Soil Carbon Sequestration in Natural and Managed Tropical Forest Ecosystems

R. Lal

SUMMARY. This review article collates and synthesizes the available information on the potential of agroforestry and tropical plantations on soil carbon (C) sequestration to mitigate the greenhouse effect. Tropical forest ecosystems (TFEs) occupy 1.8 billion hectares (Bha) of the total area of 4.2 Bha in forest biomes. The terrestrial C pool in TFEs comprises 120 Mg/ha (tons) in vegetation and 123 Mg/ha in soil to 1-m depth. Soil:vegetation C pool ratio ranges from 0.9 to 1.2 and increases with increase in latitude. Total C pool is 212 petagrams (Pg = 1×10^{15} g = 1 gigaton) in vegetation and 216 Pg in soil. The soil C pool of TFEs represents about 14% of the global soil organic C (SOC) pool of 1550 Pg. Deforestation and conversion of natural to agricultural ecosystems depletes the C pool. Thus, the SOC pool can be enhanced by restoration of degraded soils, and conversion to planted fallows, agroforestry, plantations, improved pastures, and mulch farming. The rate of SOC sequestration in soils is 100-1000 kg C/ha/yr, and total potential of SOC sequestration in TFEs is 200-500 Tg C/yr (1 Teragram = 1^{12} g) for two to five decades. There is a vast potential of converting degraded ecosystems and agriculturally marginal soils to agroforestry and forest

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plantations to restore ecosystems, sequester carbon, and mitigate the greenhouse effect.

KEYWORDS. Soil carbon dynamics, tropical soils, soil degradation, forest ecosystems, soil restoration, greenhouse effect, fossil fuel offset, global warming

INTRODUCTION

The global carbon (C) budget shows that about 3.3 Pg (petagram = 1×10^{15} g = 1 billion ton = 1 gigaton) of C is accumulating in the atmosphere annually (IPCC, 2001). The rate of increase is 1.5 to 2.0 parts per million (ppm) per year, with a high rate of 3 ppm for 2003. Terrestrial C sequestration, being a natural process, is one of the possible strategies for reducing the rate of enrichment of atmospheric CO_2. Large land area and high biodiversity of TFEs warrant a detailed study of their importance in the global C cycle.

The TFEs occur within the humid tropics or the bioclimates characterized by consistently high temperatures and high relative humidity. Total annual rainfall of these regions ranges from 1500 mm to 4500 mm received over 8-12 months. The TFE biome occupies a total area of 1.8 billion hectares (Bha); the vegetation of the humid tropics is dominated by rainforest, covering 1.1 Bha to 1.5 Bha, or about 30% of the land area within the tropics (Table 1). Bruenig (1996) estimated the area of rain-

TABLE 1. Estimates of area under tropical rainforest (adapted from NRC, 1993; FAO, 2003).

	Tropical rainforest area (Mha)		
Region	1980	1990	2000
Africa	289.7	241.8	224.8
Latin America	825.9	753.0	718.8
Asia	334.5	287.5	187.0
Total	1450.1	1282.3	1130.6

forest at 1.64 Bha in 1985 and 1.5 Bha in 1995. Predominant soils of these ecoregions are Oxisols, Ultisols, Alfisols, and Inceptisols (Table 2). Of the total land area of TFEs of 1.8 Bha, 35% are Oxisols, 28% are Ultisols, 15% are Inceptisols, 14% are Entisols, 4% are Alfisols, 2% are Histosols, and 2% comprises Spodosols, Mollisols, Vertisols and Andisols (WRC, 1993). Soil-related constraints to crop production include nutrient imbalance characterized by low availability of N, P, Ca and Mg; low pH, and toxic concentrations of Al and Mn.

The objective of this article is to review the importance of agroforestry, plantations, and other land use and management systems which may restore or enhance SOC pool, improve soil quality and reduce the rate of enrichment of atmospheric concentration of CO_2.

ORGANIC CARBON POOL IN SOILS OF TROPICAL FOREST ECOSYSTEMS

Soil organic carbon (SOC) pool plays an important role in productivity and sustainable use of soils of TFEs through the moderation of cation exchange capacity (CEC), water holding capacity, soil structure, resistance against erosion, nutrient retention and availability and buffering against sudden fluctuations in soil pH. All other factors (clay content, landscape position, drainage, etc.) remaining the same, SOC concentration in soils of the tropics is similar to that of the temper-

TABLE 2. Predominant soils of tropical rainforest ecosystems (adapted from NRC, 1993).

