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The Biological Management of Tropical Soil Fertility
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CHAPTER 3

The importance and management of soil organic matter in the tropics

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Soil organic matter is an important regulator of numerous environmental constraints to crop productivity. Mineralisation of decomposing residues is a major source of plant nutrients in highly weathered soils with little inherent mineral fertility (Sanchez et al., 1989). The activities of microorganisms and soil fauna serve to promote soil aggregation (Oades, 1984), leading to reduced erosion (Lal, 1986) and greater moisture infiltration (Lavelle, 1988). Labile carbon compounds complex toxic aluminium and manganese species, characteristic of many highly weathered tropical soils, resulting in a more productive rooting environment (Hargrove and Thomas, 1981; Hue et al., 1986). Other important benefits resulting from the maintenance of soil organic matter in low-input agroecosystems include nutrient retention and storage (Russell, 1973; Woomer and Ingram, 1990), increased buffering capacity in low-activity clay soils (Swift and Sanchez, 1984) and an increase in their otherwise poor water-holding capacity (Lal, 1986). However, a decrease in total soil organic matter as a result of land management and increased soil aeration is an almost universal event in both the temperate regions (Cole et al., 1987; Post and Mann, 1990) and the tropics (Nye and Greenland, 1960; Ayanaba et al., 1976; Ayodele, 1986). Degradation of the soil system through soil organic matter loss results from soil tillage (Follett and Schimel, 1989) and the clearing of natural vegetation (Srivastava and Singh, 1989). Even simple land perturbations such as soil mounding in low-input systems are associated with a decline in soil organic matter (Nye and Greenland, 1960).

Overcoming soil organic matter decline is an important component in the development of more sustainable agroecosystems and the reduction of natural habitat destruction characteristic of shifting agriculture (Sanchez, 1990). The need for renewable, higher crop yields because of increasing human population pressures, the expected rise in living standards and the reduction in per capita land holding requires a greater understanding of the cropping systems themselves and a balance between human needs and environmental concerns (Swindale, 1988).

Yet in many tropical cropping systems, little or no agricultural residues are returned to the soil. This leads to a decline in soil organic matter (Lal, 1986; Bouwman, 1990b, Post and Mann, 1990; Woomer and Ingram, 1990) which frequently results in lower crop yields (Lal, 1986) or plant biomass

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productivity (Woomer and Ingram, 1990). Short of the often uneconomic and massive application of organic residues and the avoidance of burning during land preparation, few management options are available to farmers in lesser developed countries to reverse these trends. Those practices which are available include converting to less intensive tillage systems (Haines and Uren, 1990), establishing live mulches (Lal, 1986) and improving the use of resources available to the farmer.

In addition to agronomic issues, soil carbon has achieved global significance as a source of increases in atmospheric, C-based greenhouse gases (Bouwman, 1990a, b). Not all authorities agree, however. Esser (1990) suggests that there is greater C sequestering within the biosphere as a result of CO₂ fertilisation than release due to rainforest burning. This effect, however, does not minimise the consequences of natural habitat destruction.

Is soil organic matter a more important component of a productive soil system in tropical than in temperate ecosystems? In recent years, some authors have suggested that there are no major quantitative (Sanchez et al., 1982) or qualitative (Theng et al., 1989) differences between soil organic matter in temperate and tropical ecosystems. Other authors suggest that in tropical soils there is stronger metal complexation, a higher polymer nature, less importance of soil organic matter compared with the mineral fraction in aggregation effects, greater predominance of humic substance in cation retention and greater abundance of amino-acids and sugars than in temperate soils (Scharpenseel, 1988). Another distinct difference between many humid tropical and temperate ecosystems is the higher decomposition rate due to a year-round biologically active temperature regime balanced by higher primary productivity. However, decomposition in udic climates is primarily temperature regulated, while in ustic and xeric climates moisture availability and, to a lesser extent, soil pH and the nature of complexing matrices regulate soil biological activity. But the physical and chemical similarities in the soil organic matter that develops in different ecosystems may be less important than the importance of soil organic matter in overcoming individual constraints to plant productivity within an ecosystem and the loss of total system C to the atmosphere.

The Tropical Soil Biology and Fertility Programme (TSBF) considers that a detailed study of soil organic matter is essential to the efforts to develop more sustainable agroecosystems. The TSBF 'soil organic matter theme' states that 'soil organic matter can be separated into functional pools, each of which plays a particular role in nutrient release, cation exchange and soil aggregation' (Ingram and Swift, 1988; *see* Appendix 1). Furthermore, once the pools are accurately quantified, they are likely to show differences in susceptibility to land management strategies aimed at conserving plant nutrients and desirable soil physical properties.

This chapter elaborates on the importance of soil organic matter within global and ecosystem contexts, defines some of the discrete effects of soil organic matter functional pools on crucial soil processes that ameliorate the major constraints to plant productivity and identifies important environmental regulators of soil organic matter decline in agroecosystems.

THE REALITY OF CARBON 'FUNCTIONAL POOLS'

The distribution of soil organic matter within functional pools is an important consideration in developing a better understanding of soil organic matter dynamics and the diverse roles of soil organic matter in ecosystems (Jenkinson and Rayner, 1977; Molina et al., 1983; Van Veen et al., 1984; Parton et al., 1987, 1989; Jenkinson, 1990). Conceptual and computer simulation models separate soil organic matter into decomposable (or labile) and resistant fractions that are allocated between an 'active' pool (turnover times < 1 year) and a more recalcitrant pool characterised by slow turnover rates due to

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chemical or physical protection (*see* Table 3.1). This resistant pool may be divided into 'slow' pools with a turnover time of 8-50 years and 'passive' pools that remain in the soil for hundreds or thousands of years (Parton et al., 1987; Duxbury et al., 1989).

Table 3.1 Soil organic matter functional pools, their turnover times and composition

Functional pool ^a	Turnover time ^b	Composition	Alternative name
Metabolic litter	0.1-0.5 years	Cellular contents, cellulose	Plant and animal residues
Structural litter	0.3-2.1 years	Lignin, polyphenol	Plant residue
Active pool	0.2-1.4 years	Microbial biomass, soluble carbohydrates, extracellular enzymes	Labile fraction
Slow pool	8-50 years	Particulate organic matter (50 μ m - 2.0 mm)	Labile fraction
Passive pool	400-2200 years	Humic and fulvic acids, organo-mineral complexes	Humic substances

Note: a Functional pools and turnover times from the CENTURY model (Parton et al., 1987)
b Turnover times are a function of the abiotic controls on decomposition

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Some authors have questioned the usefulness of theoretical organic matter pools that cannot be physically or chemically quantified (Stevenson and Elliott, 1989). A major difficulty in validating models of soil organic matter dynamics is the inability to quantify some of these functional pools, particularly the slow pool consisting of as yet unknown physical properties and chemical composition. The active pool consists of more than the microbial biomass as determined by chloroform fumigation procedures. It also includes exoenzymes, soluble organics and metabolisable organics of low solubility. Across a range of diverse tropical agroecosystems the simulated active pool cannot be significantly correlated with microbial biomass C measurements. Nor do the chemical procedures that separate humin, humic and fulvic acids provide an accurate estimate of functional pools (Anderson et al., 1974). Physical fractionation procedures based on differential densities and sizes that separate coarse ('light') fractions from fine ('heavy') fractions provide a relationship between density or the size of the fractions and their ages (Ceri et al., 1985; Balesdent et al., 1987, 1988; Martin et al., 1990) and suggest that fractions that are 53-2000 μ m may provide an accurate estimate of the slow pool, while those finer than 53 μ m may provide an accurate estimate of the passive pool (Cambardella and Elliott, 1992). Alternatively, fractions of various densities may be recovered by density separation using sequentially heavier liquids, but this approach is time-consuming and presents difficulties when soil particles are miscible with the heavy liquid (Stevenson and Elliott, 1989). Relating functional pools to key soil processes is necessary to improve our understanding of their roles in soil fertility and changes in soil physical processes (Swift, 1986), but how can these processes be translated into improved management options if the products of these practices are themselves difficult to quantify?

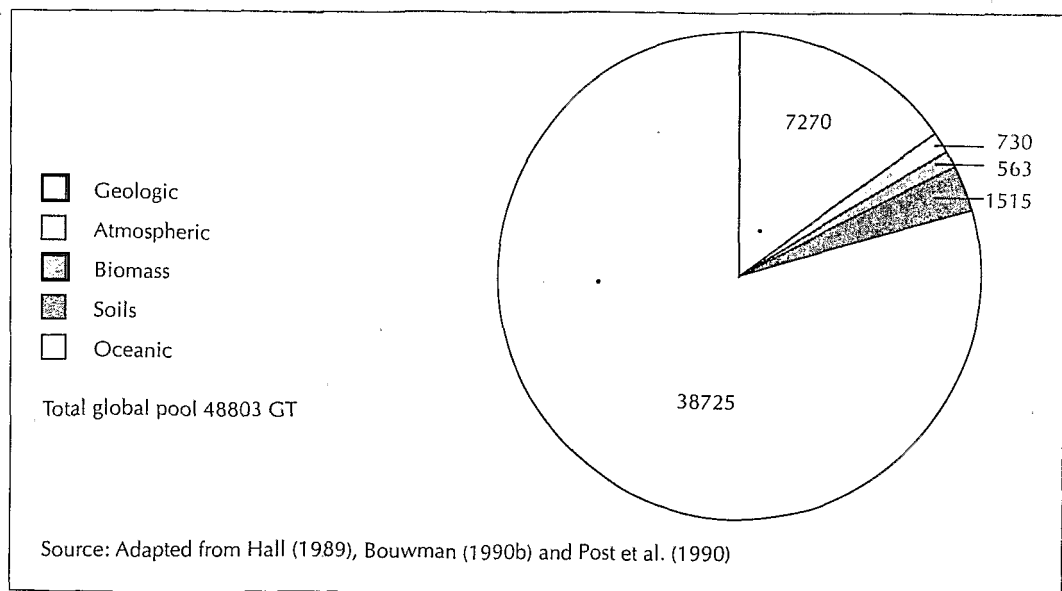
The lack of the validated existence of certain soil organic matter functional pools remains troubling to most researchers investigating and modelling soil organic matter dynamics (Stevenson and Elliott, 1989). We hope that it is a solvable methodological problem rather than an intrinsic dilemma of contradictory scientific approaches. Despite these methodological or conceptual difficulties, the rationale of soil organic matter functional pools are, in part, validated through the development of an accurate simulation of total soil C and N dynamics using models that are based upon these pools (Parton et al., 1987, 1989).

GLOBAL SIGNIFICANCE OF BIOMASS CARBON AND SOIL ORGANIC MATTER

Biomass pools and fluxes

Recent concerns about greenhouse gas emission have focused world attention on global C pools and fluxes. At present, the 0.5% annual increase in CO₂ (Hall, 1989), the 1.1% annual increase in CH₄ (Bouwman, 1990a) and the 3.0% annual addition to atmospheric chlorofluorocarbons (Bouwman, 1990b) are believed to have contributed to an increase in global temperatures of about 0.5°C in the past 100 years (Jones et al., 1988). Atmospheric C is a dynamic but relatively small global C pool (*see* Figure 3.1), currently estimated at 748 gigatons (1GT=1 billion metric tons = 10¹⁵ g) by Post et al. (1990), 99.5% of the non-particulate carbon being CO₂ (*see* Bouwman, 1990b). Bouwman (1990b) also estimates that 50% of the greenhouse warming effects may be attributed to increases in atmospheric CO₂. This does not guarantee temperature increases everywhere in the world because the

Figure 3.1 The distribution of global carbon among generalised carbon pools, indicating that relatively little carbon is atmospheric or biospheric

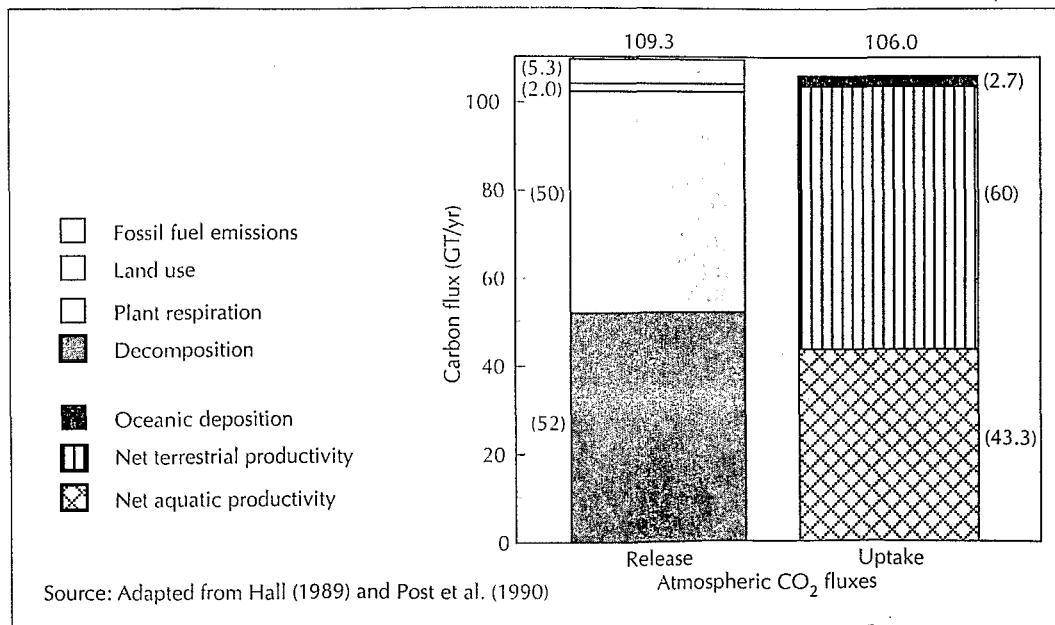


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major thermostat of global temperatures is the distribution of water vapour that may change as a result of warming trends.

