Nutrient Cycling in Agroecosystems **49:** 243–253, 1997.

Conservation tillage for carbon sequestration

R. Lal[1] & J.M. Kimble[2]
[1]*School of Natural Resources, The Ohio State University, Columbus, Ohio, USA;* [2]*National Soil Survey Laboratory, NRCS, Lincoln, Nebraska, USA*

Key words: C cycle, C sequestration in soil, greenhouse effect, no-till farming, residue management, soil processes, soil quality

Abstract

World soils represent the largest terrestrial pool of organic carbon (C), about 1550 Pg compared with about 700 Pg in the atmosphere and 600 Pg in land biota. Agricultural activities (e.g., deforestation, burning, plowing, intensive grazing) contribute considerably to the atmospheric pool. Expansion of agriculture may have contributed substantially to the atmospheric carbon pool. However, the exact magnitude of carbon fluxes from soil to the atmosphere and from land biota to the soil are not known. An important objective of the sustainable management of soil resources is to increase soil organic carbon (SOC) pool by increasing passive or non-labile fraction. Soil surface management, soil water conservation and management, and soil fertility regulation are all important aspects of carbon sequestration in soil. Conservation tillage, a generic term implying all tillage methods that reduce runoff and soil erosion in comparison with plow-based tillage, is known to increase SOC content of the surface layer. Principal mechanisms of carbon sequestration with conservation tillage are increase in micro-aggregation and deep placement of SOC in the sub-soil horizons. Other useful agricultural practices associated with conservation tillage are those that increase biomass production (e.g., soil fertility enhancement, improved crops and species, cover crops and fallowing, improved pastures and deep-rooted crops). It is also relevant to adopt soil and crop management systems that accentuate humification and increase the passive fraction of SOC. Because of the importance of C sequestration, soil quality should be evaluated in terms of its SOC content.

Introduction

World soils play an important role in carbon (C) cycling. Being a principal terrestrial C pool, soils contain more than twice the C than in the atmospheric pool or in the land plant or biotic pool (Fig. 1). An exact magnitude of fluxes from soil to the atmosphere and from biota or land plant to the soil are not known. It is apparent, however, that atmospheric C pool has increased at the expense of soil pool since the beginning of agriculture. Converting prairies, grassland, forest and woodlands into arable landuse has increased efflux of C from soil to the atmosphere. Agricultural practices with drastic impact on increasing C efflux include deforestation, burning, plowing, and continuous cropping (Houghton et al., 1983; Lal and Logan, 1995). In general, intensive cultivation or continuous cropping leads to decline in soil organic matter content (Post and Mann, 1990), and release of soil organic carbon (SOC) to the atmosphere. The mineralization rate of SOC may range from about 20% in 20 years in temperate climate to about 50% in 10 years in the tropics (Woomer et al., 1994). Several researchers (Bram, 1971; Jenkins and Ayanoba, 1977; Lal, 1979) observed an exponential decline in soil organic matter content with cultivation time in soils of West Africa. Agricultural practices affect soil C reserve by influencing at least two processes: (i) increasing rate of biomass decomposition and mineralization releasing CO_2 into the atmosphere, and (ii) exposing SOC in the soil surface to the climatic elements thereby increasing mineralization of C. The rates of these processes are governed by several exogenous and endogenous factors including inherent soil properties, micro and meso-climate, and management practices. Extensive agricultural systems, with none or a little external input may accentuate C efflux from soil (Lal et al., 1995b). Carbon efflux from agricultural land is also accentu-

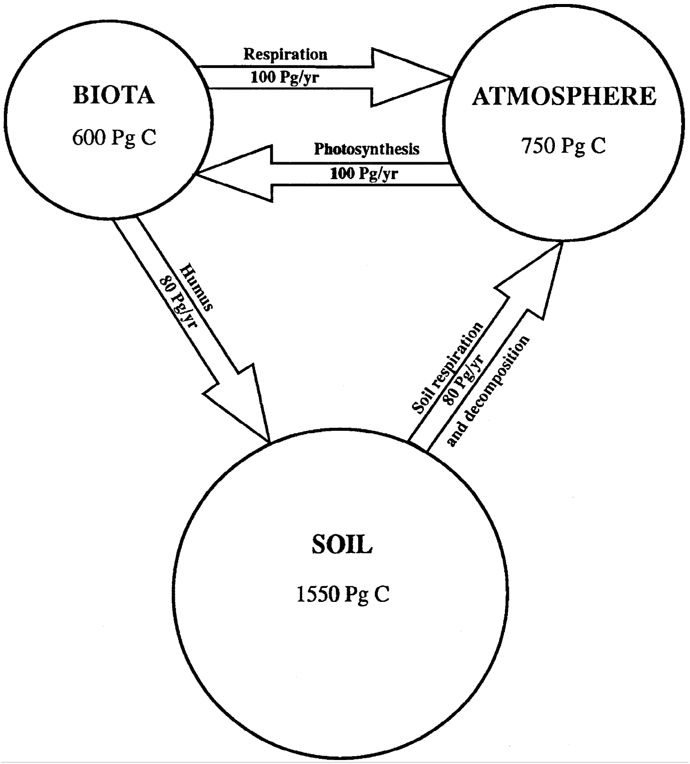

Figure 1. Role of soil in C cycling (adapted from Lal et al., 1995a; Hall, 1989; Bouwman, 1990; Post et al., 1990).

ated by on-set of soil degradative processes. Those processes which are accentuated by agricultural practices and exacerbate C flux include erosion, leaching and soil fertility depletion, and decline of soil structure.

The purpose of this manuscript is to: (i) illustrate the role of soil in C cycling, (ii) describe properties and processes that enhance SOC reserves and decrease turnover rate of SOC, and (iii) illustrate the importance of conservation tillage and other practices and management systems that reverse the degradative trend and facilitate C sequestration in soil. These objectives are achieved by rationalizing basic concepts and citing examples of SOC dynamic in relation to processes and practices with drastic impact on C cycling. This manuscript is not a comprehensive review on terrestrial C pools and their dynamics, and readers are referred to relevant literature on the subject (Bouwman, 1990; Hall, 1989; Post et al., 1990a; b; Lal et al., 1995a; b).

