-poor farmers is based on short-term productivity considerations rather than long-term conservation goals.

Viability

Economic viability is valued by farmers who see OM management in terms of money, time, and labour. For this reason, many practices developed and tested on experimental stations are simply not used by farmers (see Table 1). Most experts now agree that farmer participatory approaches to research on OM management must be used as these are more likely to yield appropriate technologies. Credit and land tenure significantly affect perceptions of appropriate land management by farmers, yet control of these criteria are largely in the hands of policy-makers (Scherr 1999). Setting regulations that control the labelling of products as, for instance, ‘organically grown’, is another area in which policy makers affect trade and commodity prices, and thus sustainability (Australian Quarantine and Inspection Service (AQIS) 1998).

Table 1. Options for organic matter management in tropical production systems.

Production system	Organic matter source	Key constraints to adoption
Lowland rice	Azolla	Poor water control, labour, P fertilizer
	Green manure	Labour, cost of seed
	Rice straw compost	Labour
	Food legume rotation	Water, seedbed physical conditions
Upland food crops	Green manures	Labour, cost of seeds
	Farmyard manure	Alternative uses, labour
	Food legume intercrops	Weed control
	Grassy weed residues	Labour
	Zero till	Input costs, management skills
Hedgerow systems	Shrub legumes	Labour, land tenure
Peri-urban	Organic wastes	Transport costs, health concerns (adapted from Smyth and Dumanski (1993))

Wise implementation of such policies, particularly in relation to marketing, can increase the adoption of sustainable land management practices.

Acceptability

Many farmers in the tropics are influenced greatly by their cultural and social systems, particularly when the technologies and practices involve the use of organic wastes (Pongsapich 1998; Drechsel and Quansah 1998). Farmer participatory approaches to all stages of the research will limit the extent to which cultural and social beliefs limit the adoption of sustainable land management systems.

Improved soil organic matter management

In developing strategies with farmers for improved SOM management, an important goal is to meet as many of the criteria for sustainable land management listed above. Diverse management systems that approach the ecological diversity of natural systems are especially risk-averse, can protect the resource base, and may meet economic viability and social acceptability criteria. Thus systems that include a mix of perennial and annual crops, and a livestock component can spread the biophysical and economic/commodity risks, while reducing losses and encouraging nutrient cycling and SOM conservation.

Improved management of SOM may be achieved by attempting to mimic the natural ecosystems from which the agricultural systems developed (Lefroy et al. 1995a). One component of mimicking natural Systems involves increasing residue returns and minimizing C removal, both of which are recognized as important components of sustainable systems. This is similar to the principles of balanced nutrient management, and indicates the value of considering C in the same manner as nutrients. Another aspect of many natural systems in terms of C dynamics is the relatively continuous input of C of varying quality, as opposed to the more cyclical input of fairly uniform C in a manner that encourages rapid breakdown. The inclusion of fallows, pasture rotations, perennial components, and animals, and the move to reduced or no-till systems are all ways of moving agricultural systems closer to being mimics of natural systems. With the impact of C dynamics on the availability of nutrients and water, and the impact of nutrients and water on C cycling, it is essential that the C, nutrient, and hydrologic cycles are considered in concert.

Farmers need sustainable land management systems that maintain the OM and nutrient reserves. Many available practices, whether based on indigenous or scientific knowledge, do not meet social and economic criteria that govern farmer behaviour. Furthermore, we believe that much of the scientific knowledge on the various roles of SOM does not reach farmers and other decision-makers in a form that can be used easily. Perhaps the biggest challenge to researchers is to engage with clients to utilize new and existing information to devise decision-support systems tailored to their needs and pinpoint knowledge gaps that require further research.

Revising the research approach and agenda

Assessing research needs requires a clear understanding of the purpose of creating new knowledge, combined with a clear understanding of the requirements of the intermediate and end-users of that knowledge (Uehara 1998). The absence of this connection is illustrated by the deliberations of a policy-makers' meeting on biological nitrogen fixation (BNF), which concluded that the gap between the fundamental understanding of BNF and farmers' needs for information on this topic is widening (Kokke and Shaw 1984). In the case of SOM, scientists' understanding of the ecosystem processes has developed reasonably well, but our ability to integrate and synthesize that knowledge so that the behaviour of particular ecosystems can be predicted is not well developed. Even worse is our capacity to enable research clients to use the knowledge to influence farm management and policy decisions.