The importance of atmospheric, biospheric and soil C pools is disproportionate to their relative amounts within the total C pools (see Figure 3.2). The terrestrial C pools are widely subject to management and manipulation. Losses from these pools resulting from deforestation and soil degradation directly contribute to the atmospheric increase in CO₂. Quite often, agricultural practices that maximise yields also accelerate this depletion of terrestrial C pools, which results in falling crop yields in absence of fertiliser inputs (see Chapter 9). Recent emphasis on agricultural sustainability demonstrates an awareness that conventional management strategies leading to a continuous reduction in terrestrial C assets may be detrimental to the future of humankind, despite shorter-term yield increases.

Figure 3.2 Annual atmospheric CO₂ fluxes, indicating that there is currently an annual imbalance of approximately 3.3 GT



Calculations of biotic and soil C in the tropics are crude estimates, mainly because of the incompletely documented array of ecosystems and the variety of land uses practised within each of these ecosystems. The renewal of terrestrial C pools in agroecosystems is of crucial importance. In temperate Europe, well-managed croplands are capable of an annual productivity equal to or greater than those of natural plant communities (about 450 g/m²/yr) (Esser, 1990). Large portions of food crops, however, are respired by consumers and residues may be burned or removed from the cropping system. Even when large quantities of high-quality (nutrient-rich) materials are applied to soils, a net C loss may result from a nutrient priming effect (Jenkinson, 1966).

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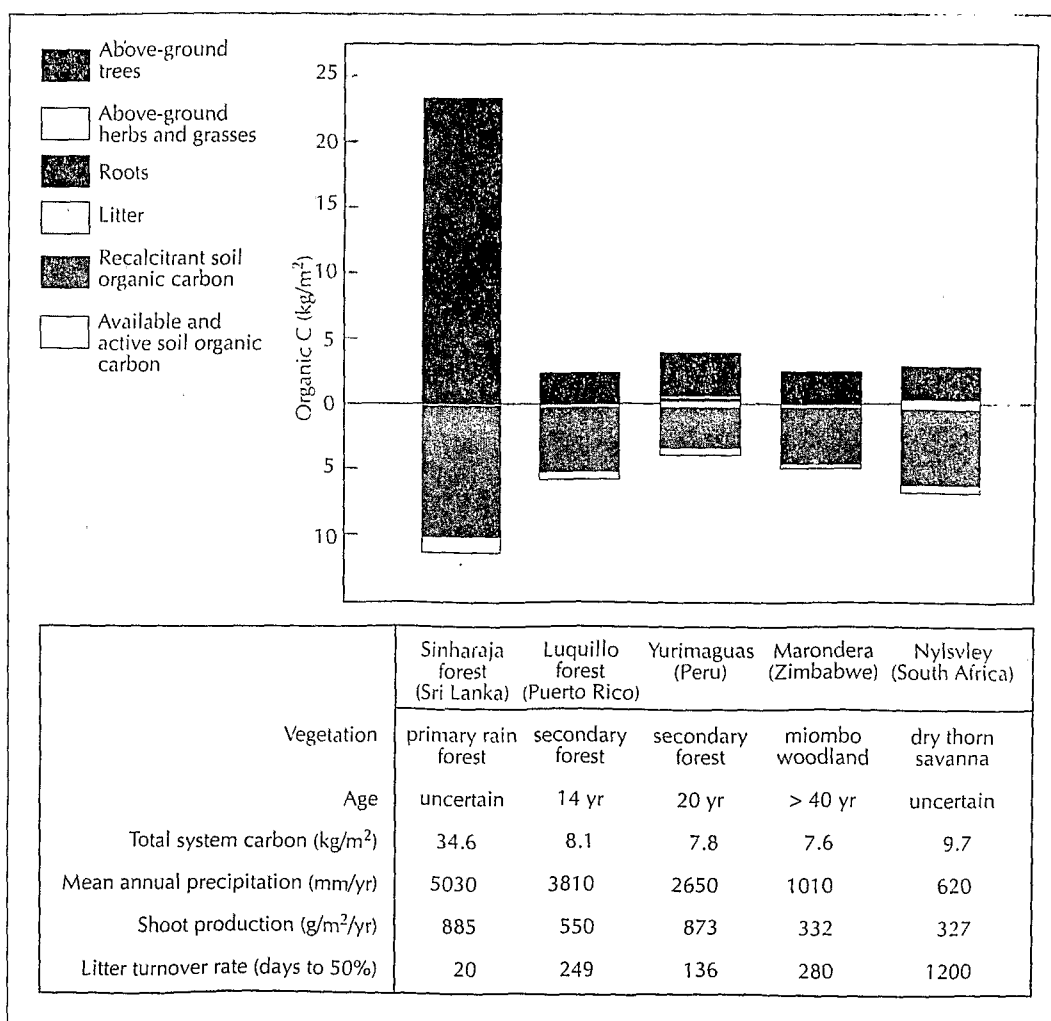
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Carbon partitioning in tropical ecosystems

Natural ecosystems

The quantities and partitioning of total system C in diverse tropical forest, woodland and savanna ecosystems are presented in Figure 3.3. The ability of primary rainforests to store biomass in living tissues is apparent in the large differences between the C storage in the Sinharaja Forest Reserve, a primary rainforest, and other forest ecosystems studied by TSBF. Of the forest sites featured in this figure, the primary rainforest has the greatest above-ground annual productivity, storage of biomass

Figure 3.3 Carbon partitioning in primary and secondary forests, indicating that the carbon storage in previously disturbed forests may be considerably reduced

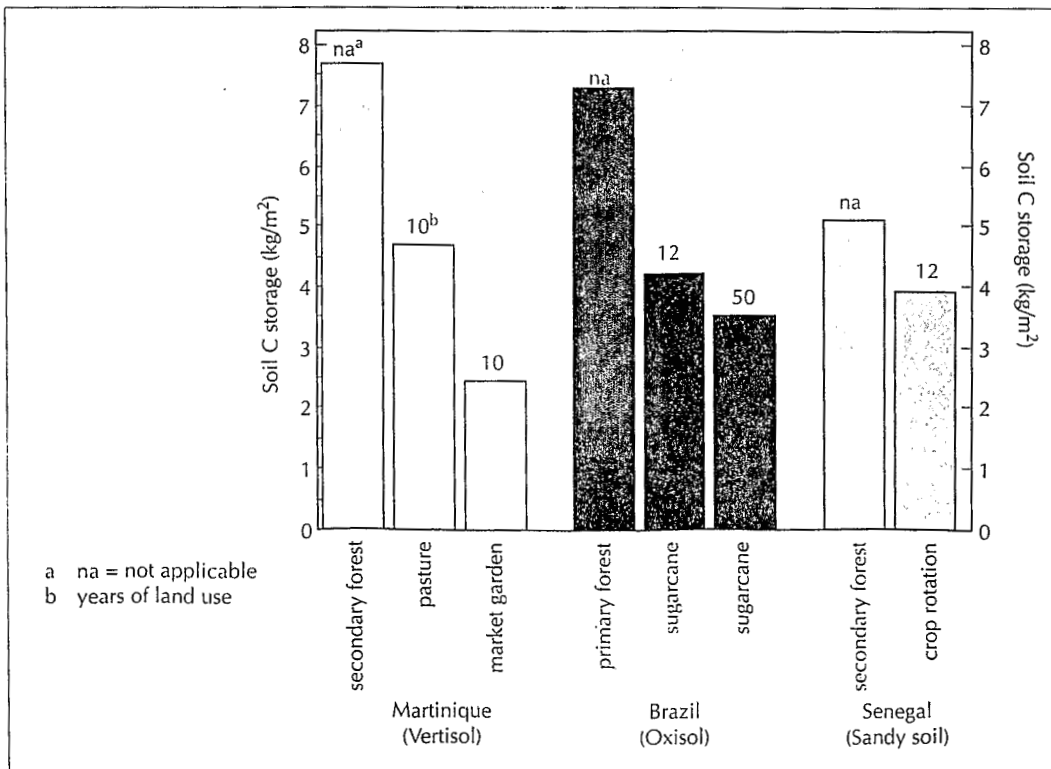


and soil C and 'available and active' soil organic C, as well as the most rapid rate of litter turnover. When standing vegetation and soil are compared, only the primary rainforest stores more C as plant biomass than soil. Secondary tropical forests acquire similar quantities of organic carbon across a diverse range of annual precipitation patterns and forest formations. Young secondary forests accumulate less than 25% of the C measured in primary rainforests. The carbon storage in dry miombo woodlands (Marondera, Zimbabwe) and dry thorn savannas (Nylsvley, South Africa) is greater than that of the secondary tropical forests despite reduced net above-ground productivity. The regulatory role of soil moisture on decomposition rates allows for increased storage of C in the litter layers and soils despite lower net productivity in semi-arid environments.

Managed ecosystems

The conversion from natural to managed ecosystems generally induces a substantial decrease in soil C storage (see Figure 3.4). The storage of soil C in long-term cropping systems in the tropics (sugarcane, crop rotation, market gardening) is often only 50% of the natural ecosystem. On the other hand, the development of a permanent grass cover results in greater soil C storage within pastures,

Figure 3.4 Soil carbon storage in different agroecosystems compared with their respective natural conditions



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mainly because of high C inputs from the roots. The dynamics of soil organic matter in managed soils of the tropics will be elaborated upon in later sections of this chapter.

ORGANIC CARBON DYNAMICS IN TROPICAL SOILS

Characterisation of soil organic matter

Soil organic components may be characterised on the basis of their main components in terms of density, size and chemical properties (*see* Chapter 2). The simplest method of characterisation is strictly chemical, based on determining, for example, total organic C and total N. These simple analyses may be combined to produce the C/nutrient ratio which serves as an estimate of soil organic matter availability as a source of plant nutrients through decomposition and subsequent mineralisation (Mellilo et al., 1982, 1989). More sophisticated soil organic matter characterisation requires combined physical fractionation and chemical analyses (Stevenson and Elliott, 1989). Further sophistication in characterisation is achieved through the use of isotope-labelled materials in order to study transformations within the soil.