Soil management for C sequestration

The principal objectives of soil management are to maintain or enhance: (i) productivity per unit input, area, and time, and (ii) environmental regulatory functions e.g. filtering pollutants from water and regulating atmospheric quality. Atmospheric quality, an important issue of modern times, is a global concern because of the potential greenhouse effect. The greenhouse effect in relation to soils is attributed to release of radiatively-active gases from soil to atmosphere. The release of radiatively-active gases from soil related processes depends on functional pools of SOC. The turnover time depends on the type of SOC content, and ranges from 0.2 to 1.4 year for active or labile fraction to several thousand years for passive pool (Table 1). Judicious soil management should reduce emissions (of CO_2, CH_4 and NO_x), and reverse the trends by increasing C reserves of the passive pool comprising resistant humic substances.

There are three principal components of soil and water management in relation to C sequestration in soil (Fig. 2). Soil surface management involves: (i) seedbed preparation through varying frequency, intensity, and type of tillage operations, and (ii) crop residue management and return of organic byproducts to the soil surface. Seedbed preparation, based on mechanical soil manipulation, is a principal factor respon-

Table 1. Functional pools of soil organic carbon and their turnover time (adapted from Parton et al., 1987; Woomer et al., 1994).

Functional pool	Turnover time (yr)	Composition
Active or labile fraction	0.2 - 1.4	Microbial biomass, soluable carbohydrates exocellular enzymes
Slow or labile fraction	8 - 50	Particulate organic matter (50 μm - 2 mm)
Passive pool, humic substances	400 - 2200	Humic and fulvic acids, organo-mineral complexes.

Table 2. World estimate of crop residues production (adapted from Lal, 1995).

Crop	Estimated residue production (10^6 Mg/yr)
Cereals	2562
Legumes	238
Oil crops	162
Total	2962

Table 3. Soil drainage and tillage effects on soil organic matter content in 0–50 cm depth of a Crosby-Kokomo association in Ohio (adapted from Fausey and Lal, 1992).

	Soil organic matter content (%)		
Tillage method	Drained	Undrained	t-Test
No-till	2.1	3.3	*
Raised beds	2.3	3.0	NS
Ridge till	1.5	2.5	*
Moldboard plow	1.6	2.4	*
$LSD_{.05}$ (tillage)	0.40	0.57	

* Significant at 10% probability level.

sible for exacerbating soil processes that accentuate C mineralization and decomposition. Several experiments have shown that plowing decreases SOC content both in temperate (Carter, 1993) and tropical ecosystems (Lal, 1989). In contrast to plowing, conservation tillage practices reduce frequency and intensity of tillage, retain crop residues as mulch on the soil surface, reduce risks of runoff and soil erosion, and increase SOC content of the surface soil. Conservation tillage is known to enhance SOC in the surface soil horizons through several mechanisms (e.g., alterations of soil temperature and moisture regimes, and erosion control) (Lal, 1989; Kern and Johnson, 1993).

The SOC content also depends on the type of conservation tillage and amount of crop residues returned to the soil surface, and may be linearly related to crop residue returned to the soil. In tropical West Africa, Lal et al. (1980) reported a linear relationship between crop residue returned and SOC content. These and other findings indicating positive effects of residue return on SOC highlight the importance of judicious management of large quantity of crop residue produced in the world (Lal, 1995). Crop residues produced in the world are estimated at 2962 million Mg/yr (Table 2). Even a fraction of these residues returned to the soil through conservation tillage can increase SOC content and lead to C sequestration. Soil water management also affects SOC content by optimizing the soil moisture regime for plant growth. Three aspects of water management in relation to SOC content are in-situ conservation, water harvesting and supplemental irrigation, and drainage. Both in-situ conservation and supplemental irrigation are important for improving biomass production and increasing SOC in arid and semi-arid ecoregions. In contrast to irrigation, drainage of excessively wet soils may decrease SOC content by increasing soil temperature and increasing the rate of mineralization. Fausey and Lal (1992) reported from Ohio that sub-surface drainage decreased SOC and soil aggregation (Table 3).

Soil fertility management is equally important in maintenance of SOC at high level (Fig. 2). Fertility maintenance may involve use of organic wastes and other byproducts, supplemental use of inorganic fertilizers to balance soil nutrient reserves, and biological nitrogen (N) fixation. Beneficial effects of applying organic materials on SOC are well known from several long-term experiments (Wilson, 1991; Brown, 1994). Long-term fertilizer experiments conducted in the tropics have also shown beneficial effects on SOC. It is important to realize that low input agricultural systems deplete SOC and accentuate risks of the greenhouse effect. These systems include shifting cul-

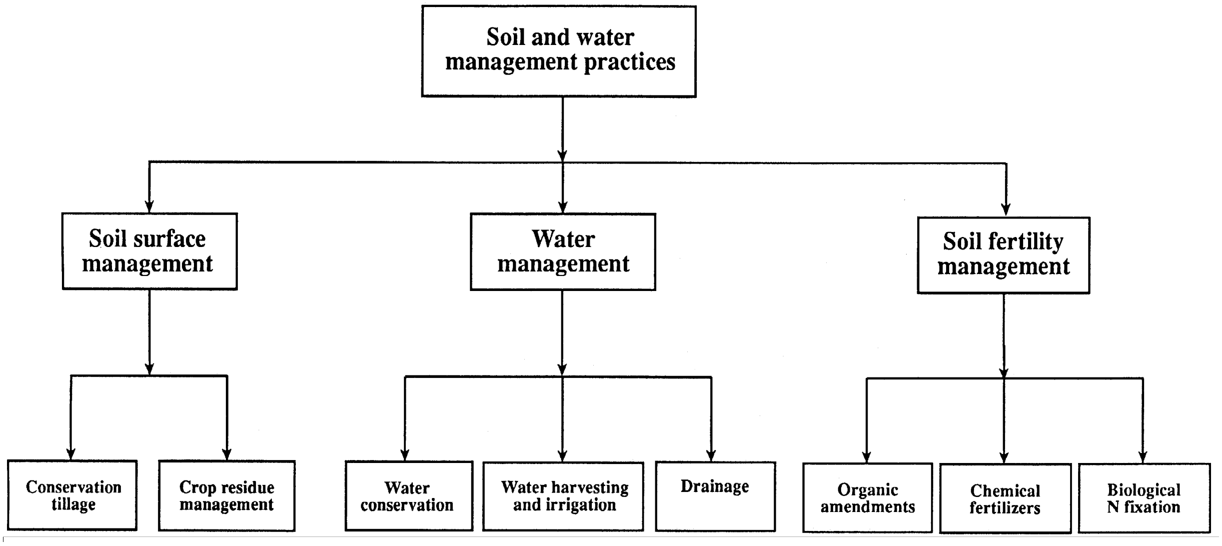

Figure 2. Soil management practices for C sequestration.