	Area (Mha)			
Soil order	Asia	Africa	Latin America	Total
Oxisols	14	179	332	525
Ultisols	131	69	213	413
Alfisols	15	20	18	53
Inceptisols	90	75	61	226
Entisols	31	91	90	212
Histosols	23	4	–	27
Spodosols	6	3	10	19
Mollisols	7	–	–	7
Vertisols	2	2	1	5
Andisols	1	1	–	2
Total	379	444	666	1489

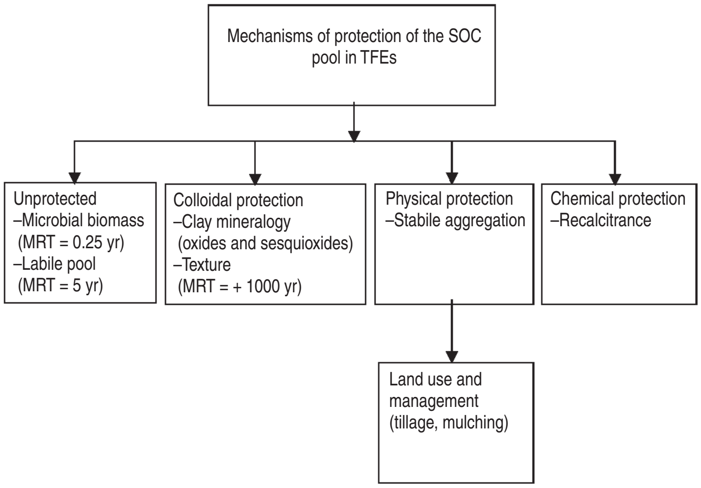
ate ecosystems (Table 3). The mean SOC pool (kg/m^2) for 0-15 cm and 0-100 cm depths, respectively, has been reported to be 3.8 and 11.3 for Oxisols, 2.9 and 6.4 for Alfisols, 2.1 and 6.4 for Ultisols of the tropics compared with 3.3 and 10.1 for Mollisols, 2.8 and 5.8 for Alfisols and 2.4 and 4.2 for Ultisols of temperate regions (Sanchez et al., 1982). The SOC pool in soils of the lowland tropics is 4-6 kg/m^2, which decreases rapidly to 1-3 kg/m^2 in cropland and 2-4 kg/m^2 under plantation (Woomer et al., 1994). Cerri et al. (2000) reported that the SOC pool in soils of the Amazon is 2.3-21.7 kg C/m^2 to 1-m depth. The mean C pool in TFE is 121 Mg/ha for vegetation and 123 Mg/ha for soil, with a total C pool of 212 Pg in vegetation and 216 Pg in soil worldwide (Dixon et al., 1994). Prentice (2001) estimated the terrestrial C pool in TFE at 553 Pg comprising 340 Pg in vegetation and 213 Pg in soil with corresponding values of 120-194 Mg/ha in vegetation and 120-123 Mg/ha in soil. Thus, the SOC pool of TFEs is about 14% of the global SOC pool of 1550 Pg.

Major differences in the SOC pool in soils of the tropics versus temperate climate lie in the rate of decomposition, land use conversion and soil management. Over and above the differences in chemical composition, the rate of decomposition can be four times faster in the tropics than in temperate climates because of high temperatures (Jenkinson and Ayanaba, 1977). There are also differences in the mechanisms of protection of the SOC pool (Figure 1). Some soils with variable charge are richer in aliphatic (colloidal material of volcanic origin) material and carboxyl groups (Oades et al., 1989). Organic materials are absorbed on oxide surfaces leading to formation of stable micro-aggregates comprising organo-variable-charge-clay systems. It is this microstructure that stabilizes SOC in allophonic soils for several thousands of years (Wada and Aomine, 1973). However, intensive tillage can disrupt these stable aggregates (Wada, 1985; 1986) and release SOC. Strong aggre-

TABLE 3. Mean soil organic carbon content of 61 soils from the tropics and in US soils from temperate regions (modified from Sanchez et al., 1982).

	SOC concentration (%)		
Depth (cm)	Tropical soils	Temperate soils	Significance
0-15	0.97	0.95	NS
0-50	0.64	0.60	NS
0-100	0.40	0.36	NS

FIGURE 1. Mechanisms of protection of organic matter in soils of the tropics.



gation is also observed in some soils of eastern Africa and Central and South America. Distribution of SOC deep in the sub-soil, away from the zone of anthropogenic perturbations, and formation of chemically and biologically recalcitrant fractions is also important to retention of C in soil. Charcoal, formed by natural or managed fires, similarly retains C. Thus, the ability of the soils and management systems to protect the SOC pool against anthropogenic perturbations is a key determinant of C sequestration.

CARBON DYNAMICS IN SOILS OF THE TROPICS

The SOC dynamics is described by addition and decomposition of biosolids (Equation 1):

$$\frac{dC}{dt} = -KC + A \tag{1}$$

where dC/dt is the rate of change of C as SOC pool, t is time, K is decomposition constant and A is accretion of biomass comprising the amount of C added to the soil through crop residue, leaf litter, root biomass and detritus material. Soil C sequestration happens when the quantity $(A-KC)$ is positive and depletion occurs when it is negative.