The chemical procedures that separate humin, humic and fulvic acids (Anderson et al., 1974) do not provide as accurate a distinction between soil organic matter fractions as that provided by radiodating, irrespective of the age of these fractions (Stout et al., 1981). Physical fractionation of organic matter provides better insight into soil organic matter dynamics. Briefly, physical fractionation of organic matter involves disruption of the soil structure by shaking or sonication and the separation of organic fractions according to density (Sollins et al., 1984), wet sieving and/or sedimentation (Cameron and Posner, 1979; Feller, 1979; Tiessen and Stewart, 1983; Anderson and Paul, 1984). Coarse fractions consist mainly of undecomposed plant debris with high C/N ratios, whereas the fine fractions associated with fine silt and clay consist of heterogeneous organic compounds with low C/N ratios. Radioisotope (^{14}C) dating of particle size organic fractions (*see* Table 3.2) indicate that the older fractions in soil organic matter are associated with coarse clay (Anderson and Paul, 1984). Studies of soil organic matter decomposition using ^{13}C natural labelling have shown that the highest

Table 3.2 Radioisotope (^{14}C) dating of particle size fractions of soil organic matter in a Haploboroll soil

Fraction	Size (μm)	Age (yr)	C/N
Plant debris	200-2000	0-30	} 13-40
	50-200	?	
	5-50	800	
Organo-mineral complexes	2.0-5.0	965	} 6-10
	0.2-2.0	1255	
	0-0.2	170	
Total		795	10

Source: Anderson and Paul (1984)

turnover rates are associated with coarser fractions, while the finest fractions result from a combination of labile and stable components (Vitorello et al., 1989; Bonde, 1991).

Functional components of soil organic matter

Dating soil organic matter

Soil organic matter consists of a continuum of components (Mellilo et al., 1989), ranging from labile compounds that mineralise rapidly during the first stage of decomposition to more recalcitrant residues that accumulate as they are deposited during advanced stages of decomposition as microbial by-products (Duxbury et al., 1989). The turnover rate of the labile and stable pools of organic matter vary from a few months to several thousand years. Radiodating of recent soils has revealed the existence of extremely old residues (> 9000 years) in many soils of the world, suggesting that some fractions are extremely resistant to decomposition (Stout et al., 1981). In most soils, humic substances represent most of the soil organic matter (60-80%). Data from combined physical fractionation of soil organic matter and radiodating or ^{13}C natural labelling indicate that the stable pool of soil organic matter is found mainly in the fractions associated with fine silt and coarse clay (20-0.2 μm) (Scharpenseel, 1971; Balesdent et al., 1987, 1988; Martin et al., 1990). The age of humus C in some paleosols exceeds the dating range of the ^{14}C method. Recently, ^{13}C natural labelling of soil organic matter resulting from the shifting of vegetation patterns between C_3 and C_4 photosynthetic pathways gave precise estimates of the long-term turnover rate of the soil organic C under *in situ* conditions, suggesting that soil organic matter dynamics is more rapid in tropical soils than in temperate soils (see Table 3.3). Similar patterns have been established for more immediate decomposition of plant residues with ^{14}C labels under laboratory conditions (Jenkinson and Ayanaba, 1977).

Table 3.3 Estimates of soil organic carbon (SOC) mineralisation rates using ^{13}C natural labelling

Site	Land use	MR of SOC ^a	Reference
Auzeville, France	Maize cropping (Eutrochrept)	22% in 13 years	Balesdent et al. (1987)
Doazit, France	Maize cropping (Haplualf)	19% in 23 years	Balesdent et al. (1987)
Piracicaba, Brazil	Sugarcane cropping (Haplustox)	51% in 12 years	Cerri et al. (1985)
Piracicaba, Brazil	Sugarcane cropping (Haplustox)	70% in 50 years	Cerri et al. (1985)
Lamto, Côte d'Ivoire	Woodland (Alfisol)	60% in 16 years	Martin et al. (1990)

Note: a Relative mineralisation rate of carbon derived from the previous vegetation

Labile components of soil organic matter

Labile soil organic matter consists of rapidly mineralised components with turnover rates ranging from a few days to a few years. The most labile components are cellular contents, such as carbohydrates, amino-acids, peptides, amino-sugars and lipids. Labile soil organic matter also includes less readily metabolised structural materials, including waxes, fats, resins, lignin and hemicellulose. Part of the labile soil organic matter consists of microbial metabolites and biomass, which can be estimated through fumigation-incubation (Jenkinson and Powlson, 1976; Jenkinson and Ladd, 1981) or fumigation-extraction (Vance et al., 1987) techniques. The labile pool also contains some rather recalcitrant plant residues.

Labile soil organic matter plays a key role in the maintenance of soil fertility as a source of plant nutrients due to its chemical composition and rapid turnover rate. Microbial biomass is of particular importance, acting alternatively as a source or sink for nutrients (Duxbury et al., 1989; Singh et al., 1989). The macroclimate, principally soil temperature and moisture, regulates the rates of decomposition of labile soil organic matter (Jenkinson and Ayanaba, 1977) and the equilibrium in soil microbial biomass (Insam et al., 1989). In the humid tropics, isothermic and isohyperthermic temperatures and uniform soil moisture availability maintain high rates of microbial metabolism and increase the turnover of the labile components of soil organic matter (Duxbury et al., 1989).

Humic substances

The most recalcitrant components of soil organic matter are highly polymerised humic substances, resulting from decomposition of plant debris (lignin-like substances) or condensation of soluble organic compounds released through the decomposition of sugars, amino-acids, polyphenols and lignin (Duchaufour, 1977; Stevenson, 1982). Humic acid represents a significant part of this fraction as a recalcitrant end-product of microbial activities transformed from plant and animal detritus (Stout et al., 1981). The climatic conditions of soils have a significant influence on the chemical properties of humic substances, with more aliphatic compounds accumulating in tropical soils (Lobartini and Tan, 1988). The mechanisms of this phenomenon are presently being studied using combined ¹³C-NMR-spectrometry analysis of aromaticity.

The resistance of humic substances to microbial degradation stems from both the physical configuration and the chemical structure of humic substances. These substances are physically protected from microbial decomposition by complexation with clays, mineral colloids (Edwards and Bremner, 1967; Oades, 1984), localisation within the soil microaggregates stabilised within macroaggregates by fine roots and hyphae (Tisdall and Oades, 1982) and the temporary metabolic inhibition of microbes. As a result, the synthesis of the humic substances is largely controlled by soil texture and structure.

Mineralogy is often dominated by metal oxides (Al and Fe) and kaolinite in highly weathered tropical soils. Cycles of soil drying and wetting in the dry tropics accelerate soil organic matter decomposition (Ladd et al., 1977), probably by disrupting microaggregates and physically protected organic matter complexes, although they also tend to reduce microbial populations (Bottner et al., 1985). As a result, humic components of soil organic matter may be less abundant in tropical soils than in temperate soils.

The contribution of humic substances to nutrient release remains unquantified and poorly defined. This is because of the relatively long turnover times of these substances and the specialised, localised

decay of organo-mineral complexes (Anderson and Flanagan, 1989). Nevertheless, the stable pool of soil organic matter remains very important in the biological amelioration of the constraints to plant productivity. Humic substances provide large reactive surfaces and play a significant role in soil aggregation and cation retention. This last property is of particular importance in oxidic soils where soil organic matter is the only major fraction with a negative charge (Scharpenseel, 1988).

Origin and diversity of soil organic components

Soil organic matter consists of diverse, heterogenous components. Theng et al. (1989) reported that living C rarely exceeds 4% of total soil organic C and is present as roots, microorganisms and soil fauna. Non-living C represents the major portion of organic C, consisting of surface litter, root litter, microbial metabolites and humic substances. The living and non-living C components constantly interact, as do the saprophytic organisms that acquire metabolites from non-living C in the soil and then die.

Part of soil organic matter consists of carbohydrates, lipids and proteins that are abundant in fresh plant residues. These are rapidly metabolised, immobilised or decomposed. These processes are better defined than are those associated with older materials such as humic residues consisting of highly condensed aromatic polymers (Scharpenseel, 1988). But, contrary to earlier theories of the association between humic substances and aromatic building stones, ¹³C-NMR-spectroscopy indicates that the aromaticity of humic substances varies and that metabolites of polysaccharides are capable of becoming stabilised in soil.

ENVIRONMENTAL REGULATORS OF SOIL ORGANIC MATTER DECLINE IN TROPICAL ECOSYSTEMS

A database was assembled based on site characterisation and experimental results provided by cooperators in the TSBF programme. The many scientists contributing to this database are given in Appendix 2. Use of the database for cross-site comparison is particularly valid in that the site data were compiled using standardised methods (Anderson and Ingram, 1989). The database also includes selected data from the Maui Soils, Climate and Land Use Network (Woomer et al., 1988), part of which is coordinated by the Nitrogen Fixation by Tropical Agricultural Legumes Project (NifTAL) at the University of Hawaii's Department of Agronomy and Soil Science. Most of the Maui data were obtained from the USDA Soil Conservation Service (USDA, 1984) and Ikawa et al. (1985).

Parameter ranges and the number of entries of key site variables on this database are presented in Table 3.4 (*overleaf*). The database was stored in ASCII format, and subsequent analyses were performed using commercially available statistical software packages (Wilkinson, 1988). Correlation matrices were developed using Pearson pairwise analysis, and multiple linear regression equations were constructed through the stepwise regression of independent variables.

Carbon pool sizes and turnover rates in natural and managed ecosystems

Carbon pools and turnover rates in sub-humid and semi-arid ecosystems are presented in Table 3.5 (*overleaf*). Woodlands and savannas exhibited greater storage of soil C (despite lower C inputs) than

Table 3.4 Ranges in site characteristics and number of observations of selected data in the TSBF study of soil organic matter decline in tropical sites

Parameter	Range	Number of observations
Annual shoot production	0.204-1.328 kg C/m ²	16
Initial soil C	2.6-15.8 kg C/m ²	19
Decline in soil C	-1.16-7.09 kg C/m ²	19
Microbial biomass	24-183 g C/m ²	16
Initial soil N	0.06-0.18%	16
Mean annual precipitation	0.32-3.81 m/yr	20
Mean annual temperature	15.8-29.7°C	19
Soil pH (1:2.5 H ₂ O)	4.4-8.2	19
Clay content	2.5-52.0%	18
Bulk density	0.42-1.50 g/cc	20
Cation exchange capacity	3.1-72.7 cmol/kg	18

Table 3.5 Carbon pools in sub-humid and semi-arid tropical ecosystems under different land uses

	Forest ^a	Savanna ^{a, b}	Cropped ^a	Extended bare fallow ^b
Soil organic C (kg/m ²) ^c	3.758	4.805	1.730	1.035
C inputs (kg/m ² /yr)	0.205	0.231	0.300	0.070
Turnover (yr) ^d	18.33	20.80	5.77	
Microbial C (kg/m ²)	0.172	0.153	0.047	0.045
C inputs/microbial C	1.19	1.51	6.43	1.54

Note: a TSBF sites (see Woomer and Ingram, 1990)
 b Sites of the Maui Soils, Climate and Land Use Management Network, University of Hawaii (see Woomer et al., 1988)
 c 0-20 cm
 d Number of years of C inputs required to equal observed soil C pool

adjacent agroecosystems, and extended bare fallow further reduced soil C content. In forest, savanna and bare fallow soils, the C inputs/microbial C ratio was relatively low (between 1.19 and 1.54), whereas cropped systems had greater microbial activities.

The data for cropped systems in Table 3.6 are from TSBF sites in the lowland humid tropics (see Woomer and Ingram, 1990). Carbon inputs were greater in the humid tropics than in the sub-humid and semi-arid regions. This greater input did not lead to higher soil organic C levels, because of the more rapid turnover rates and increased microbial activities which are inferred from the higher ratio of C inputs to microbial biomass C. Under cultivated conditions (see Table 3.6), a smaller microbial biomass more rapidly processed crop litter but, as total soil organic C declined, so did the biomass of its active fraction. It is worth noting that land disturbance resulted in decreased soil microbial biomass and increased turnover rates of soil organic matter. When a comparison was made between adjacent

Table 3.6 Carbon pools in lowland humid tropical ecosystems under different land uses^a

	Forest	Plantation	Cropped
Productivity (kg/m ² /yr)	1.062	1.086	1.076
Soil organic C (kg/m ²)	4.37	3.71	2.77
C inputs (kg/m ² /yr)	0.520	0.573	0.538
Turnover (yr)	8.4	6.47	5.15
Microbial C (kg/m ²)	0.103	0.087	0.078
C inputs/microbial C	5.06	6.59	6.92

Note: a TSBF sites (see Woomer and Ingram, 1990)

Table 3.7 Coefficient of linear regression interrelating the decline in soil carbon and nitrogen pools as a result of soil management

Decline in	Coefficient of linear correlation (r) ^a		
	Decline in soil C	Decline in microbial C	Decline in total N
Microbial C	0.69**	—	—
Total N	0.08	-0.14	—
Nematodes	0.80*	0.76*	-0.31

Note: a * $p \leq 0.05$; ** $p \leq 0.01$

natural and managed ecosystems, and the declines in soil C pools regressed with one another, there was a significant correlation between soil organic C and microbial biomass (see Table 3.7). Changes in total nematode populations covaried with the declines in total soil organic C and microbial C. Population sizes of soil microfauna responded quickly to changes in soil physical properties and availability of substrate.