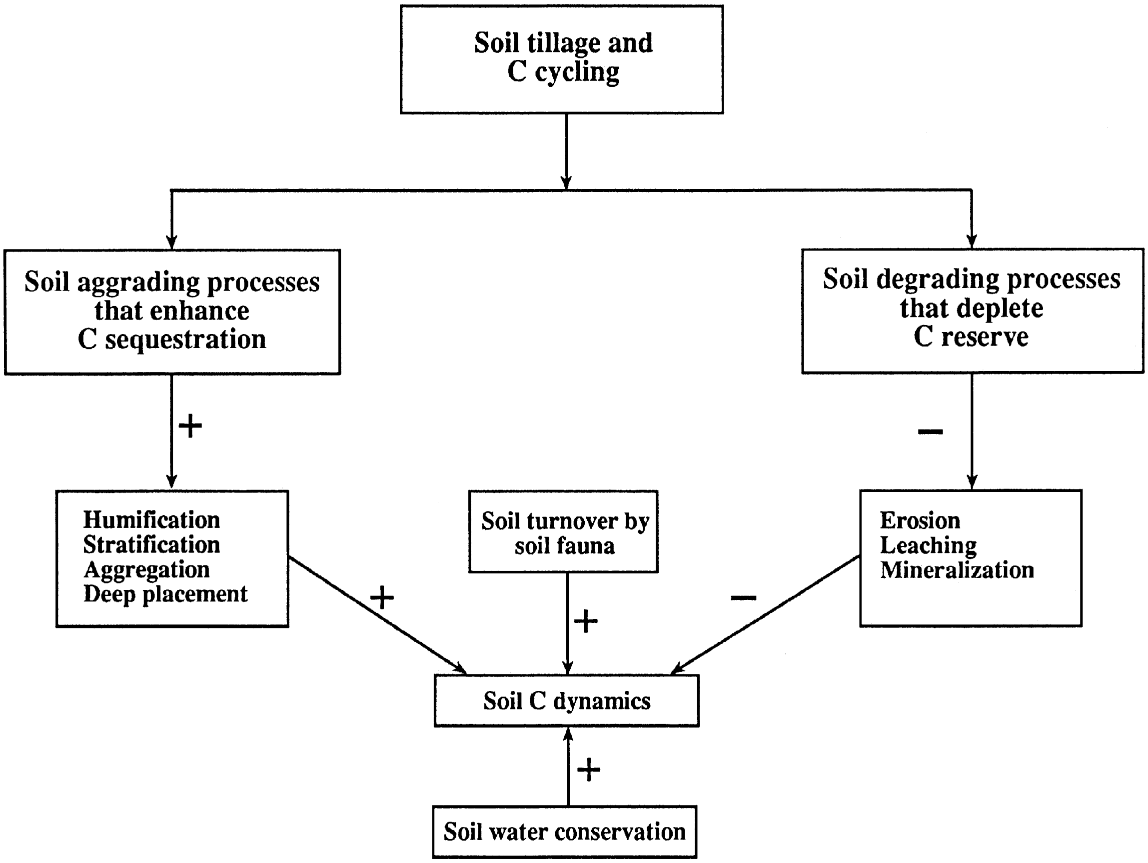

Figure 3. Tillage effects on soil processes that affect C dynamics and reserves in soil.

tivation and other traditional systems of extensive and subsistence agriculture. Improving traditional systems through incorporation of leguminous crops in rotation and growing woody shrubs and trees in association with food crops and pastures (Kang et al., 1981) for biological N fixation and nutrient cycling are good strategies to enhance SOC content.

Conservation tillage and C cycling

Soil tillage affects SOC through its influence on both aggrading and degrading processes (Fig. 3). Soil aggrading processes that enhance SOC are humification of crop residue and other biomass, increase in resistant or non-labile fraction of SOC, sequestration of SOC in the formation of organo-mineral complexes and increase in stable aggregation, and deep placement of SOC in sub-soil horizons. In contrast, soil degrading processes with negative impact on SOC are erosion, leaching, and mineralization.

Conservation tillage, a generic term denoting a range of tillage practices that reduce soil and water losses in comparison with conventional or plow-based tillage method and use crop residue mulch to provide a protection against raindrop impact, increases SOC through enhancement of soil aggrading processes and reversal of soil degrading processes (Lal, 1989; Carter, 1993). Several experiments conducted in temperate and tropical regions have demonstrated the beneficial effects of conservation tillage on SOC (Juo and Lal, 1978; Lal, 1979; Dalal, 1989; 1992; Lal et al., 1989; Carter, 1993). On an Ultisol in Eastern Nigeria, Ohiri and Ezumah (1990) observed about 8% higher SOC in conservation tillage compared with conventional tillage systems.

Conservation tillage usually has a positive impact on activity and species diversity of soil fauna (e.g., earthworms and termites). Earthworm activity is notably improved by conservation tillage (Lal et al., 1980; Lal, 1975; Lavelle, 1988). It is also due to the beneficial effects of soil fauna that conservation tillage improves soil hydrologic properties (Roth et al., 1986; 1988; Sidiras and Roth, 1987; Chan and Mead, 1989; Datiri and Lowery, 1991a; b) and soil tilth (Karlen et al., 1990). Activity of soil fauna usually has beneficial effect on SOC because of mixing and deep placement. Burrowing activity of soil fauna facilitates translocation of SOC from surface to the sub-soil. Conservation tillage also improves aggregation and stability of aggregates (Prove et al., 1990; Lal, 1989). Soil water conservation is a principal advantage of conservation tillage (Blevins et al., 1971; 1977; Lal, 1979; Sommer and Zach, 1992; Thorburn, 1992; Unger, 1990; Unger and Musick, 1990). Increase in water availability in the root zone improves biomass production and improves SOC content (Letey, 1985). Kern and Johnson (1993) evaluated the impact of conservation tillage on C sequestration in soils of the contiguous United States. They estimated that maintaining conventional tillage level of 1990 until 2020 would result in 46 to 78 Tg SOC loss. In contrast conversion of conventional tillage to no-till would result in 80 to 129 Tg SOC gain in soil for the low scenario and 286 to 468 Tg SOC for the high scenario (Table 4).