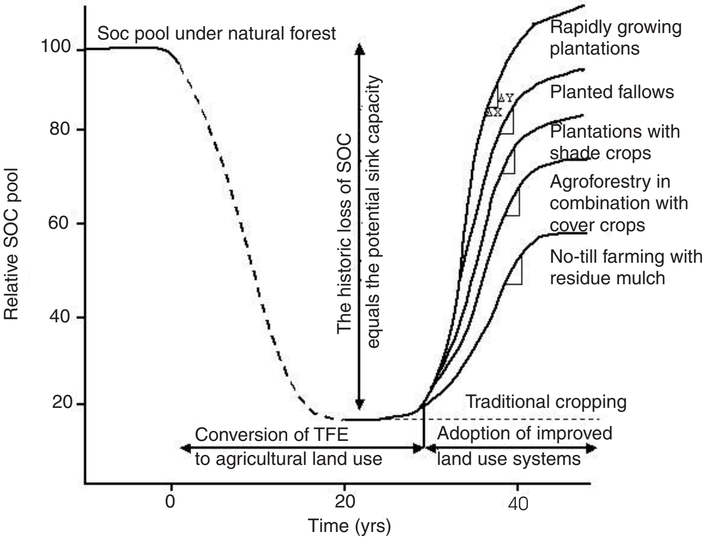
The factor K is generally higher for tropical than for temperate climates because of the higher mean annual temperature and favorable soil moisture. It also depends on the composition of the biomass, including N and lignin concentrations. For Western Ghats in India, Kumar and Deepu (1992) reported that the decomposition constant (K) was strongly affected by the N content rather than lignin:N content ratio. At equilibrium, as is the case for undisturbed TFEs, the addition of C equals the loss (by decomposition, erosion, leaching) and the rate of change is zero. Thus, the C pool at steady state is given by Equation 2:

$$C = \frac{A}{K} \tag{2}$$

The functional relationship depicted in Equations 1 and 2 is also influenced by availability of N, P and other nutrients. Deforestation and harvesting of biomass in croplands and grazing lands depletes the SOC pool. The rate of SOC depletion upon conversion from natural to agricultural ecosystems is higher in TFEs than in soils of higher latitudes, and it depends on the clay content, degree of aggregation and the frequency and intensity of disturbance. SOC depletion is exacerbated by accelerated soil erosion and other degradative processes.

Conversion of natural TFEs to agricultural land use leads to a rapid decline in the SOC pool which, in severely degraded soils, may decrease to 20% of the antecedent pool (Figure 2). Adoption of recommended management practices (RMPs) on degraded soils can help sequester more SOC. These practices include: no-till cropping of root or grain crops with crop residue mulch and integrated management of soil fertility, adoption of agroforestry measures, establishing plantations (cocoa, coffee) with companion shade crops, and afforestation with rapidly growing and site-adapted plantations (Figure 2). The rate of SOC sequestration in these restorative strategies depends on the amount and quality (C:N ratio, lignin content, etc.) of biomass added, depth and proliferation of the root system, conservation-effectiveness of these measures for erosion control and change in soil moisture and temperature regimes that decreases the rate of decomposition of the biomass. The strategy is to select land use and soil management systems that increase biomass addition to the soil and decrease the rate of its decomposition, so that the quantity $(A-KC)$ in Equation 1 is positive and large.

FIGURE 2. A schematic representation of the dynamics of soil organic carbon in TFEs. The rate of increase in the SOC pool depends on the restorative land use. The rotation time is 12 years for fast-growing species and 20-25 years for slow-growing species. The symbol Δ on each curve denotes the rate (ΔY/ΔX) of SOC sequestration, and it depends on the reference point or base line. The rate may be high and positive when degraded cropland is used as a reference point, and slow or negative when natural TFE is chosen as reference. Afforestation of degraded agricultural soils with rapidly growing plantations may have SOC sequestration rate of 1 Mg C/ha/yr.



LAND USE AND MANAGEMENT SYSTEMS

The principal land uses in TFEs discussed here are planted fallows, agroforestry, pastures, short rotation tree plantations and root crops based systems. The SOC pool and its dynamics depend on the specific management system.