Declines in total soil C and microbial soil C covaried significantly ($p = 0.05$), as shown in Table 3.7). However, these results must be viewed with some caution as total organic C and microbial biomass comparison represent a whole-part relationship. Microbial biomass is a small component of the total C of humid lowland forests and sub-humid croplands (for example, 4.5% and 2.7%, respectively).

Values of selected ecological parameters observed in managed ecosystems were autocorrelated with those in adjacent natural ecosystems (see Table 3.8 *overleaf*). As shown in the table, the initial size of C pools, microbial biomass and nematode populations significantly influenced the respective decline in these parameters. This is not surprising when stated thus: the size of a pool determines the potential decline of that pool. The covariance of the relative decline in soil organic C and microbial biomass with selected site parameters provides another approach to cross-site comparisons (see Table 3.9 *overleaf*). The proportion of soil organic C lost from the managed ecosystems covaried significantly ($p > 0.05$) with mean annual precipitation, soil pH and clay content. Relative declines in microbial biomass C covaried negatively with mean annual temperatures and positively with soil pH, clay content and CEC.

Table 3.8 Coefficient of linear regression relating the decline in soil pools as a result of soil management to the initial sizes prior to land clearing

	Coefficient of linear correlation (r) ^a		
	Decline in total soil C	Decline in microbial C	Decline in nematodes ^b
Total soil C	0.51*	0.14	0.56
Microbial C	0.26	0.78**	0.59
Soil N	0.33	-0.05	0.62
Nematodes	0.83*	0.72	0.99

Note: a * $p \leq 0.05$; ** $p \leq 0.01$
 b Nematode data were obtained from only six sites

Table 3.9 Coefficient of linear regression relating the decline in soil organic matter and microbial biomass to selected environmental parameters

Parameter	Coefficient of linear correlation (r) ^a	
	Relative decline in soil organic C	Relative decline in microbial biomass C
Mean annual precipitation	-0.47*	-0.31
Mean annual temperature	-0.23	-0.74**
Soil pH	0.67**	0.67*
Clay content	0.76***	0.63*
Bulk density	0.05	-0.27
Cation exchange capacity	0.43 ^b	0.65*

Note: a * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$
 b $p = 0.08$

Declines in total soil organic C in two contrasting ecosystems, humid lowlands and sub-humid woodland savannas, were observed following the disturbance of natural vegetation (*see* Tables 3.5 and 3.6). The establishment of agroecosystems reduced soil C storage because of increased microbial activities and more rapid turnover of C inputs. Mean C inputs were relatively constant within ecosystems which occurred in similar moisture regimes: 0.205-0.300 kg/m²/yr in sub-humid woodlands, savannas and croplands; and 0.520-0.573 kg/m²/yr in humid lowland forests, plantations and croplands.

Additional data suggest that these declines may be long-term trends, as illustrated in the data for the C content of adjacent natural and managed ecosystems presented in Table 3.10. Twelve years after the replacement of secondary forest with teak at the Ticoporo site in Venezuela, soil C storage was 33% below the original forest level. Sanchez (1987) presents evidence that, for a similar plantation, soil C storage levels re-attained those of natural vegetation after 60 years. In an Australian Brigalow woodland soil 55 years after the establishment of pasture and high-input wheat cropping, C storage declined by 55% and 65%, respectively (Woomer and Ingram, 1990). In a related study in Australia, Dalal and Mayer (1986) found that most of the C loss from soils was associated with the larger particle

.lit of soil

Table 3.10 Decline in soil organic carbon at TSBF sites as a result of land management

Ecosystem	Total soil organic C (kg/m ²)
Venezuela	
Deciduous Andean rainforest	6.03
Cleared 12-year-old teak forest	4.39
Australia	
Brigalow dry woodland	4.50
After <i>Chloris</i> pasture (55 years)	2.03
After wheat (55 years)	1.58

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size fractions (sand and silt). The results of these and other investigations (Lal, 1986; Persson and Mattsson, 1988; Follett and Schimel, 1989; Srivastava and Singh, 1989; Post and Mann, 1990) illustrate the declines in soil organic C and microbial biomass C that are associated with land clearing and subsequent management. While this phenomenon is well documented, the processes are not well understood because of the variety of land use strategies involved.

Insam et al. (1989) and Insam (1990) developed predictive relationships between climatic and environmental variables and the microbial C/soil C ratio. Precipitation, evaporation, pH and clay percentage accounted for 75% of the observed declines. These relationships were developed for soils that had reached a steady state of soil organic matter, and the authors proposed that deviation from this equilibrium served as an indication of a soil system's gain or loss in organic matter. In the present study, we have found that clay content and pH are also related to the microbial C loss from disturbed and managed ecosystems when compared with their natural counterparts.

Prediction of soil organic matter losses as a result of land management

The observed losses in soil organic C from managed ecosystems were greater in semi-arid environments than in the humid lowlands. This suggests that a larger portion of the soil organic matter in natural ecosystems of semi-arid regions is less recalcitrant than is the case in more humid tropical soils. However, estimates of microbial activities in cropped soils of semi-arid regions resemble those of more humid ecosystems. Microbial communities in the humid tropics process available organic substrate more rapidly than in semi-arid regions (*see* Table 3.6). A multiple regression equation predicting the relative loss of C due to the disequilibrium imposed by land management was derived. The relative loss of carbon (C_{loss}) was estimated as:

$$C_{\text{loss}} = 0.16 - (0.09 \text{ MAR}) + (0.01 \text{ Clay } \%) \quad \text{Adj } R^2 = 0.68, p < 0.001$$

where:

$$C_{\text{loss}} = (C_{\text{initial}} - C_{\text{final}}) / C_{\text{initial}}$$

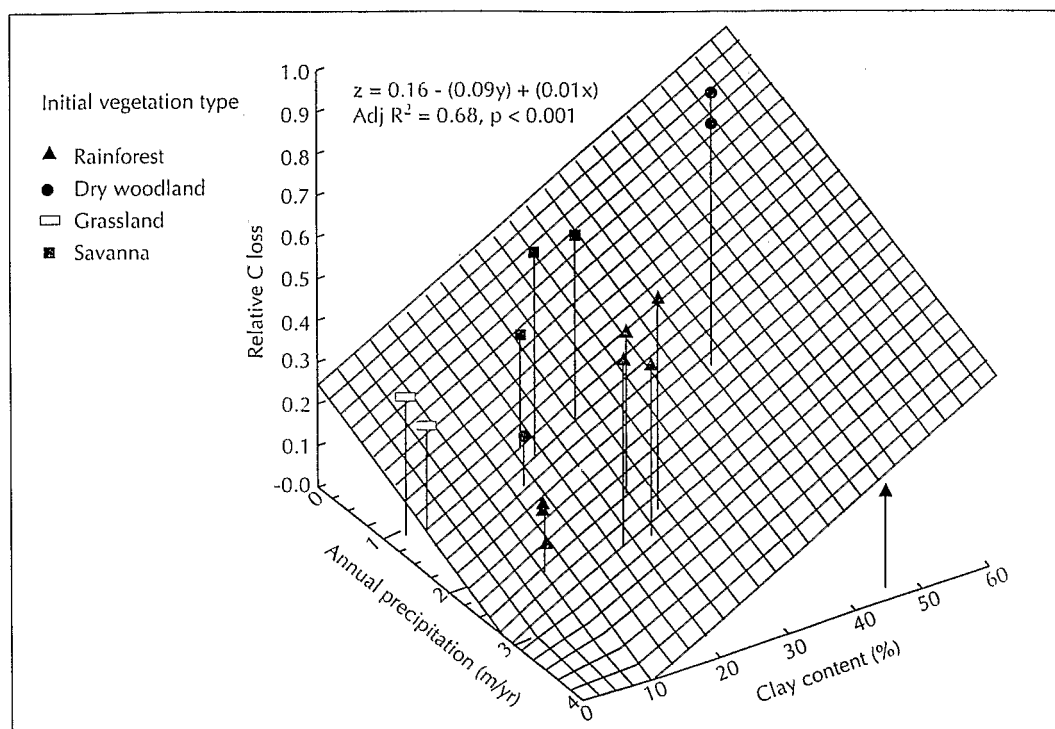
MAR = mean annual rainfall (m/yr)

Clay = percentage of soil particles < 0.002 μm in diameter

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This relationship is plotted in Figure 3.5. The deviation of the observed and predicted values are plotted in Figure 3.6a. There is no clear pattern of deviation by original vegetation type and, from the scatter, this relationship must be regarded as approximate. Fortunately, the simplicity of the relationship could be used with current georeferenced databases for predictive mapping. Much of the tropical land cleared of natural vegetation is placed into low-external-input systems. The relationship may therefore be useful in estimating CO₂ contributed to the atmosphere from soils recently brought into cultivation, thus improving our predictive abilities on global change issues, identified as an important priority by the International Geosphere-Biosphere Programme (IGBP, 1990).

Figure 3.5 Relative loss of soil organic carbon as a result of land management after the transition from various natural ecosystems as a function of annual precipitation and soil clay content



Another multiple linear regression equation was developed to estimate the carbon loss from field soils on an absolute (kg/m²) basis (C_{loss}) due to land management:

$$C_{\text{loss}} = -0.55 + 0.26 C_{\text{init}} + 0.055 \% \text{ Clay} - 0.49 \text{ MAR} \quad \text{Adj } R^2 = 0.66, p < 0.001$$

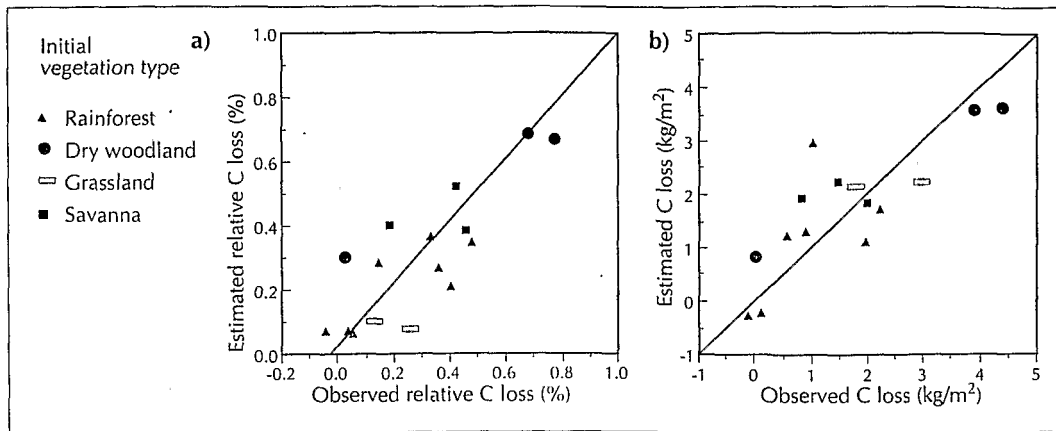
where:

C_{init} = C storage within the natural ecosystem (kg/m²)

MAR = mean annual precipitation (m/yr)

Clay = percentage of soil particles < 0.002 μm in diameter

Figure 3.6 Relative (a) and absolute (b) observed and estimated carbon losses from soils as a result of land disturbance, based on annual precipitation and soil clay content



The agreement between observed and estimated carbon losses is presented in Figure 3.6b. The relationships between soil C loss upon conversion from natural to cultivated conditions with precipitation and soil texture appears at first to be counter intuitive. But it must be remembered that organic matter which forms under more humid conditions has been exposed to a greater intensity of decompositional processes prior to land clearing and cultivation. Furthermore, clayey soils have a greater surface area and are less aerated than sandy soils, resulting in greater physical and chemical protection of decomposable organic matter within soil aggregates in the clay soil. In a sandy, humid soil there is less readily decomposable organic matter likely to be lost upon land disturbance than in a dry, clayey soil. Again, this must be regarded as a first-generation approach, and is best applied in broad-based estimation rather than in interpreting finer resolution studies. Simulation models (Parton et al., 1987, 1989) provide a more detailed and instructive predictive tool when adequate data for model initialisation are available (see Chapter 7).