Effective mechanisms of C sequestration in soil

Dynamics of SOC, that determines the equilibrium status, depends on several factors including soil properties and especially the aggregation. It is the increase in amount of SOC in slow or inactive pool that is an important factor in C sequestration, and the slow pool may be involved in aggregation. Therefore, improved SOC reserves may imply increasing the slow or resistant pool. There are two strategies or mechanisms of C sequestration: (i) increasing stable proportion of macro- and micro-aggregates, and (ii) deep placement of SOC in the sub-soil horizons with sub-surface incorporation of biomass (Fig. 4). Cementation of primary particles and clay domains and micro-aggregates is based on formation of organo-mineral complexes. These complexes bind clay into aggregates, thereby immobilizing and sequestering the C. There are several techniques for improving micro-aggregation. However, these techniques are soil and ecoregion specific. Resck et al. (1991) observed in the Cerrado region of Brazil that continuous cultivation for 11 years altered aggregate size distribution and SOC content of the aggregates. About 90% of aggregates were > 2 mm in natural Cerrados, but after 11 years of cultivation only 62% were in this size range. This change in aggregation shows that the slow SOC pool is also an important component of macro-aggregates. Further, disturbed systems contain low levels of SOC compared with undisturbed systems. Many experiments have shown increase in total aggregation by application of organic amendments and compost (Tisdall, 1996). Aggregation is also improved by application of even a low level of polymers or soil conditioners (Williams et al., 1968; Greenland, 1972; Levy, 1996). Soil conditioners

Table 4. Changes in soil organic carbon (SOC) and fossil fuel C emissions for the three tillage scenarios (adapted from Kern and Johnson, 1993).

Tillage System	Scenario 1				Scenario 2				Scenario 3			
	SOC			Fuel C	SOC			Fuel C	SOC			Fuel C
	Mean	Min	Max		Mean	Min	Max		Mean	Min	Max	
	Tg C											
Conventional	-62	-46	-78	-121	-36	-27	-45	-87	-19	-14	-24	-67
Minimum-Till	0	0	0	-30	0	0	0	-52	0	0	0	-66
No-Till	0	0	0	-6	+104	+80	+129	-10	+377	+286	+468	-13
Totals	-62	-46	-78	-157	+68	+53	+84	-149	+358	+272	+444	-146
	Mean	Min	Max		Mean	Min	Max		Mean	Min	Max	
Net C Gain/Loss ±	-219	-203	-235		-81	-96	-65		+212	+126	+298	

† *Scenario 1* = 1990 mix of tillage practices continues unchanged through 2020.
Scenario 2 = Beginning with 1990 mix of tillage practices, conservation tillage practices are increased until they reach 57% of major crop land area in 2010. The SOC accumulation until 2020 is included.
Scenario 3 = Beginning with 1990 mix of tillage practices, conservation tillage practices are increased until they reach 76% of major crop land area in 2010. The SOC accumulation until 2020 is included.
‡ Negative numbers refer to net C loss and positive numbers to net C gain.

are generally used in stabilizing soil structure and for erosion control on steep slopes. However, conditioners may also be used in improving aggregation for increasing SOC and C sequestration. Deep incorporation of humus or non-labile fraction beneath the plow layer is another effective strategy for C sequestration (Bouwman, 1990; Fisher et al., 1994). Carbon placed beneath the plow layer is not easily decomposed because it is not exposed to climatic elements. Practices that lead to deep placement of SOC include activity of soil fauna, vertical mulching, and growing deep-rooted annuals and perennials (Lal and Kang, 1982; Wilson, 1991). Vertical mulching is a technique of soil-water conservation whereby crop residues and other biomass are placed in trenches 30 to 50 cm deep. Deep placement of residues keeps trenches open and facilitates water infiltration into the soil. Vertical mulching, practiced regularly with substantial quantity of crop residue, can also facilitate increase in SOC in the sub-soil horizons (Lal, 1986).

Growing deep-rooted plants is another useful and a practical technique of improving soil structure (Steinert et al., 1990) and increasing SOC content in the sub-soil horizons. Fisher et al. (1994) observed that growing improved pastures in acid savanna soils in South America may drastically improve SOC content of the sub-soil. In West Africa, Lal et al. (1978; 1979) also observed significant positive effects of growing cover crops on increase in SOC content.

Cultural practices to enhance C sequestration with conservation tillage

An absolute quantity of SOC within a natural ecosystem depends on many ecological factors. Important among these are annual precipitation, mean annual temperature, and soil texture. Conversion from natural to an agricultural land use often results in loss of SOC. Woomer et al. (1994) proposed the model shown in Eq. 1 to estimate loss of C from managed ecosystems.

$$C_{\mathrm{floss}} = -0.55 + 0.26C_0 + 0.055\%\mathrm{clay} - 0.49P \quad (1)$$

where C_{floss} is C loss from field soils in kg/m^2, C_0 is C storage within the natural ecosystem (kg/m^2), P is mean annual precipitation (m/yr), and clay is percentage of soil particles < 0.002 μm. Over and above the effect of climate and soil, the rate of decline of SOC also depends on soil and crop management. Agricultural practices with a profound positive effect on SOC content are cover crops and fallowing, agroforestry and agro-pastoral systems, rotations with deep-rooted crops, and crop residue management or mulching. Cultural practices with proven positive effect on SOC outlined in Fig. 5 are of two categories: (a) those that increase biomass production, and (b) those that increase humification:

(a) Increasing biomass production:

Any system that produces and returns biomass to the soil has potentially positive effect on SOC content.