Planted Fallows

Planted fallows are cover crops specifically established to restore degraded soils and ecosystems, and generally follow the rotation cycle. Fast-growing annuals, herbaceous species and trees can produce a large quantity of biomass which increases the SOC pool and improves soil structure. Ghuman and Lal (1990) assessed the litter fall under planted fallows on an Ultisol in southern Nigeria. The litter fall under *Cassia siamea* was 5.4 Mg/ha and 6.8 Mg/ha two and three years after planting, respectively. The biomass added contributed 113, 91, 13 and 40 kg/ha/yr of N, Ca, Mg and K, respectively. The rate of biomass production for different species grown in southwestern Nigeria ranged from 7-9 Mg/ha/yr three years after planting and 10-14 Mg/ha/yr eight years after planting (Table 4). These rates were comparable to those of biomass production in the bush fallow system. The litter fall comprised 74-96% of the total production three years after planting and 82-91% of the total production eight years after planting. In southern Senegal, Manlay et al. (2002) observed that the biomass production of 5.5 Mg C/ha in cropland increased to 17.7 Mg C/ha in ten years of fallowed plots. In Zambia, Barrios et al. (1997) reported that trees grown for two to three years in rotation with crops (tree fallows) increased soil fertility in maize *(Zea mays)* based cropping systems. In southwestern Nigeria, Salako et al. (1999) observed that the SOC contents of the 0-5 cm layer under planted fallows were the highest for *Pueraria phaseoloides* for 1-year cropping and 2-year fallow, and for *Leucaena leucocephala* for 1-year cropping and 3-year fallow. Calculations of the SOC pool for 0-15 cm depth from the data on SOC concentration reported by Juo et al. (1995) from southwestern Nigeria (Table 5) show that the SOC pool under bush fallow was lower than that under *Leucaena*, similar to that under Guinea grass and more than that under perennial pigeon pea and maize-based cropping systems. In the tropical Andes, Sarmiento and Bottner (2002) reported that the SOC pool was maintained under a fal-

TABLE 4. Biomass production by a range of planted fallows grown on a degraded Alfisol in western Nigeria (adapted from Salako and Tian, 2001).

	Total biomass production	
Species	3 year growth rate	8 year growth rate
	----------kg/ha/yr----------	
Senna siamea	7,779 (91.5)	10,368 (82.1)
Leucaena leucocephala	8,783 (74.0)	10,049 (83.4)
Acacia leptocarpa	7,602 (83.3)	10,665 (90.7)
Acacia auriculiformis	6,919 (96.1)	12,107 (86.9)
Bush fallow	7,714 (87.6)	13,612 (84.0)
Hedgerows	8,250	11,320

Numbers in parenthesis refer to litter fall as % of the total biomass.

TABLE 5. Temporal changes in SOC stock of 0-15 cm depth of an Alfisol in western Nigeria with cultivation and fallowing treatments (recalculated from Juo et al., 1995).

Years after clearing	Bush fallow	Guinea grass	Leucaena	Pigeon pea	Maize + stover	Maize − stover
	-----------------------------------	-Mg C/ha-	---	---	---	--
0	22.5	28.2	22.9	23.9	29.0	24.1
4	18.0	20.8	19.1	20.0	18.5	14.4
7	15.1	17.1	18.5	16.0	18.2	12.8
10	27.4	31.2	35.1	25.2	27.1	24.8
12	27.4	30.0	33.0	20.8	28.1	27.0
13	30.0	30.9	34.3	25.2	29.8	26.0

low system and did not decrease further. In Brazil, Denich et al. (2000) observed that fallow management is a good strategy for SOC sequestration by small-scale farmers who cannot afford chemical fertilizers.

It is apparent, therefore, that planted fallows are important to maintaining the SOC pool at an optimum level for sustainable use of soils of the TFEs. Determining the frequency of incorporating planted fallows in the rotation cycle is important to the sustainability of the cropping system. The duration of cropping (t_c) and planted fallows (t_{pf}) can be adjusted to attain the desired level of SOC. If the mean SOC content of the soil is C_m, Equation 1 can be re-written as follows:

$$(-K_c C_m + A_c)t_c + (-K_{pf} C_m + A_{pf})t_{pf} = 0 \tag{3}$$

where K_c and K_{pf} refer to decomposition constants, A_c and A_{pf} are accretion constants, and t_c and t_{pf} are the duration of cultivation and planted fallows, respectively. Rearrangement of Equation 3 allows computation of the ratio of cropping periods to the planted fallow period to maintain the desired level of SOC.

$$\frac{t_c}{t_{pf}} = \frac{\left(A_{pf} - K_{pf} C_m\right)}{\left(K_c C_m - A_c\right)} \tag{4}$$

where K and A are determined experimentally and the desired level of C_m can be fixed for a specific ecoregion.

Agroforestry Systems

It is widely recognized that establishing trees in degraded ecosystems improves soil quality (Buresh and Tian, 1998). Therefore, growing trees in association with crops or pastures can also improve soil quality or reduce the risks of soil degradation. Agroforestry is a strategy of growing trees/woody perennials and crops or pastures on the same land at the same time. There are numerous types of agroforestry systems (Sanchez, 1995; Sanchez et al., 1994), and these are useful because some can duplicate important characteristics of undisturbed ecosystems (Tornquist et al., 1999). Agroforestry systems which increase the biomass returned to the soil and decrease the rate of its decomposition make the quantity $(A-KC)$ in Equation 1 positive and enhance the SOC pool. The SOC pool of the cropland increases only if either the addition of the biomass is enhanced (A) and/or the decomposition rate (K) is decreased (Sauerbeck, 2001). Site-specific agroforestry systems provide opportunities by which such improvements can be achieved. Wright et al. (2001) compared C sequestration potential of a maize-based system with that of an agroforestry system to sequester C at global scale. They estimated that an additional 670-760 Mha of maize area under improved management would be required to assimilate 3.3 Pg C yr^{-1} being added annually into the atmosphere (Wright et al., 2001). In contrast, adoption of agroforestry on just 460 Mha would achieve the same objectives (Wright et al., 2001). Wright and colleagues argued that agroforestry is the only system that could realistically be implemented to reduce global CO_2 levels through terrestrial C sequestration, a claim that needs to be verified and critically assessed.