We consider that the accumulation of large arnounts of data and research results that are relatively unused by major clients, such as farmers or policy-makers, represents a serious failure by the scientific community. Enlightened policy-makers seek the best available scientific advice (Brundtland 1997), but too often our knowledge is not organized in forms that can be used readily to respond on major policy issues. Brundtland (1997) emphasized a paradigm shift towards an interdisciplinary and client-oriented approach to research. This kind of thinking is reflected in the landmark paper by Greenland et al. (1994), and forms the basis for the Soil, Water, and Nutrient Management Programme of the Consultative Group for International Agricultural Research (Craswell and Latham 1998). Increasingly, these approaches are being adopted, with the central tenet being the use of inter-disciplinary and farmer participatory approaches to research that integrate indigenous knowledge and scientific knowledge to define the research agenda.

Defining broad-scale research priorities for policy-makers and scientific institutions requires a framework that delineates areas with similar biophysical and social and economic characteristics, or resource management domains (RMDs) (Craswell et al. 1998b). The use of well-defined RMD can increase the efficiency with which technologies are transferred and practices improved. For example, research with farmers on biological soil conservation measures in the steepland areas of Asia and the Pacific (Craswell et al. 1997) provide insights that can be applied to RMDs in other areas. The characteristics of this particular RMD include infertile acid Soils, steep slopes, high erosion risk, a warm, humid tropical climate, poor farm families, often minority ethnic groups, high population growth, and poor infrastructure – which are common features of farming communities in many locations.

Developing systems that maintain good soil fertility through improved management of soil C is a major challenge at the biophysical level. New approaches to the improved management of research results and information provide new challenges and opportunities to help meet the needs of the rural poor and policy-makers. We consider that the needs for research on OM in tropical soils can be categorized in three main areas: (i) improved understanding of the role of SOM in particular agroecosystems, including the underlying dynamic biophysical and socio-economic processes, (ii) improved synthesis and management of knowledge of SOM, and (iii) improved aids to decision making for the wide range of clients. Some research activities will involve all three areas, while others will focus on only one. We consider tbe following research needs to be of particular importance:

Agroecosystem analysis

- More long-term measurements of appropriate tropical agroecosystems, including the more marginal areas, so as to improve understanding of ecosystem processes. The systems must include the necessary complexity of annual, perennial, and livestock components. This complexity is a major reason for the relatively limited knowledge base and for the need to use new experimental techniques, at the same time as being a significant component of the greater sustainability of these diverse systems.
- Wider use of improved methods for measuring total organic C and the various component C pools, particularly measures of labile C.
- Greater focus on methods for measuring specific parts of these agroecosystems for which data are lacking, such as root production and turnover, the factors that control the breakdown of organic material, and the interactions between the organic and inorganic cycles.
- More participatory research with farmers on appropriate OM management practices to determine the key biophysical, social, cultural, political, and economic factors affecting their decision-making. Such approaches must be designed to address sustainability issues, utilize inter-disciplinary approaches, and involve all clients from farmers through to policy-makers. An additional outcome will be better understanding of indigenous knowledge and of the needs of end users.
- Greater attempts to identify the limitations to broad scale adoption of improved management and

determine areas for government and non-government intervention.

Knowledge synthesis

- Improved use of databases and meta-databases of SOM research such that more of the existing data is converted into useable information and knowledge.
- Development and maintenance of geo-referenced databases of biophysical and socio-economic data, and greater use of geographic information systems and expert systems to manage and access information and to characterize RMDs.
- Development and use of models that predict the impacts of land management on SOM based on improved understanding of residue and SOM breakdown, and their controlling parameters, and of the interactions between the carbon, nutrient, and hydrologic cycles. Amongst other things, this should help to improve the synchrony between nutrient supply from organic and inorganic sources and nutrient demand for plant growth, which should increase productivity, reduce losses and associated polluting and acidifying consequences, and improve sustainability.

Decision-support systems

- Combine well-characterized RMDs and more comprehensive understanding of relationships and processes within agroecosystems to produce predictive tools that can be a framework for research planning and technology transfer and serve as user-friendly decision-support aids for farmers and policy-makers.

Much is still to be learned by scientists about the role and function of OM in tropical soils, but perhaps the most urgent challenge is to apply existing knowledge to enhance the sustainability of land management, particularly where the pressures to increase production and the restrictions on improved production are greatest – the marginal lands occupied by the poorest farming communities and productive lands threatened by massive degradation.

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