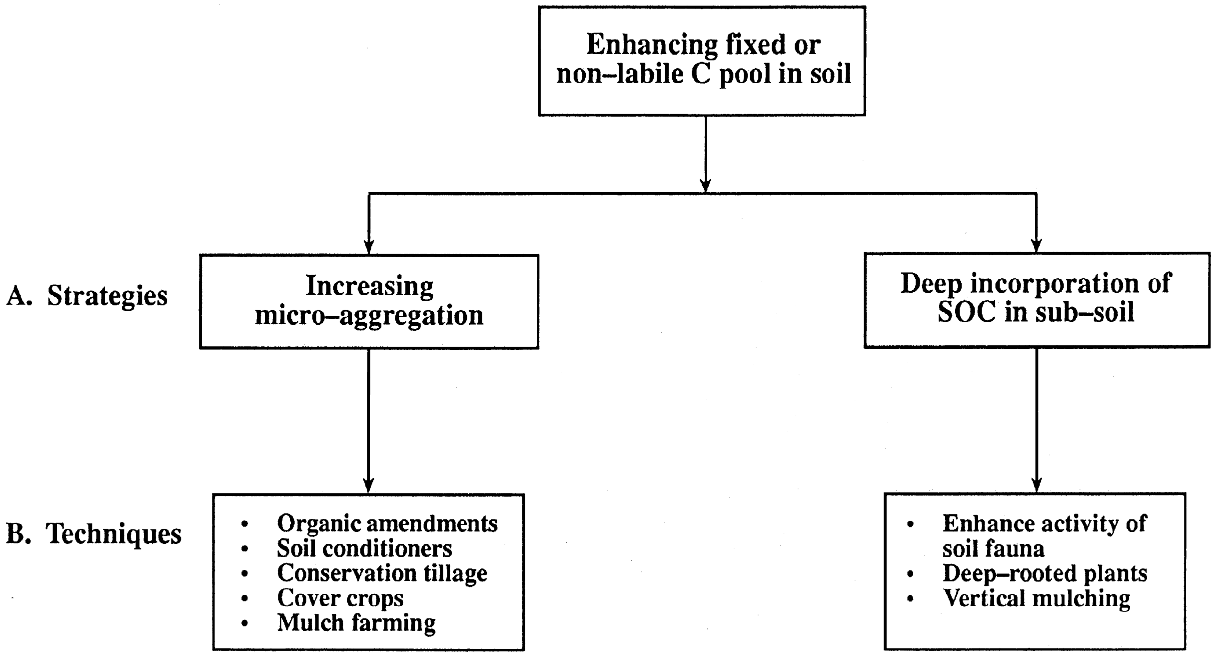

Figure 4. Effective mechanisms of C sequestration in soil.

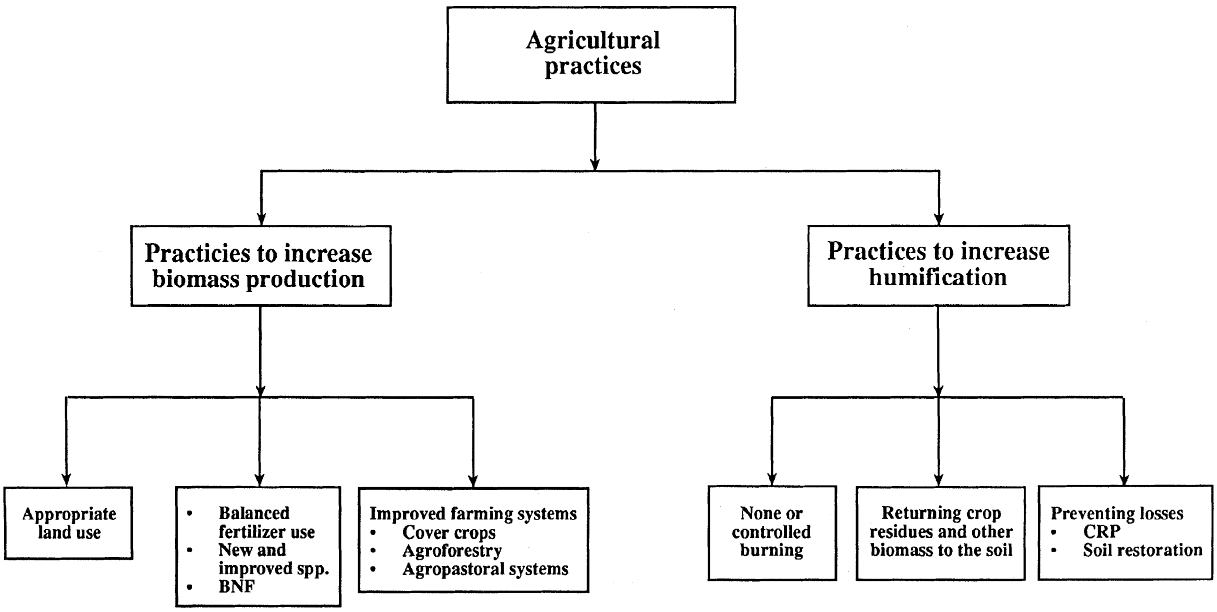

Figure 5. Some relevant agricultural practices to enhance C sequestration.

The SOC pool can also be substantially increased by change in landuse if a cultivated or managed ecosystem produces and returns more biomass to the soil than the natural ecosystems. Experiments conducted in Cerrados, Brazil by Resck et al. (1991) showed that change of land use from native savanna to continuous rice cultivation for 2 years increased SOC by about 21%. However, SOC decreased by 7% by continuous cultivation of soybeans for 3 years. Nye and Greenland (1960) and Young (1976) proposed the model in Eq. 2 to show the rate of SOC increase in soil during fallowing:

$$I = A(1 - P) \tag{2}$$

where I is increase in SOC content, A is addition of SOC to the soil and P is SOC in a natural ecosystem.

Cover crops and fallowing:
Growing aggressive cover crops and managed fallow systems enhance SOC content. Lal et al. (1978) observed that growing grasses and leguminous cover crops for 2 years increased SOC content of a degraded Alfisol in western Nigeria. In the Amazonian region, Martins et al. (1991) observed that fallowing increased SOC content of the sand fraction.

Agroforestry and agro-pastoral systems:
Cropping systems that produce and return biomass to the soil surface enhance SOC content. Relatively low biomass produced in monoculture grain crops may be greatly enhanced by mixed or polycultures (e.g., agroforestry or agro-pastoral systems). However, removal of biomass or intensive cultivation may reduce SOC contents even in these systems (Lal, 1989; 1995).

Improved pastures and deep-rooted crops:
Deep-rooted crops with capacity to produce biomass in large quantities may enhance SOC content of the sub-soil horizons where it is not easily mineralized and decomposed (Pereira et al., 1954; Kannegieter 1969; Kemper and Derpsch, 1981). Ley farming systems, with controlled grazing and low stocking rate, are effective in reducing losses and improving SOC pool (McCown et al., 1979; 1985). Deep- rooted grasses may increase SOC both in coarse and fine soil fractions (Albrecht 1988; Feller et al., 1987). In the Amazonia region of Brazil, Teixeira and Bastos (1989) observed that conversion of primary forest to improved pasture maintained a high level of SOC in the top 0 to 20 cm depth (Table 5). In the Cerrado region of Brazil, Resck et al. (1991) observed that SOC content was considerably more in less disturbed systems (e.g. native savanna, pastures, and trees) than in disturbed systems (e.g. soybean). Soils under Brachiaria pasture contained 23 to 29 Mg/ha more SOC than soils under cultivation for 11 years. Experiments conducted in acid savanna soils of Colombia have shown large increases in SOC content by deep-rooted pastures (Table 6). If these data are representative, Fisher et al. (1994) claim that C sequestration in 250 million ha of acid savanna soils of Latin America may be as much as 500 Mg C/ha/yr.