DECLINE IN SOIL ORGANIC MATTER AS A RESULT OF LAND MANAGEMENT

Soil organic matter is not a direct requirement for plant growth. Rather, its amelioration of other direct constraints to plant performance provides an improved rooting environment. The direct soil-based constraints to plant performance include nutrient and water availability and plant toxicities. Soil organic matter dynamics and the interactions between plant constraints result from a series of plant, microbial and physicochemical processes. Decline in soil organic matter as a result of land management strategies, particularly excessive removal of crop residues and soil disturbance, has an array of negative effects on plant productivity.

Soil organic matter amelioration of constraints to crop production

The ameliorative effect of soil organic matter on the principal soil constraints to crop production is illustrated in Figure 3.7 (*overleaf*) (Swift and Woomer, 1993). The production and deposition of

values are from the relationship may be important

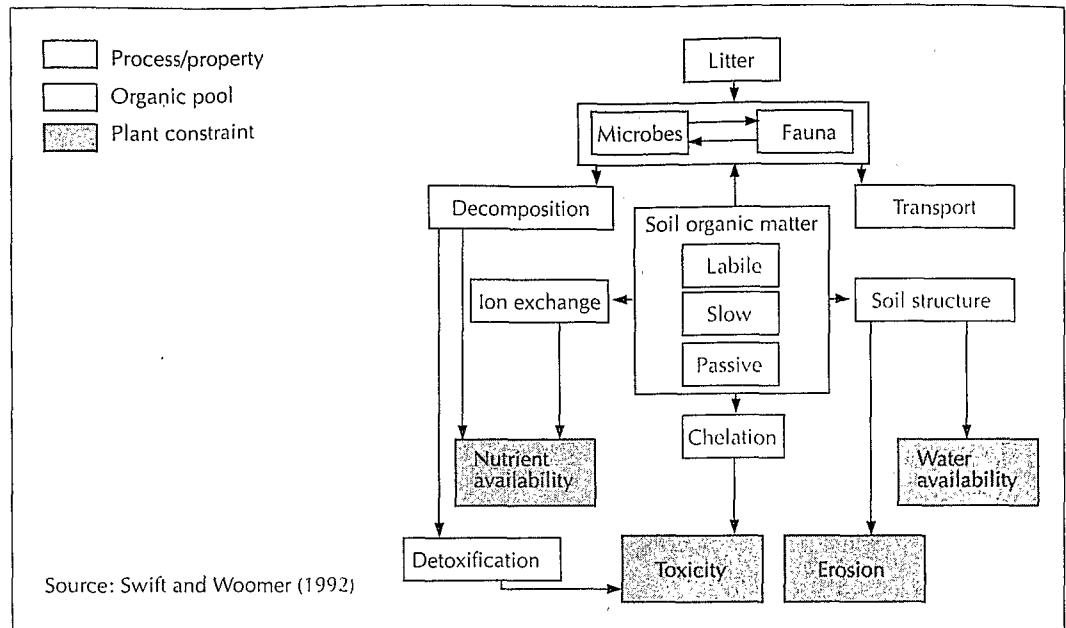
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Figure 3.7 The relationship between organic inputs, soil organic matter functional pools, key soil biological processes associated with different soil organic matter pools and soil constraints to crop productivity



organic materials provide substrate for microbial processes and the accumulation of soil organic matter. The processes associated with the incorporation and transformations of soil organic matter directly affect the constraints to plant productivity: acidity and plant toxicities, soil erosion and nutrient and water availability, especially in low-activity clay soils. Soils have a lower water-holding capacity, which is greatly improved by soil organic matter. Individual soil processes have a specific impact on one or many of these constraints. These processes include soil faunal activities, decomposition, detoxification and soil structure formation. The interdependence of these processes and their selective impact on soil constraints suggest that the manipulation of soil biological processes to improve soil fertility is a viable but often overlooked management strategy.

Soil faunal activities

The effects of soil faunal activities on soil constraints to crop production are presented in Figure 3.8. In the soils of the humid tropics, soil faunal activity may affect both labile and stable pools of soil organic matter (see Chapter 6). Litter-feeding organisms such as epigeic termites (Lee and Wood, 1971) and epigeic earthworms (Lavelle, 1978) may influence the dynamics of labile soil organic C by preventing litter accumulation (Stout et al., 1981; Anderson, 1988; Jones, 1990), including comminution, enhancing C and N mineralisation through metabolic processes (Cheshire and Griffith, 1989; Martin, 1991) and nutrient release. Macroorganisms may also control the dynamics of stable soil organic C through their interactions with soil microbes. The release of C substrate by root exudation

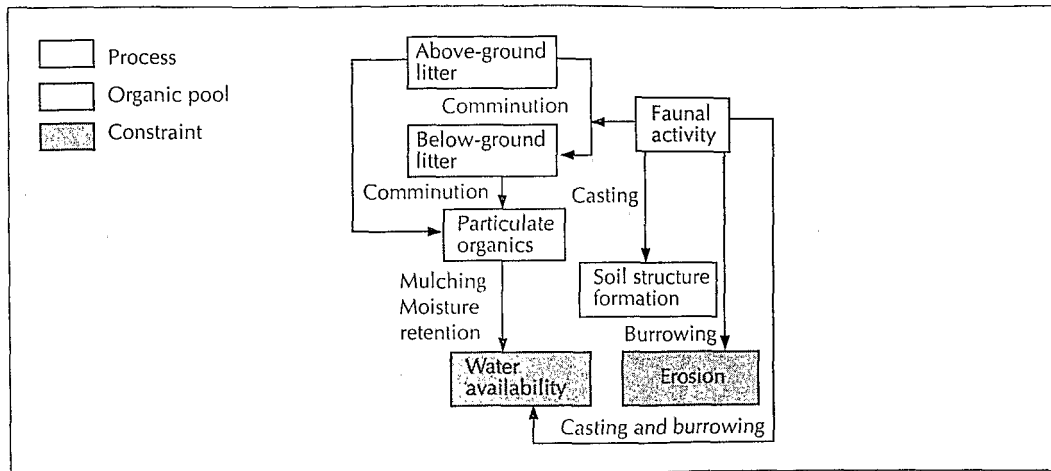
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(Clarholm, 1985), termites (Abbadie and Lepage, 1989) or earthworms (Barois and Lavelle, 1986) enhance local microbial activity and induce the mineralisation of organic fractions that normally would be resistant to microbial degradation. The activity of soil macroorganisms may thus accelerate, on a small spatial and temporal scale, the turnover of the stable pool of soil organic C through priming effects (Jenkinson, 1966). On the other hand, soil-feeding fauna may enhance soil aggregation through casting and significantly reduce long-term C mineralisation (Martin, 1991) through the physical protection of organic matter in casts (Blanchart et al., 1989, 1991; Shipitalo and Protz, 1989). Faunal burrowing also results in improved water infiltration (Aina, 1984). In areas of intensive faunal activities, plant nutrient and moisture availability may be increased and soil erosion reduced as a result of faunal interactions with residues and soil organic matter. Declines in soil organic matter and standing litter reduce soil faunal activities markedly (Lavelle and Pashanasi, 1989).

Figure 3.8 Effects of soil faunal activities on soil processes and constraints to plant productivity

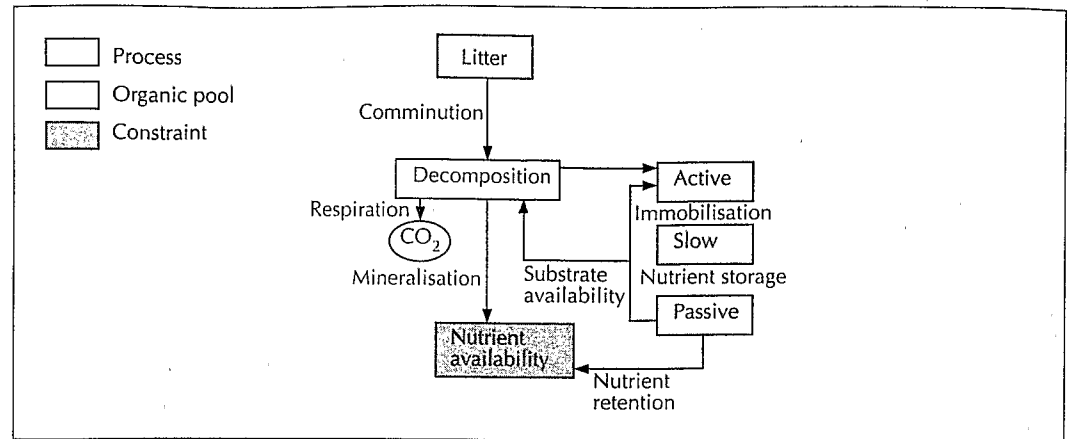


Decomposition

Plant nutrients accumulate in the recalcitrant soil organic matter (see Figure 3.9 overleaf). They are released into the soil solution by the activities of soil microorganisms (active pool) but at the same time protected from loss to deeper soil horizons through immobilisation (Duxbury et al., 1989). The principal loss of C from soil organic matter is through respiration during decomposition; additional losses result from leaching of soluble organic materials and erosion. The passive pool increases nutrient availability through the charging of soil particles and increased cation and anion exchange capacity. Despite their resistance to decomposition, humic substances do affect nutrient availability through anion and cation retention, a property of particular importance in low-activity oxidic soils dominated by low-activity clays, including positively charged oxide minerals (Scharpenseel, 1988). Decline in soil organic matter occurs when the respiration losses as CO₂ and leaching exceed the inputs of C in crop residues. This may also lead to a decline in plant nutrient storage and release in soils. To date, most studies of soil organic matter decomposition and nutrient mineralisation have relied on laboratory incubation of soils because of the difficulties of *in situ* observation. For this reason, the rates

Figure 3.8. Effects of soil faunal activities on soil processes and constraints to plant productivity. (Clarholm, 1985; Wood, 1989; Shipitalo and Protz, 1989; Lavelle and Pashanasi, 1989)

Figure 3.9 Effect of decomposing soil organic matter pools on plant nutrient availability

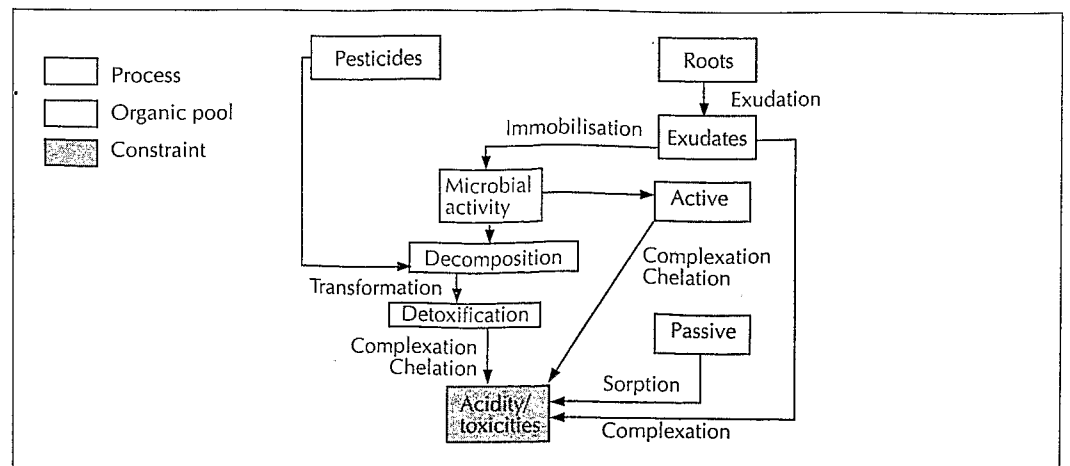


of decomposition and nutrient release characteristics of a given residue introduced into a particular field soil cannot be predicted with sufficient accuracy to optimise soil fertility strategies, although candidate equations of N mineralisation have been identified by Vigil and Kissel (1991).