Alley cropping, or hedgerow cropping, is a system of agroforestry where trees and crops are intercropped, the former being periodically pruned to produce mulch and minimize the adverse impact of shading (Haggar et al., 1993). Beneficial effects of alley cropping on improvements in soil fertility and crop yield have been reported from Ghana (Astivor et al., 2001), and the sub-humid highlands of Kenya (Mugendi et al., 1999). In Ghana, Astivor and colleagues reported that mean SOC concentration at 0-15 cm depth was 18.6 g/kg under eight-year old woodlot of *Leucaena leucocephala*, 14.0 g/kg under alley cropping, 14.5 g/kg under natural fallow and 13 g/kg under conventional tillage. In Kenya, Mugendi et al. (1999) reported that *Leucaena* hedges contributed more prunings and N than those of *Calliandra*. However, these hedges decreased yield of maize due to competition for light, nutrients and water. For an Ultisol in southern Nigeria, Ghuman and Lal (1990) reported that the biomass production by hedgerows of *Gliricidia sepium* in an alley cropping system contributed 10.8 Mg/ha/yr of biomass containing 2.3 Mg/ha/yr of leaves and 81.2 kg/ha/yr of N. Similar observations have been reported by Kang (1987) and Mulongoy and van der Meersch (1988). Kang (1997) reported that SOC concentration at 0-15 cm depth after establishing five years of *Leucaena* hedgerows was 12.3 g/kg under the hedgerows, 9.4 g/kg in the alleys between the hedgerows, and 5.9 g/kg in the control without hedgerows. The data in Table 6 shows the SOC pool under different cropping systems on an Alfisol in southern Nigeria. Over a five year period, the SOC pool declined in all ecosystems. The mean rate of decline in the 0-10 cm layer over the five-year period was 3.0 Mg C/ha/yr in plow till, 1.2 Mg C/ha/yr in no-till, 1.4 Mg C/ha/yr in *Leucaena* hedgerows 4 m apart, 1.9 Mg C/ha/yr in *Leucaena* hedgerows 2 m apart, 2.2 Mg C/ha/yr in *Gliricidia* hedgerows 4 m apart, and 2.4 Mg C/ha/yr in *Gliricidia* hedgerows 2 m apart.

In northern India, Chander et al. (1998) assessed the impact of intercropping of wheat (Triticum aestivum) and cowpeas (Vigna unguiculata) with 12-year old N_2-fixing *Dalbergia sissoo*. They observed that the SOC and microbial biomass C increased in soils under *D. sissoo*. Sev-

TABLE 6. Alley cropping effects on soil organic carbon pool of 0-10 cm depth under maize-cowpea rotation for an Alfisol in western Nigeria (recalculated from Lal, 1989a; b; c).

	Years after establishment of tree hedgerows				
Treatment	1	2	3	4	5
	Mg C/ha				
Plow	20.0	14.6	10.8	10.6	5.2
No-till	18.9	20.4	11.2	16.2	13.1
Leucaena-4 m	20.5	22.6	17.1	19.9	13.6
Leucaena-2 m	20.6	17.6	19.3	15.5	11.1
Gliricidia-4 m	22.0	22.2	14.6	16.4	11.0
Gliricidia-2 m	20.4	13.8	11.7	17.2	8.2

eral agro-forestry systems used in southeastern Asia have reportedly improved the SOC pool. In the Philippines, Malab et al. (1996; 1997) reported that hedgerows of Desmanthus virgatus increased SOC concentration in the surface layer from 11.4 g/kg to 15.3 g/kg after four years of continuous mulching produced by the prunings. Lasco (1991) evaluated biomass production and soil properties for three species grown as hedgerows at Los Baños, Philippines: *Leucaena leucocephala*, *Sesbania grandiflora* and *Pennisetum purpureum*. Mulching with the herbage significantly improved the SOC pool, total soil N, and available P and K. In Thailand, Patma-Vityakon (1991) reported that the SOC concentration was high in systems with frequent return of biomass to the soil.