Table 5. Mean soil organic carbon (SOC) content of 0–20 cm depth under primary forest and pasture of *Brachiaria humidicola* in a clayey Oxisol in Central Amazon, Brazil (adapted from Teixeira and Bastos, 1989).

Ecosystem	SOC (%)
Primary forest	2.62
1-year old pasture	2.40
2-year old pasture	2.10
6-year old pasture	2.32
7-year old pasture	2.48
8-year old pasture	2.40

Residue management and mulching:
Judicious use of crop residue and mulch farming techniques are effective in C sequestration (Lal, 1975; 1976; Lal et al., 1980). Feller et al. (1987) observed that mulching of a sandy soil in West Africa increased SOC especially in the fraction finer than 50 μm. Farming systems that produce a large quantity of biomass and return it to the soil support more SOC pool than those that produce less.

(b) Increasing humification:

Improving the slow C pool or humus content is an important strategy to enhance the SOC pool. The labile or active fraction is easily decomposed. Management practices to enhance humification include none or controlled burning, returning crop residue mulch and other biomass to the soil, and preventing losses through conservation- effective measures [e.g., Conservation Reserve Program (CRP), afforestation, and soil restoration (Fig. 5)]. Benefits of these programs in improving SOC contents are well documented (Johnson, 1995; Lal et al., 1995,b).

Soil quality indicators for C sequestration

Soil quality, soils capacity to produce economic goods and services and perform environmental regulatory functions, is governed by SOC through its effect on numerous soil properties and processes. Soil quality is a function of SOC, median aggregate size as a measure of soil structure and tilth, and C content in aggregates of different size fractions (Fig. 6). These attributes are affected and in turn influenced by: (i) activity and

Table 6. Increase in soil organic carbon (SOC) content (Mg/ha) in some Savanna soils of Colombia by deep-rooted pastures (adapted from Fisher et al., 1994).

Depth	A. *gayans*/S. *capitata*	B. *humidicola*	B. *humidicola*/A. *pintol*
	Mg/ha		
0 - 20	7.1±2.0	5.7±4.3	17.8±4.2
20 - 40	9.3±2.8	5.3±3.2	18.6±6.0
40 - 100	34.3±9.3	14.9±6.2	34.0±10.0
Total increase	50.7±11.4	25.9±7.7	70.4±15.5

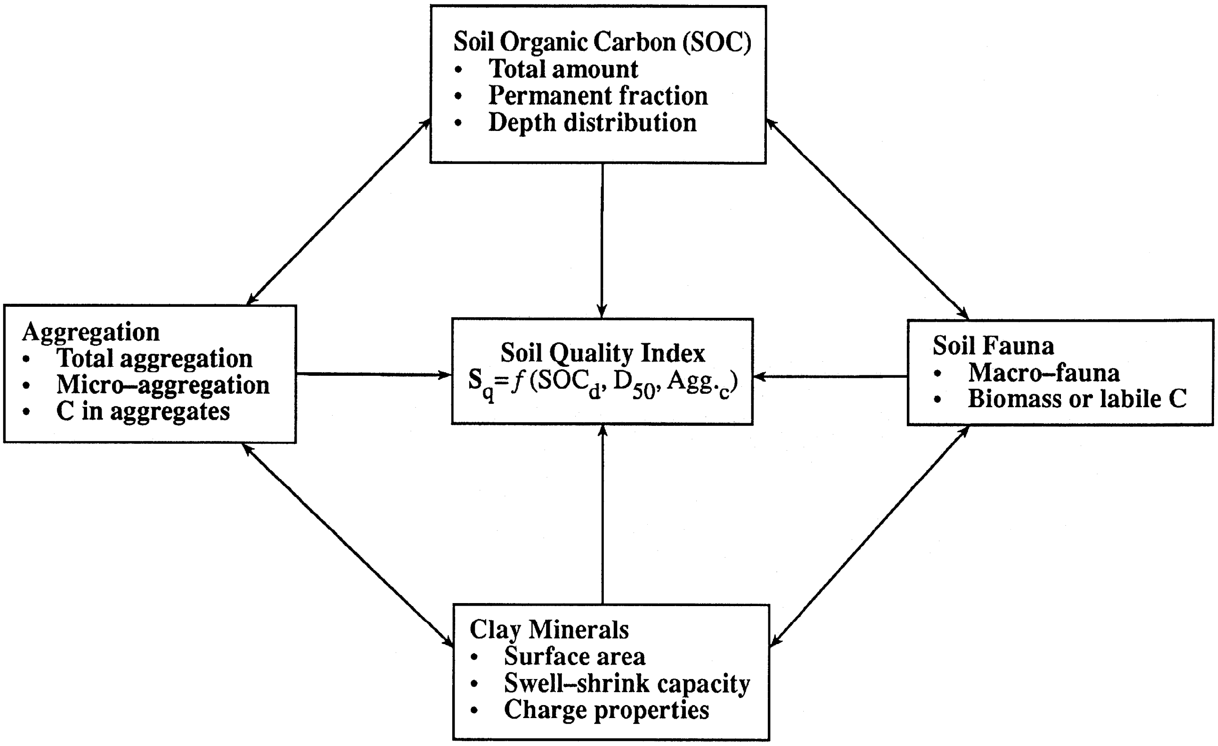

Figure 6. Soil quality index for C sequestration in relation to soil properties.

species diversity of soil fauna, (ii) quantity and quality of SOC, (iii) structural properties and (iv) interaction with clay minerals (Fig. 6). Soil quality enhancement implies improvements in SOC content through judicious soil and crop management, appropriate land use, and science-based improved agriculture. Sustainability is also intimately linked to soil quality. Management of SOC, therefore, is crucial to high soil quality and attainment of agricultural sustainability.

References

Albrecht, A., 1988. Influence du systéme de culture sur é aggrégation d'un vertisol et d'un sol ferrallitique (Antilles). Cahiers ORSTOM, Séries Pedologie 24: 351–353.