Detoxification

The reaction of soil organic compounds with phytotoxic chemicals is an important component of the beneficial effects of soil organic matter (see Figure 3.10). Root exudates and microbial by-products complex and chelate toxic cations (such as Al, Fe and Mn species) in the soil solution (Hargrove and

Figure 3.10 The role of soil organic matter pools and soil processes in detoxification

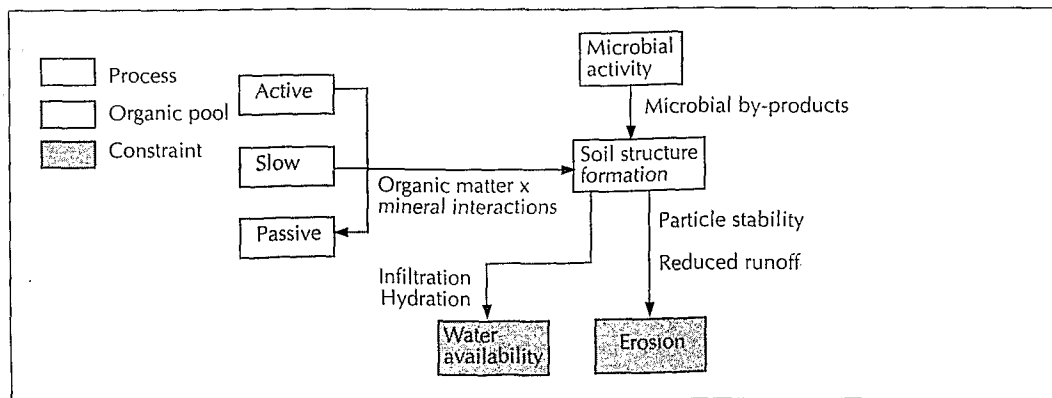


Thomas, 1981; Hue et al., 1986). Extracellular enzymes of microbial origin decompose urea and uric acids, resulting in improved N availability and reduced toxicity. Decomposition and transformations of applied pesticides by soil microorganisms prevent the accumulation of soil toxicities. The passive pool reduces the activity of pesticide residues through absorption into polymethylene matrices. Reduction of soil organic matter and microbial activities reduce the capacity of the soil system to adjust to the toxic effects of natural and applied phytotoxic compounds and residues.

Soil structure formation

The integration of soil minerals into larger units (aggregation) is due mainly to roots, the activities of soil organisms and the interaction of recalcitrant soil organic matter with soil minerals (Oades et al., 1989). Fungal mycelia, microbial by-products and mucilages from roots and soil fauna bind the soil mineral fractions into soil aggregates that allow for greater water infiltration and retention, enhanced aeration and more rapid gaseous diffusion. These aggregates also protect beneficial soil organisms during periods of moisture stress and allow for localised sites of anaerobiosis, influencing mineral nutrient transformations. Increased particle stability reduces soil erosion caused by wind and water runoff (see Figure 3.11). While the role of soil biota and soil organic matter in the formation of soil structure has been widely studied, the detrimental influence of declining soil organic matter on soil physical properties for a given ecosystem cannot be predicted for most agroecosystems, although studies have been conducted by Voss (1988) on incorporating straw into paddy soils.

Figure 3.11 Effect of soil organic matter pools and processes on soil structure formation, water availability and erosion



Organic matter binds the mineral fraction in soils and promotes the water stability of soil aggregates (Tisdale and Oades, 1982; Oades, 1984). Three types of binding take place, based on the residence time of the organic materials involved:

- *Transient binding agents.* Polysaccharides are associated with large aggregates (> 250 μm) by binding together clay-sized particles into sub-units (10-50 μm). These polysaccharides originate

from plant roots, microorganisms (Tisdall and Oades, 1982) and soil invertebrates (Blanchart et al., 1989, 1991). Because of the rapid degradation of polysaccharides in soils (Swift et al., 1979) these aggregates are only transiently stable. The displacement which results from the growth of plant roots may also disrupt this aggregation and re-expose physically protected organic matter (Oades, 1984).

- *Temporary binding agents.* Plant roots and fungal hyphae combine fine soil particles into stable macroaggregates. This occurs partly because of localised drying in the rhizosphere but continues after necrosis and may persist for months or years (Tisdall and Oades, 1982). Plant roots and fungal mycelia indirectly influence macroaggregation through soil faunal activities. Stable macroaggregates are formed from ingested organic materials through earthworm activities (Lavelle, 1988). Soil aggregates formed by these binding agents are those most subject to management strategies; they decline as roots and hyphae decay, without being replaced (Tisdall and Oades, 1982).
- *Persistent binding agents.* Humic substances and aluminosilicates form organo-mineral complexes that are associated with microaggregation (Tisdall and Oades, 1982). These complexes are further stabilised by multivalent cations that act as clay bridges (Oades, 1984). The reaction of organic materials with amorphous clays and metal cations (such as Fe and Al) improves soil aggregate stability in highly weathered or other charge-variable soils (Oades et al., 1989). Microaggregation is generally less sensitive to management strategies other than the massive addition of polyvalent cations (Oades, 1984) or peptisation by sodium ions.

Management of soil organic carbon dynamics in the tropics

Resource quality of organic inputs

An assumption underlying models of soil organic matter dynamics is that plant residues with a high lignin/N ratio (Mellilo et al., 1982; Cuevas and Medina, 1988), low nutrient content and/or high polyphenol content (Palm and Sanchez, 1991) result in chemical recalcitrance, with a greater proportion decomposing into stabilised soil organic matter. Furthermore, the chemical composition of residue inputs control the proportion of various soil organic matter functional pools, especially when physical regulators of decomposition are not limiting.

Effect of land management on soil organic matter functional pools

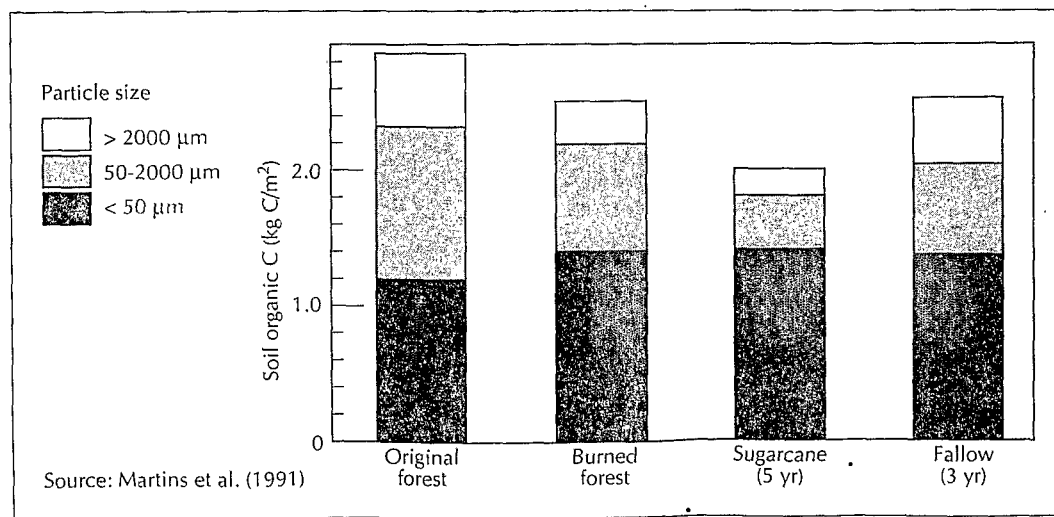
Continuous cultivation in conjunction with residue removal and tillage (Follett and Schimel, 1989) are known to induce a more rapid mineralisation of soil organic matter within the first few years of cultivation by disrupting macroaggregates and leading to the mineralisation of soil organic matter within physically protected aggregates (Tiessen and Stewart, 1983). Land management often intensifies cycles of soil drying and wetting in the dry tropics, accelerating soil organic matter decomposition (Ladd et al., 1977) because of the disruption of macroaggregates and physically protected organic matter complexes, combined with accelerated microbial activities following irrigation or the onset of rains (Stevenson, 1982).

The analysis of the TSBF dataset has shown that climatic and edaphic factors are major determinants of soil organic matter dynamics in tropical ecosystems. However, factors operating at

smaller spatial and temporal scales may participate in a significant way in regulating soil organic matter dynamics. Land management alters the pattern of residue inputs and affects the relative proportion of soil organic matter pools in both cropped and grazed land.

Land clearing and cultivation induce a lower equilibrium level of soil organic matter, partly because of reduced organic inputs and removal of the harvest. For example, in a low-input agrosystem established after forest burning in Amazonia, Martins et al., (1991) observed a 33-45% decrease in soil organic C content after 5 years of continuous cropping (see Figure 3.12). The decline in soil organic C was primarily the result of the mineralisation of 60% of the coarse fractions of soil organic matter. Above-ground crop residues may provide a significant organic input and therefore can help reduce soil C loss in tropical cropping systems. Feller et al. (1987) showed that mulching on a sandy soil cultivated for 3 years with a millet/peanut rotation led to a slight increase in soil organic matter, consisting mainly of the fraction finer than 50 μm (see Figure 3.13 overleaf). The incorporation of crop residues provides substrate to microbial biomass, resulting in increased soil aggregation, mainly through the production of mucigels and gums. The application of crop residues reduces soil erosion and bulk density (Dalal and Mayer, 1986) and improves water conservation. The introduction of manure into a cropping system limits soil C losses and maintains soil microbial biomass (Srivastava and Singh, 1989) (see Table 3.11 overleaf).

Figure 3.12 Effect of cultivation on soil organic carbon distribution among particle size fractions in an Amazonian forest and subsequent land uses



Because of the higher root production, there is a greater potential to increase soil organic matter in pastures and vegetated fallows than in cropped systems. Root debris tends to be less decomposable than shoot material because of its higher lignin content. As a result, pasture or fallow promote the restoration of soil C content after declines resulting from intensive cropping. In Amazonia, Martins et al. (1991) observed that a 3-year period of fallow after 5 years of continuous cropping on an Oxisol raised the soil C content to 80% of that of the original forest soil. Similar observations were made by

Figure 3.13 Carbon storage within particle size fractions in a Psammentic Ustropept in Senegal related to three types of management: burning straw, incorporating straw (400 g/m²) and mulching (400 g/m²)

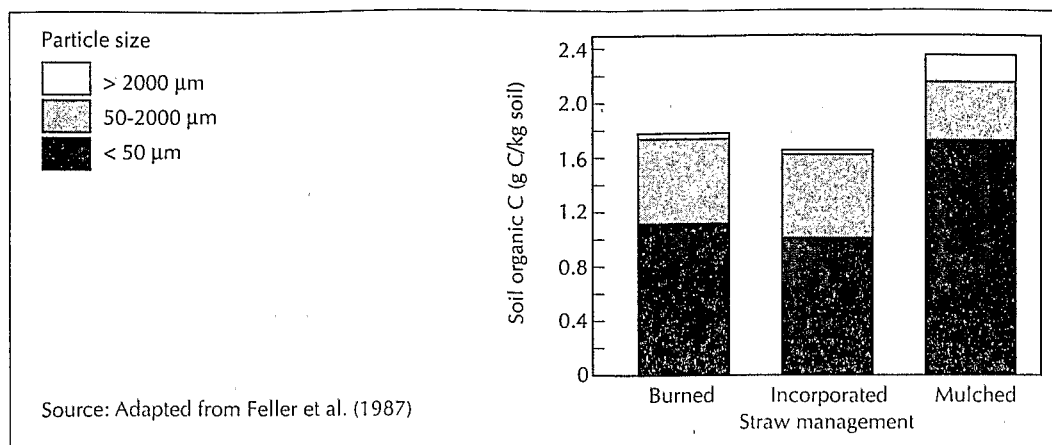


Table 3.11 Effect of manure introduction (250 g C/m²) on carbon content and microbial biomass in an Ultisol (0-10 cm) in a dry tropical forest and 15- or 40-year-old maize fields, Uttar Pradesh, India

Site	Soil C content (g C/m ²)	Soil microbial C (g C/m ² in summer)
Sal forest	2854	87
Mixed forest	2530	90
15 years under maize	1148	38
40 years under maize + manure	1638	45

Source: Srivastava and Singh (1989)

Lugo et al. (1986). Albrecht et al. (1986) observed that the soil C content of a 10-year-old pasture following sugarcane cultivation on a Vertisol had increased by 106% in the 0-10 cm layer; as a result, there was an improvement in soil aggregation and aggregate stability (see Table 3.12). Comparing the C distribution among size fractions of a pasture soil to a soil under intensive market gardening, Feller (1988) demonstrated that grass cover may significantly increase soil organic matter in both coarse and fine fractions (see Figure 3.14).