Several studies conducted in Africa indicate the importance of agroforestry systems on erosion control (Lal, 1989a). Roose and Barthes (2001) reported that the rate of SOC loss by erosion and leaching ranged between 10 and 100 kg C/ha/yr on sloping cultivated lands in west Africa. Established perennial hedgerows in Rwanda reduced losses from runoff and erosion, and observed that agroforestry systems which produce good-quality litter are an important part of the solution. *Leucaena* hedgerow intercropping systems with cattle manure have also been successful in Ethiopia (Lupwayi and Haque, 1999a; b; Lupwayi et al., 1999). In Kenya, Maroko et al. (1998) observed tree-root competition with maize can be minimized through species selection. Barrios et al. (1996a; b; 1997) reported improvement in soil fertility and N-availability by using prunings of *Sesbania* and *Gliricidia*. Woomer et al. (2000) reported that a 23-year old agroforestry system had a total system C pool (including plant components) of 130 Mg C/ha compared to 48 Mg C/ha in a pastoral system.

Agroforestry systems have been widely used in South and Central America. In Brazilian Amazonia, Schroth et al. (2002) observed that 7 years after establishment, multi-strata systems had an above-ground biomass of 13.2-42.3 Mg/ha, a below-ground biomass of 4.3-12.9 Mg/ha and a litter mass of 2.3-7.2 Mg/ha compared with those for monoculture at 7.7-56.7 Mg/ha, 3.2-17.1 Mg/ha and 1.9-5.6 Mg/ha, respectively. The combined biomass and litter was the highest in peach palm (*Bactris gasipaes*) for fruit. In comparison, 14-year old secondary forest had a combined biomass and litter stock of 127 Mg/ha. At Yurimaguas, Peru, Woomer (1993) reported that the SOC pool in the surface layer was 2.7 kg/m^2 for rainforest, 2.8 kg/m^2 for field crop and 2.6 kg/m^2 for an agroforestry system. In the Atlantic region of Costa Rica, Tornquist et al. (1999) studied the impact of tropical hardwoods (*Vochysia* *ferruginea*, *Vochysia guatemalensis*, *Stryphnodendron microstachyum* and *Hieronyma alchorneoides*) as a tree component of an agroforestry system and compared soil properties with pasture systems. Higher mineralizable C levels were observed in pastures than under agroforestry. Also in Costa Rica, Mazzarino et al. (1993) observed no significant differences in the SOC pool of a Eutric Cambisol after nine years of alley cropping and control, although the SOC concentration increased by 10% under alley cropping over this period. Kass et al. (1989; 1997) also studied the impact of agroforestry systems using *Erythrina poeppigiana* and *Gliricidia sepium*. They observed that for systems with low nutrient removal trees that are allowed to grow for long periods of time without being pruned would make greater contributions to the improvement of soil quality than those in which frequent pruning is the normal practice. In the French Antilles, Dulormme et al. (1999) reported that the SOC concentration after ten years of agroforestry increased from 2.41% to 2.84% at 0-10 cm depth, and from 1.83% to 2.16% at 10-20 cm depth.

The sign and magnitude of the term $(A-KC)$ for an agroforestry system determines the dynamics of the SOC pool and management-induced changes in soil properties. The magnitude of $(A-KC)$ depends on species of tree/shrub, soil type, rainfall, climate and the management. Differences in the site-specific factors lead to differences in soil and crop response to agroforestry systems. The term $(A-KC)$ in Equation 1 was negative in all systems in Table 6 because the biomass returned was not enough to balance the decomposition rate. Incorporating *Mucuna utilis* in the rotation cycle along with a combination of no-till and a hedgerow system may have made the term $(A-KC)$ positive and maintained or enhanced the SOC pool. For example, in Pakistan eucalyptus + wheat-based agroforestry systems decreased the SOC pool in several soils (Bhatti and Khan, 2002), but improved crop yield and soil quality in Sudan (El-Amin et al., 2001). Such contradictions may need to be resolved by using ^{13}C analyses and modeling techniques (Diels et al., 2001), in conjunction with an evaluation of the effects of soil type, nutrient availability, soil moisture regime, species, and the biomass returned.