Blevins, R.L., D. Cook, and S.H. Phillips, 1971. Influence of no-tillage on soil moisture. Agron. J. 63: 593–596.

Blevins, R.L., G.W. Thomas, and P.L.. Cornelius, 1977. Influence of no-tillage and N fertilization on certain soil properties after 5 years of continuous corn. Agron. J. 69: 383–386.

Bouwman, A.F. (ed), 1990. Soils and The Greenhouse Effect. J. Wiley & Sons, Chichester, U.K.

Brams, E.A., 1971. Continuous cultivation of West African soils: organic matter diminuition and effects of applied lime and phosphorus. Plant and Soil 53: 401–414.

Brown, J.R., 1994. The Sanborn field experiment. In R.A. Leigh and A.E. Johnson (eds) "Long-term Experiments in Agriculture and

Ecological Sciences", CAB International, Wallingford U.K.: 39–51.

Carter, M.R. (ed), 1993. Conservation tillage in temperate agroecosystems. Lewis Publishers, Boca Raton, Fl, 390 pp.

Chan, K.Y. and J.A. Mead, 1988. Surface physical properties of a sandy loam soil under different tillage practices. Aust. J. Soil Res. 26: 549–559.

Dalal, R.C., 1989. Long-term effects of no-tillage, crop residue, and nitrogen application on properties of a Vertisol. Soil Sci. Soc. Am. J. 53: 1511–1515.

Dalal, R.C., 1992. Long-term trends in total nitrogen of a vertisol subjected to zero-tillage, nitrogen application and stubble retention. Aust. J. Soil Res. 30: 223–231.

Datiri, B.C. and B. Lowery, 1991a. Effects of conservation tillage on hydraulic properties of a Griswold silt loam soil. Soil Tillage Res. 21: 243–256.

Datiri, B.C. and B. Lowery, 1991b. Effects of conservation tillage on hydraulic properties of a Griswold silt loam soil. Soil Tillage Res. 21: 257–271.

Fausey, N.R. and R. Lal, 1992. Drainage-tillage effects on a Crosby-Kokomo soil association in Ohio III. Organic matter content and chemical properties. Soil Technology 5: 1–12.

Feller, C., J.L. Chopart, and F. Dancette, 1987. Effet de divers modes de restitution de pailles de mil sur le niveau et al nature du stock organique dans deux sols sableux tropicaux (Senegal). Cahiers ORSTOM, Series Pedologie 24: 237–252.

Fisher, M.J., I.M. Rao, M.A. Ayarza, C.E. Lascano, J.I. Sanz, R.J. Thomas and R.R. Vera, 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature 371: 236–238.

Greenland, D.J., 1972. Adsorption of PVA by oxides and clays with non-expanding lattices. In M. De Boodt (ed) "Fundamentals of Soil Conditioning", Symp. Proc. 17–21 April, 1972, Gent, Belgium.

Hall, D.O., 1989. Carbon flows in biosphere: present and future. J. Geographical Society 146: 175–181.

Houghton, R.A., J.E. Hobbie, J.M. Melillo, B. Moore, B.J. Peterson, G.R. Shaver and G.M. Woodwell, 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere. Ecol. Monogr. 53: 235–262.

Jenkins, D.S. and A. Ayanaba, 1977. Decomposition of carbon–14 labelled plant material under tropical conditions. Soil Sci. Soc. Am. J. 41: 912–916.

Jenkinson, D.S. and J.H. Rayner, 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. 123: 298–305.

Johnson, M.G., 1995. The role of soil management in sequestering soil C. In R. Lal et al. (ed) "Soil Management and Greenhouse Effect", CRC/Lewis Publishers, Boca Raton, Fl.: 351–363.

Johnson, M.G. and J.S. Kern, 1991. Sequestering carbon in soils: A workshop to explore the potential for mitigating global climate change. EPA/600/3–91/031. USEPA, Corvallis, 85 pp.

Juo, A.S.R. and R. Lal, 1978. Nutrient profile in a tropical Alfisol under conventional and no-till systems. Soil Sci. 127: 168–173.

Kang, B.T., G.F. Wilson, and L. Sipkens, 1981. Alley cropping maize with Leucaena in Southern Nigeria. Plant Soil 63: 165–179.

Kannegieter, A., 1969. The combination of a short term pueraria fallow, zero cultivation and fertilizer application: Its effects on a following maize crop. Trop. Agr. 125: 1–18.

Karlen, D.L., D.C. Erbach, T.C. Kasper, T.S. Colvin, E.C. Berry and D.R. Timmons, 1990. Soil tilth: a review of past perceptions and future needs. Soil Sci. Soc. Am. J. 54: 153–160.

Kemper, B. and R. Derpsch, 1981. Results of studies made in 1978 and 1979 to control erosion by cover crops and no-tillage techniques in Parana, Brazil. Soil Tillage Res. 1: 253–267.

Kern, J.S. and M.G. Johnson, 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci. Soc. Am. J. 57: 200–210.

Lal, R., 1975. Role of mulching techniques in tropical soil and water management. IITA Tech. Bull. 1, 38 pp.

Lal, R., 1978. Influence of within- and between-row mulching on soil temperature, soil moisture, root development and yield of maize in a tropical soil. Field Crops Res. 1: 127–139.

Lal, R., 1979. Influence of six years of no-tillage and conventional plowing on fertilizer response of maize on an Alfisol in the tropics. Soil Sci. Soc. Am. J. 43: 399–403.

Lal, R., 1986. Soil surface management in the tropics for intensive land use and high and sustained production. Adv. Soil Sci. 5: 1–105.

Lal, R., 1989. Conservation tillage for sustainable agriculture. Adv. Agron. 42: 85–197.

Lal, R., 1995. The role of residues management in sustainable agricultural systems. J. Sustainable Agric. 5: 51–78.

Lal, R. and B.T. Kang, 1982. Management of organic matter in soils of the tropics and sub- tropics. XII Cong. Int/l Soc. Soil Sci., New Delhi, India: 152–178.

Lal, R. and T.J. Logan, 1995. Agricultural activities and greenhouse gas emissions from soils of the tropics. In R. Lal, J. Kimble, E. Levine and B.A. Stewart (eds) "Soil Management and Greenhouse Effect", CRC/Lewis Publishers, Boca Raton, Fl: 293–307.

Lal, R., G.F. Wilson, and B.N. Okigbo, 1978. No-tillage farming after various grasses and leguminous cover crops in tropical Alfisols I. Crop performance. Field Crops Res. 1: 71–84.