Soil management

The effects of cultivation on the soil organic matter content of highly weathered clayey Oxisols over time is illustrated by changes which occur in soil properties of the Cerrados in Brazil (Resck et al., 1991) (see Figure 3.15 overleaf). After clearing the Cerrados, the soil organic matter content was 3.2%

Soil organic C content (g/m²)



Soil organic C content (g/m²)

Soil organic C content (g/m²)

Soil organic C content (g/m²)

Table 3.12 Comparison of total soil organic carbon, medium diameter of soil aggregates and dispersibility of a Vertisol under *Digitaria decumbens* pasture and market gardening

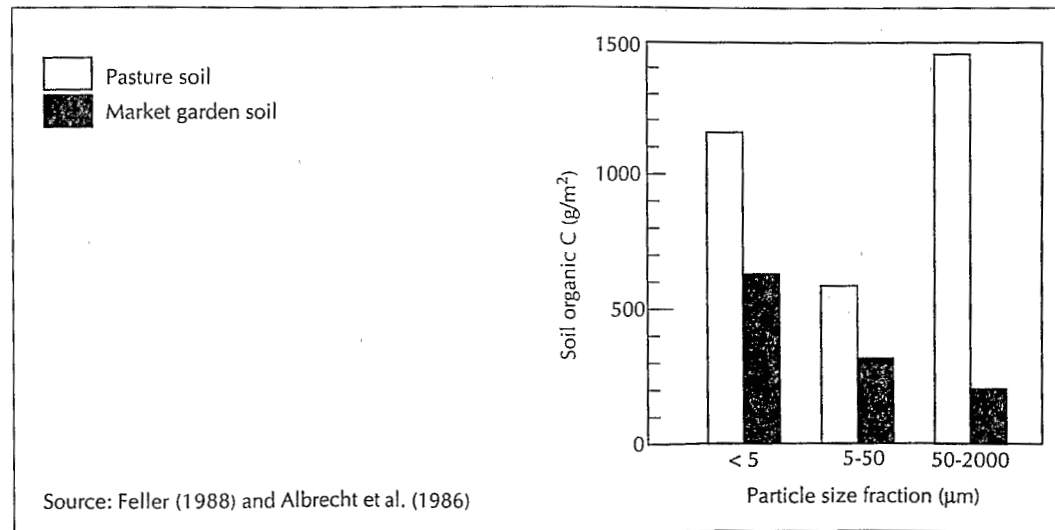
Management	Soil C content (g C/m ²)	MWD (1) ^a (μm)	MWD (2) (μm)	MWD (3) (μm)	Dispersibility ^b
Pasture	3180	65	15	2	14.5
Market gardening	1230	20	7	2	46.5

Note: a MWD (1) = medium diameter after 0.5 hours of shaking; MWD (2) = medium diameter after 18 hours of shaking; MWD (3) = medium diameter after combustion of soil organic matter

b % of > 0.5 μm particles immediately dispersible in water

Source: Albrecht et al. (1986); Albrecht (1988)

Figure 3.14 Distribution of carbon within particle size fractions of a Latosol (0-10 cm) in Martinique after 2 years of management



Source: Feller (1988) and Albrecht et al. (1986)

in the surface horizon. During the following 2 years of upland rice cultivation, it increased to about 3.9%, presumably because of the decomposition of root residue from the natural vegetation. Under continuous cultivation of soybean, soil organic matter content fell to less than 3.0%, because of a decrease in total residue inputs and an increase in microbial activities resulting from liming and fertilisation. After 11 years of cultivation, this soil had lost many of its aggregation characteristics. In the virgin Cerrados the soil surface horizon contained 90% of the soil aggregates greater than 2.0 mm, but after 11 years of cultivation only 62% of the aggregates exceeded 2 mm, although the organic matter content of this size of aggregates was 3.6%. This indicates that soil organic matter belonging to the slow functional pool is an important component of larger aggregates. In support of this, there was a 32% decrease in aggregates greater than 2 mm and an even redistribution of aggregates into sizes

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Figure 3.15 Effects of land use and cultivation on soil organic matter in a Brazilian Oxisol during continuous cropping

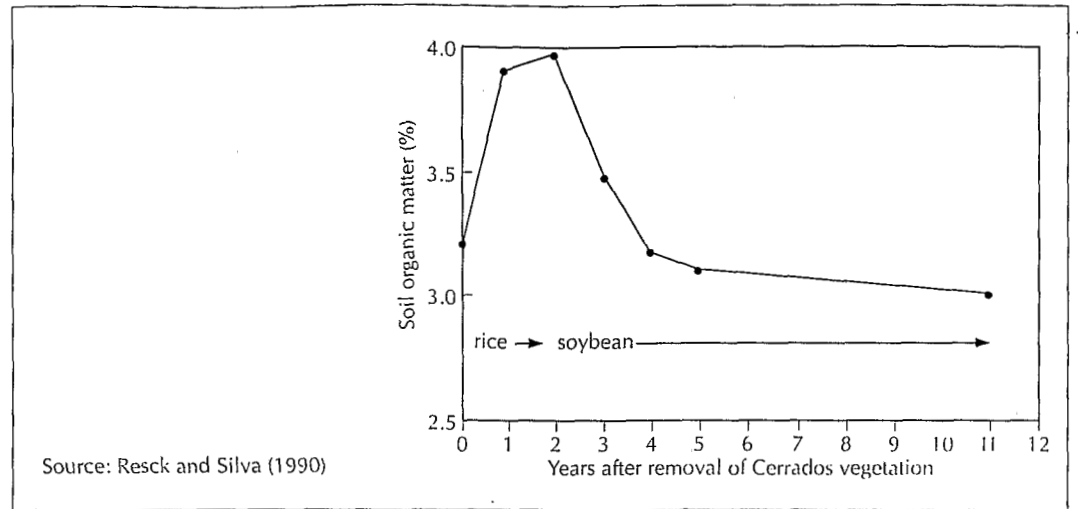
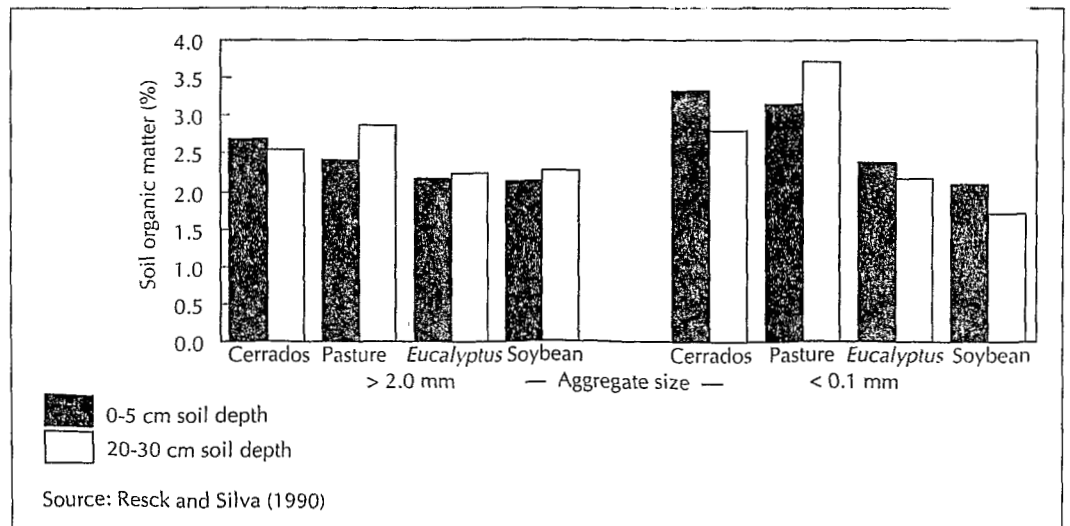


Figure 3.16 Effects of land use on soil organic matter content in different aggregate size fractions at two soil depths in the Cerrados region, Brazil



greater than 1 mm, 0.5 mm, 0.25 mm, 0.1 mm and 0.1 mm, as a result of long-term cultivation with heavy disk harrow implements, suggesting a collapse of larger aggregates.

In their investigation into how soil organic matter is conserved in the Oxisols of the Cerrados, Resck and Silva (1990) classified different systems as: disturbed (areas cultivated with heavy disk harrow

of during



implements in soybean-maize rotations and with rototillers where several species of green manure were grown); or non-disturbed (virgin area under Cerrados vegetation, *Brachiaria* pasture or *Eucalyptus* forest). The organic matter content of these systems is presented in Figure 3.16. The percentage of organic matter did not differ greatly between the pasture and tree plantation soils and the total amount of organic matter was considerably reduced in the more disturbed soils.

The highest organic matter content (5.76%), mainly at a depth of 0-5 cm, was under Cerrados vegetation, followed by *Brachiaria* (3.54%) and *Eucalyptus* (2.78%). When compared with *Brachiaria* after 10 years of cultivation, there was a loss of 22.8 t C/ha and 29 t C/ha within the crop rotation and pasture systems, respectively.

In general, the soils in which over 81% of stable aggregates exceeded 2 mm at depths of 0-5 cm and 20-30 cm in both dry and wet conditions were those that had not been subjected to disturbances and the resultant decline in soil organic matter (see Figure 3.16). Areas cultivated with green manure and prepared with rototillers had no more than 42% of stable aggregates greater than 2 mm at depths of 0-5 cm and less than 50% at depths of 20-30 cm, despite high crop yields (10 t/ha) (data not shown). The loss of larger, water-stable aggregate (> 2.0 mm in diameter) as a result of land cultivation is not unexpected but the disappearance of soil particles of 0.1 mm or more in diameter suggests that this disaggregation is limited and that finer aggregates (0.1-2.0 mm) may combine with the smallest size class (< 0.1 mm)

SUSTAINABILITY AND SOIL ORGANIC MATTER DYNAMICS

fractions



Organic materials in all ecosystems, terrestrial or aquatic, natural or managed, are confined within three main subsystems (Swift et al., 1979). The plant subsystem assimilates organic materials through the conversion of solar energy and supplies organic materials to the other subsystems. The herbivore subsystem consists of herbivores that consume plant material and are under predation by first-order carnivores that are, in turn, subject to higher-order predation. The decomposer subsystem is driven by necrosis within other subsystems and is characterised by the catabolism of plant and animal materials and the deposition of recalcitrant organic materials into the soil.

It is through successional events and the interactions of these subsystems that natural ecosystems achieve a steady state with little net change in assimilated, stored or lost organic materials (Odum, 1969). The relationship between ecosystem complexity and function is by no means clear and, with the current global focus on biodiversity, is the subject of intense intellectual debate and developing research activity. Swift and Anderson (1992) have hypothesised that, for agricultural systems, optimal ecosystem function and increased sustainability is promoted by maintaining in the system a minimum number (two to five) of plant species which differ in their architecture and chemical composition. This geometrical and chemical heterogeneity promotes ecosystem function by permitting a wide range of micro-environmental and food resource niches for consumer and decomposer organisms. For example, the heterogeneity of catabolic pathways and plant rooting structures result in minimal nutrient losses during the decomposition of dead plants and animals. Earlier human activities such as hunting and foraging contributed to this homeostasis, providing added complexity to the detritus pathway between animal and decomposition subsystems. But is this what we mean by 'sustainable'?

It may be said that, while climax natural ecosystems exist to subsist, agricultural ecosystems exist to exploit. Modern agricultural systems rely on exports from the plant or herbivore subsystems for the sustenance of human populations in a manner that, to the same extent, defies natural homeostasis. Undoubtedly, some human populations persist in lesser defiance of the 'homeostasis of sustainability'.

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Pastoralists and subsistence farmers may be viewed in the short term as adjusting rather than defying the balances of nature. Yet when overgrazing by domesticated animals leads to massive land erosion and desertification, or rural over-population results in the marginal sub-division of land holdings followed by migration to urban centres and hopeless poverty, this is definitely not what is meant by 'sustainable'. It appears, indeed, that although it is easy to define what 'is not sustainable', it is more difficult to say what 'is sustainable'.