Pastures

Pastoral land use is an economically important agroecosystem in the TFEs. Yet conversion of TFE into pasture leads to release of CO_2 and other greenhouse gases into the atmosphere. The undisturbed TFE may contain as much as 406 Mg of biomass/ha of which 309 Mg may be the above-ground material (Fearnside, 2000). Thus, deforestation and burning of TFE leads to large emissions of CO_2 on a global scale (IPCC, 2001). The establishment of pastures can improve (Cerri et al., 1991; 1994; Moraes et al., 1995; 1996; Neill et al., 1997; Noordwijk et al., 1997), deplete (Trumbore et al., 1995; Desjardin et al., 1994; Luizao et al., 1992) or have no effect (Feigl, 1995) on the SOC pool, depending on the soil type and antecedent SOC pool, pasture species and management. Neill and Davidson (2000) reported that nineteen of the 29 pastures examined in the Amazon accumulated C in surface soils and ten showed C loss. Pastures formed on forest soils with high antecedent SOC pool tended to lose C, while those formed on soils with low SOC pool (< 5 kg/m^2) tended to gain SOC. Pastures planted with *Brachiaria humidicola* tended to lose SOC; those planted with *Panicum maximum* and *Brachiaria brizantha* tended to gain SOC. In the Cerrado region of Brazil, Resck et al. (2000) reported that decomposition rates are high especially in loamy Latosols and quartz sand, and that managed pastures have a high capacity to recover the degraded SOC pool and improve soil physical quality. In the Atlantic region of Costa Rica, Veldkamp (1994) observed a very slow decrease in the SOC pool under pasture. In the acid soil savanna region of Colombia, Fisher et al. (1994) reported drastic increase in the SOC pool by growing deep-rooted grasses. Some planted fallows can be used as pastures, and SOC under pastures can be greatly enhanced with controlled grazing, establishing improved species and fertility management (Koutika et al., 1999; 2000). See Amezquita et al. (this volume) for more on this subject.

Plantations

In addition to C sequestration in biomass and soil, tropical plantations are needed for timber, and more importantly, as fuel wood for cooking. Thus, the area under tropical plantations has increased drastically since the 1960s, from 7 Mha in 1965 to 21 Mha in 1980, 43 Mha in 1990 (Evans, 1992) and 187 Mha in 2000 (FAO, 2003). Despite the rapid expansion, tropical plantations occupy a relatively small area in relation to other land uses. Extensive literature supports the conclusion that afforestation of degraded soils increases the SOC pool with accompanying improvement in soil quality. Tropical plantations cause less soil disturbance, generally involve no prunings and return a large quantity of leaf litter and detritus material to the soil. Consequently, the SOC pool is either maintained or enhanced under plantations.

Tree plantations are intensively managed tracts of land that are populated by fast-growing single or mixed species to maximize timber or fuelwood production. Establishment of such plantations on degraded lands has large potential for terrestrial C sequestration. It is important, however, to use site-adapted and well-domesticated trees (Bruenig, 1996; Leaky and Newton, 1994). Commonly used species of relatively fast-growing trees in TFEs include: *Acacia mangium, Albizia* spp., *Anthocephalus chinensis*, *Carapa guianensis*, *Casuarina* spp., *Dalbergia nigra*, *Dinizia excelsa*, *Eucalyptus* spp., *Euxylophora paraensis*, *Gmelina arborea*, *Leucaena* spp., *Octomeles sumatrana*, *Paraserianthes falcataria*, *Parkia multijuga*, *Pinus caribaea*, *Prosopis* spp., *Pterocarpus* spp., *Shorea javanica*, *Swietenia machophylla*, *Tectona grandis*, among others. Also, there are large areas in the tropics of plantations of tree crops such as oil palm, rubber, coffee, cashew and cocoa. Establishment of such plantations is a useful strategy whenever natural succession is not effective in rehabilitating degraded ecosystems (Appanah and Weinland, 1992). Timber trees and tree crops sequester C in soil and biomass when established on degraded soils and ecosystems, and nutrient losses during site preparation can be minimized through reducing soil disturbance, minimizing erosion and avoiding burning (Nykvist et al., 1994).

In western Nigeria, Ekanade et al. (1991) reported that the SOC pool under forest was 29 g/kg and that under cocoa was 19 g/kg. Similar observations were made by Adejuwon and Ekanade (1988) in Oyo state, Nigeria. Also in southern Nigeria, Ojunkunle and Eghaghara (1992) observed that the SOC concentration under 10-year old cocoa plantation was 25 g/kg compared with 35 g/kg under forest. In Nigeria, Aweto (1987) reported that the SOC concentration was 14 g/kg under primary forest and 12 g/kg under a 18-year old rubber plantation. The SOC concentration under rubber increased over time. In Kade, Ghana, Duah-Yentumi et al. (1998) reported that the SOC concentration of a soil under 40-year old rubber plantation was lower than that under virgin forest or 20-year old cocoa. Both rubber and cocoa received no fertilizer or manure.

At Turriabla, Costa Rica, SOC concentration under cocoa increased from 28 g/kg to 32 g/kg in 0-15 cm and 23 g/kg to 25 g/kg in 15-30 cm depth in 9 years when cocoa was shaded with *Erythrina poeppigiana* (Beer et al., 1998). Similar improvements in SOC concentration were observed when the cocoa was shaded with *Cordia alliodora* (Beer et al., 1998).