Lal, R., G.F. Wilson, and B.N. Okigbo, 1979. Changes in properties of an Alfisol produced by various crop covers. Soil Sci. 127: 377–382.

Lal, R., D.De Vleeschauwer, and R.M. Nganje, 1980. Changes in properties of a newly cleared Alfisol as affected by mulching. Soil Sci. Soc. Am. J. 44: 827– 833.

Lal, R., T.J. Logan and N.R. Fausey, 1989. Long-term tillage effects on a Mollic Ochraqualf in northwest Ohio. III Soil nutrient profile. Soil Tillage Res. 15: 371– 382.

Lal, R., J. Kimble, E. Levine and B.A. Stewart (eds), 1995a. Soils and Global Change. CRC/Lewis Publishers, Boca Raton, Fl., 440 pp.

Lal, R. J. Kimble, E. Levine and B.A. Stewart (eds), 1995b. Soil Management and Greenhouse Effect. CRC/Lewis Publishers, Boca Raton, Fl., 383 pp.

Lavelle, P., 1988. Earthworm activities and soil systems. Biol. Fertil. Soils 6: 237–251.

Letey, J., 1985. Relationship between soil physical properties and crop production. Adv. Soil Sci. 1: 277–294.

Levey, G.J., 1996. Soil stabilizers. In M. Agassi (ed) "Soil Erosion, Conservation and Rehabilitation", Marcel Dekker, Inc., New York, 402 pp.

McCown, R.L., G. Haaland, and C. de Hann, 1979. The interaction between cultivation and livestock production in semi-arid Africa. In: A.R. Hall, G.H. Cannell, and H.W. Lawton (eds), Ecological Studies 34, Agriculture in Semi-Arid Environments. Springer-Verlag, Berlin, pp. 297–332.

McCown, R.L., R.K. Jones, and D.C.I. Peake, 1985. Evaluation of a no- till tropical legume ley farming strategy. In: R.C. Muchow (ed), Agro-research for Australias semi-arid tropics, Univ. Qld., Australia, pp. 450–472.

Martins, P.F., C.C. Cerri, B. Volkoff, E. Andreux and A. Chauvel, 1991. Consequency of clearing and tillage on the soil of a natural Amazonian ecosystem. Forest Ecol. Manage. 38: 273–282.

Nye, P.H. and D.J. Greenland, 1960. The Soil Under Shifting Cultivation. Technical Communication 51. Commonwealth Bureau of Soils, Harpenden,U.K.

Ohiri, A.C. and H.C. Ezumah, 1990. Tillage effects on cassava production and some soil properties. Soil & Tillage Res. 17: 221–229.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima, 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Amer. J. 51: 1173–1179.

Pereira, H.C., E.M. Chenery, and W.R. Mills, 1954. The transient effects of grasses on the structure of tropical soils. Emp. J. Exp. Agric. 22: 148–160.

Post, W.M. and L.K. Mann, 1990a. Changes in soil organic carbon and nitrogen as a result of cultivation. In: A.E. Bouwman (ed) “Soils and The Greenhouse Effect”, J. Wiley, Chichester, U.K.:

Post, W.M., T. Peng, W.R. Emmanuel, A.W. King, V.H. Dale, and D.L. De Angelis, 1990b. The global carbon cycle. Am. Scient. 78: 310–326.

Prove, B.G., R.J. Loch, J.L. Foley, V.J. Anderson, and D.R. Younger, 1990. Improvements in aggretation and infiltration characteristics of a Krasnozem under maize with direct drill and stubble retention. Aust. J. Soil Res. 28: 577–590.

Resck, D.V.S., J. Pereia, and J.E. da Silva, 1991. Dinâmica da matéria orgânica na Regiao dos Cerrados. Documentos 36. Planaltina, Brazil, EMBRAPA, CPAC.

Roth, C.H., B. Meyer, H.G. Frede and R. Derpsch, 1986. The effect of different soybean tillage systems on infiltrability and erosion susceptibility of an Oxisol in Parana, Brazil. J. Agron. Crop Sci. 157: 217–226.

Roth, C.H., B. Meyer, H.G. Frede, and R. Derpsch, 1988. Effect of mulch rates and tillage systems on infiltrability and other soil physical properties of an Oxisol in Parana, Brazil. Soil Tillage Res. 11: 81–91.

Sidiras, N. and C.H. Roth, 1987. Infiltration measurements with double- ring infiltrometers and a rainfall simulator under different surface conditions on an Oxisol. Soil Tillage Res. 9: 161–168.

Sommer, C. and M. Zach, 1992. Managing traffic induced Oxisol compaction by using conservation tillage. Soil Tillage Res. 24: 319–326.

Teixeira, L.B. and J.B. Bastos, 1989. Materia organica nos ecosistemas de floresta primária e pastagens na Amezônia Central. EMBRAPA-CPATU, Belem, Brazil, 26 pp.

Thorburn, P.J., 1992. Structural and hydrological changes in a Vertisol under different fallow management techniques. Soil Tillage Res. 23: 341–359.

Tisdall, J.M., 1996. Formation of soil aggregates and accumulation of soil organic matter. In M.R. Carter and B.A. Stewart (eds) “Structure and Organic Matter Storage in Agricultural Soils”, CRC/Lewis Publisher, Boca Raton, Fl: 57–95.

Unger, P.W., 1990. Conservation tillage systems. Adv. Soil Sci. 13: 27–68.

Unger, P.W. and J.T. Musick, 1990. Ridge tillage for managing irrigation water on the U.S. Southern Great Plains. Soil Tillage Res. 19: 267–282.

Williams, B.G., D.J. Greenland, and J.P. Quirk, 1968. Water stability of natural clay aggregates containing polyvinyl alcohol. Aust. J. Soil Res. 6: 59–66.

Wilson, W.S. (ed), 1991. Advances in Soil Organic Matter Research: The Impact of Agriculture and the Environment. Royal Society of Chemistry. Cambridge, U.K., 400 pp.

Woomer, P.L., A. Martin, A. Albrecht, D.V.S. Resck, and H.W. Scharpenseal, 1994. The importance and management of soil organic matter in the tropics. In: P.L. Woomer and M.J. Swift (eds) “The Biological Management of Tropical Soil Fertility”, J. Wiley & Sons, Chichester, U.K.: 47–80.

Young, A., 1976. Tropical soils and soil survey. Cambridge Univ. Press, Cambridge, 467 pp.