CONCLUSION

Agricultural ecosystems may be maintained through a variety of means. Highly productive conventional agriculture has been sustained in North America and Europe by high subsidy from the industrial base. Lower levels of production sufficient for subsistence have been maintained for centuries by shifting fallow management in Asia, South America and Africa. The former system bypasses the management and conservation of soil organic matter but the latter depends upon it. Is there a middle ground which is both productive and sustainable? As suggested in Chapter 4, intermediate types of cropping systems that incorporate crop rotation, agroforestry and mulches may well be the best way forward for farmers in the tropics.

The almost universal loss of organic matter from soils brought under cultivation (Post and Mann, 1990) is central to the issue of 'agricultural sustainability'. If the loss of soil organic matter reduces nutrient storage and retention capabilities and is an inevitable consequence of land management, how can such a cropping system be regarded as sustainable? When nutrients are inevitably removed by crop harvesting and are often transported to other countries as export commodities (Miwa, 1990), in what ways other than direct amelioration of nutrient deficiencies can yields be sustained at acceptable levels? Even in the case of enhanced symbiotic N fixation by the legume/*Rhizobium* symbiosis, the nitrogen removed as grain (Duke, 1981) is often greater than the replenishment from biological nitrogen fixation (FAO, 1984).

Has agricultural sustainability become synonymous with improved traditional agricultural practices applicable to lower population densities, such as fallow rotation and slash-and-carry green manuring? By 'improved sustainability', do we in fact mean reduction of the loss of non-renewable assets (soil) and conservation of renewable resources and variable inputs? If this is the case, conservation agriculture and the regulation of soil biological processes through improved management strategies play an important role in reducing soil resource losses. In this respect, pasture systems seem to be among the more suitable agroecosystems in terms of soil C storage and conservation. Innovative cropping systems, such as the inclusion of deep-rooted companion crops, trees and symbiotic legumes into traditional cropping systems, coupled with effective residue management, erosion control and improved tillage practices, must be developed in order to retard soil degradation. It should be remembered, however, that direct replacement of lost plant nutrients with fertilisers, and practices which optimise the efficient use of applied fertilisers, constitute an equally valid and often more economic nutrient management strategy.

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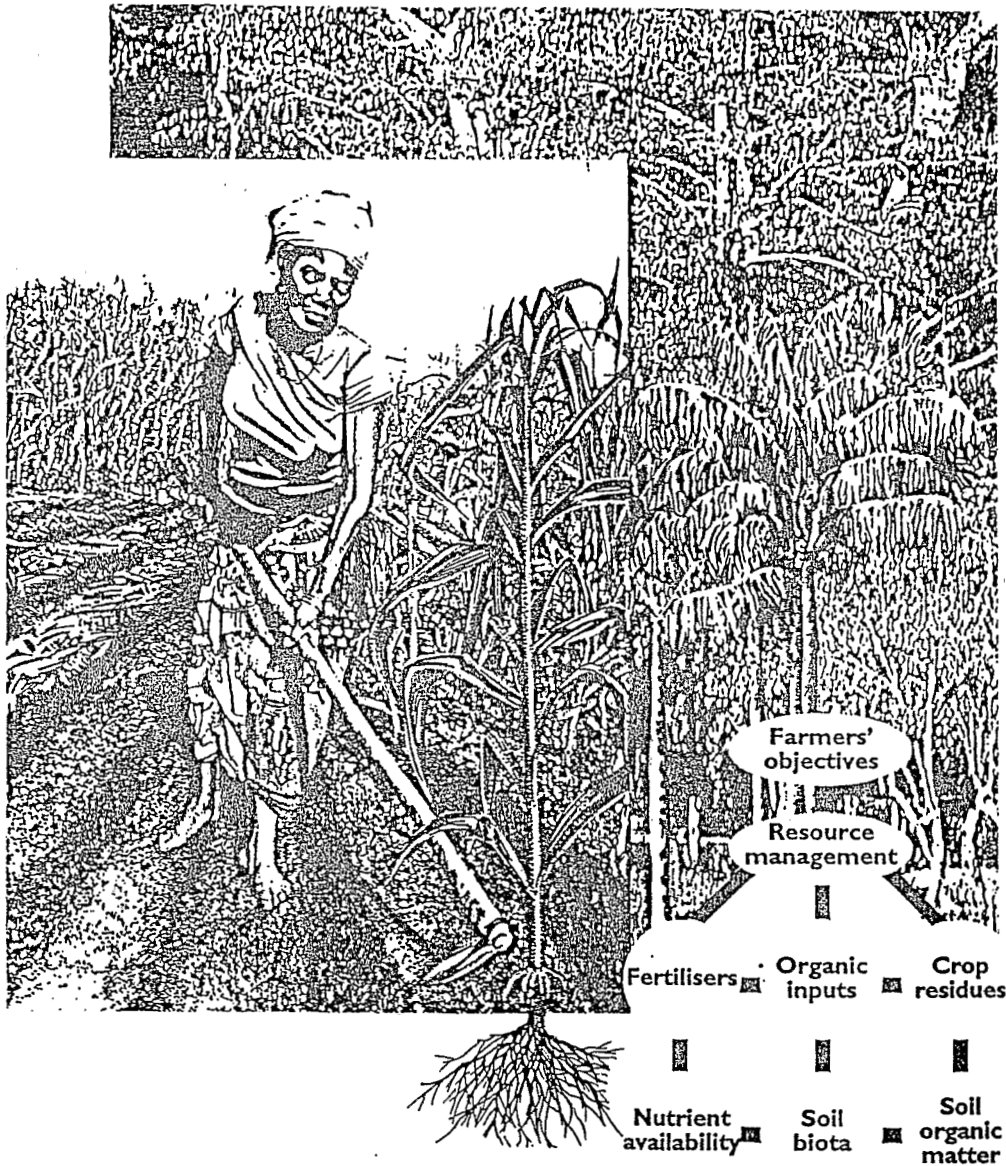
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Contents

Preface		vii
Contributors		viii
CHAPTER 1	Soil fertility research in response to the demand for sustainability <i>M.C. Scholes, M.J. Swift, O.W. Heal, P.A. Sanchez, J.S.J. Ingram and R. Dalal</i>	1
CHAPTER 2	Soil biological processes in tropical ecosystems <i>S. Brown, J.M. Anderson, P.L. Woomer, M.J. Swift and E. Barrios</i>	15
CHAPTER 3	The importance and management of soil organic matter in the tropics <i>P.L. Woomer, A. Martin, A. Albrecht, D.V.S. Resck and H.W. Scharpenseel</i>	47 —
CHAPTER 4	The synchronisation of nutrient mineralisation and plant nutrient demand <i>R.J.K. Myers, C.A. Palm, E. Cuevas, I.U.N. Gunatilleke and M. Brossard</i>	81 —
CHAPTER 5	Soil physics and fertility: The effects of water, temperature and texture <i>R.J. Scholes, R. Dalal and S. Singer</i>	117
CHAPTER 6	The relationship between soil macrofauna and tropical soil fertility <i>P. Lavelle, M. Dangerfield, C. Fragoso, V. Eschenbrenner, D. Lopez-Hernandez, B. Pashanasi and L. Brussaard</i>	137 —
CHAPTER 7	Modelling soil organic matter dynamics and plant productivity in tropical ecosystems <i>W.J. Parton, P.L. Woomer and A. Martin</i>	171
CHAPTER 8	The Jhum agroecosystem in north-eastern India: A case study of the biological management of soils in a shifting agricultural system <i>P.S. Ramakrishnan</i>	189
CHAPTER 9	Biological management of tropical soils: Integrating process research and farm practice <i>M.J. Swift, L. Bohren, S.E. Carter, A.M. Izac and P.L. Woomer</i>	209
Appendices		229
Acronyms		238
Index		239

Preface

The fertility status of many tropical soils, particularly those of smallholder farmers, is regulated by key biological processes and the organic resources available to farmers. Too often, these processes are not understood well enough by agriculturalists to be placed in the soil management context. Failure to understand the complexities of tropical soil fertility has resulted in the lack of well-integrated management strategies, and this has led to the recognition that agricultural systems must become more sustainable if the food requirements of future generations are to be met.

This book reports on the first five years of research by scientists of the Tropical Soil Biology and Fertility Programme (TSBF). TSBF is sponsored as a component project of the International Biological Sciences (IUBS) programme The Decade of the Tropics and of the Man and the Biosphere (MAB) programme of UNESCO, and is hosted by the UNESCO Regional Office for Science and Technology in Nairobi, Kenya. TSBF is a voluntary participatory international research programme whose members are committed to the concept that the fertility of tropical soils is controlled by biological processes and can be managed by the manipulation of these processes. Participating network scientists conduct field studies in Central and South America, sub-Saharan Africa, South Asia and Australia, and maintain close institutional links with researchers in Europe and North America. TSBF's main intention is to review the potential for the biological management of tropical soils, focusing on the programme's four main research themes: soil organic matter management; nutrient-use efficiencies; manipulation of the soil water regime; and the potential for the utilisation of soil fauna for soil fertility improvement. Each theme is discussed, together with accompanying chapters which set the context of the drive for sustainable agriculture, lay the foundations for an agroecological approach to soil and discuss the socio-economic implications of TSBF research.

The book contains nine multi-author chapters but it has been prepared as a continuous discursive text. The authors have all worked together at workshops and in the field and share a common philosophy of research and soil management. The book is thus intended as a basic text for research in sustainable soil management. It is aimed primarily at young, post-graduate scientists in the disciplines of soil science, agronomy, forestry or ecology, as well as senior scientists and decision-makers concerned with the sustainable development of agriculture and other land uses in the tropical regions.

The publication of this book would not have been possible without the generous financial support from several organisations. Direct funding for the initial meeting of the authors was received from the Rockefeller Foundation, ORSTOM and the United Nations Environment Programme (UNEP). The editors' salaries were provided by the Natural Environment Research Council (NREC, UK) through the Institute of Terrestrial Ecology (ITE), the Overseas Development Administration (ODA, UK) through the International Centre for Research in Agroforestry (ICRAF) and the International Institute of Tropical Agriculture (IITA). Financial support for TSBF Headquarters in Nairobi, Kenya was also provided by the United Nations Scientific, Cultural and Educational Organisation (UNESCO) through the Man and Biosphere Programme (MAB) and the Regional Office for Science and Technology for Africa (ROSTA). We gratefully acknowledge the involvement by, and the financial contributions from, all of the above organisations.

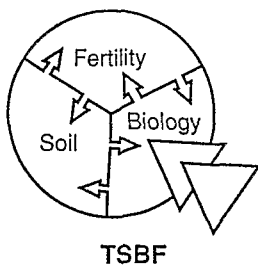
P.L. Wooster and M.J. Swift
Tropical Soil Biology and Fertility Programme (TSBF)

Tropical Soil Biology and Fertility Programme (TSBF)

TSBF was established in 1984 under the patronage of the Man and Biosphere programme of Unesco and the Decade of the Tropics initiative of the International Union of Biological Sciences (IUBS). The objective of the programme is to develop appropriate and innovative approaches for sustaining tropical soil fertility through the management of biological processes and organic resources. To achieve this objective, TSBF aspires to:

- make available to farmers and other land managers in the tropics methods for soil management which will improve agricultural productivity but conserve the soil resource
- contribute to increasing the carbon storage equilibrium in tropical soils in the face of global changes in land use and climate
- improve understanding of the role of biological resources in soil fertility and the sustainability of tropical land-use systems
- improve the research and training capacity of national institutions in the tropics in the fields of soil biology and management of tropical ecosystems

TSBF is a voluntary participatory international research programme whose members are committed to the concept that the fertility of tropical soils is controlled by biological processes and can be managed by the manipulation of these processes. Research is conducted at both the ecosystem level and the process level on the basis of two principles: that the capacity to manage soil fertility depends on a mechanistic understanding of the biological processes regulating nutrient flux, organic matter dynamics and soil physical structure maintenance, and that successful management for sustainable soil fertility must be implemented at the ecosystem level by integrating soil biological processes with those of human decision making in relation to all components of the ecosystem.



International Union
of Biological Sciences



Man and Biosphere
programme of Unesco