On the basis of a 16-year study on a rubber plantation in Malaysia, Sanchez et al. (1985) reported that the SOC concentration decreased from 18 g/kg under forest to 10 g/kg under rubber. The SOC concentration increased when *Pueraria* was grown under rubber. In Malaysia, Pushparajah (1998) reported that the SOC concentration increased after 20 years of oil palm plantation. In Sumatra, Indonesia, Lumbanraja et al. (1998) reported that the SOC concentration in degraded cropland and primary forest, respectively, was 15.0 g/kg and 60.4 g/kg for 0-20 cm depth, and 7.5 g/kg and 25.0 g/kg for 20-40 cm depth. Conversion of forest to annual crops leads to drastic reductions in the SOC pool in most soils of the TFEs (Hartemink, 2003). Thus, conversion of degraded cropland to plantation would increase the SOC pool over time. In another study, Lumbanrajah et al. (1998) reported that the SOC concentration under 20-year old coffee plantations were 29 g/kg compared with 60 g/kg under forest, and the SOC concentration in cropland were half of that under coffee (15 g/kg) (Table 7). In Papua New Guinea, Kunu and Hartemink (1997) observed no differences in soil chemical properties under coffee and primary forest. Härdter et al. (1997) reported a slight increase in SOC concentration under five-year old oil palm plantation in Malaysia, and indicated that plantations could be established on 11 Mha of degraded land in Indonesia and 1 Mha in Malaysia. Growing legumes in between young plantation trees during the first 5 years is an important strategy for erosion control, nutrient cycling, and SOC sequestration (Beer et al., 1998).

TABLE 7. Changes in SOC concentration by land use conversion in south Sumatra between 1970 and 1990 (adapted from Lumbanraja et al., 1998).

	SOC concentration (g/kg)					
	Bukit Ringgis		Sekinaku		Trimulyo	
Land use	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
Primary forest	60.4	25.0	73.1	32.7	58.0	18.2
Secondary forest	41.4	21.7	42.9	24.5	38.7	12.5
Coffee plantation	28.5	10.1	30.9	11.2	26.7	7.0
Cropland	15.0	7.5	19.3	7.0	14.2	5.5

Considerable research on C balance under plantations has been done in Costa Rica (Montagnini and Sancho, 1990; Stanley and Montagnini, 1999; Montagnini, 2000). Montagnini and Porras (1998) analyzed soil properties 4 years after establishing plantations. Although there is no control (cropland) for comparison, the data in Table 8 show differences in the SOC pool among species. The maximum SOC pool was measured under *Jacaranda copaia* in Site 1, regeneration in Site 2, and *Balizia elegans* in Site 3. The difference in the the SOC pool to 60-cm depth between the minimum and the maximum over a 4-year period was 16.7 Mg/ha for Site 1, and 24.8 Mg/ha for Sites 2 and 3. Smith et al. (2002) studied the impact of plantation forestry on the SOC pool at the Curua-Una Forest Reserve, Pará, Brazil. Several plantations were established between 1959 and 1973, and soil was sampled in 2000. The data in Table 9 show that the SOC pool in the top 20-cm depth ranged from 72 to 115 Mg C/ha. In comparison with the undisturbed forest, the SOC pool decreased by 27% in *Pinus caribaea* and increased by 16% in *Euxylophora paraensis*. There were also differences in forest floor biomass and fine roots among species. The data on SOC sequestration under plantation at Toa Baja in Puerto Rico are shown in Table 10. The mean rate of SOC sequestration in the 0-20 cm layer under *Albizia*

TABLE 8. SOC pool (Mg C/ha) to 60-cm depth 4 years after planting (calculated from Montagnini and Porras, 1998).

Site 1		Site 2		Site 3	
Species	SOC pool	Species	SOC pool	Species	SOC pool
Jacaranda copaia	90.4	*Albizia guachapele*	75.3	*Genipa americana*	61.1
Calophyllum brasiliense	73.7	*Dipteryx panamensis*	73.1	*Hieronyma alchorneoides*	64.4
Stryphnodendron microstachyum	74.8	*Terminalia amazonia*	70.6	*Balizia elegans*	85.9
Vochysia guatemalensis	76.1	*Virola koschnyi*	71.9	*Vochysia ferruginea*	66.9
Mixed	74.9	Mixed	73.2	Mixed	68.5
Regeneration	85.1	Regeneration	95.4	Regeneration	76.8

Assumptions: Organic matter comprised 58% C, and soil bulk density equals 0.6 Mg/m^3 (Fisher, 1995) for all depths and under all species.

TABLE 9. Effects of plantations of 27-41 years duration on organic carbon pool at 0-20 cm depth for a soil in Curua-Una Forest Reserve, Para, Brazil (adapted from Smith et al., 2002).

Treatment	Soil bulk density (Mg/m^3)	Soil organic carbon	
		Concentration (g/kg)	Pool (Mg/ha)
Forest	0.77a	63.9ab	98.4ab
Pinus caribaea	0.84a	42.8c	71.9c
Carapa guianensis	0.80a	49.4bc	79.0bc
Leguminosae	0.81a	51.4bc	83.3bc
Euxylophora paraensis	0.82a	69.9a	114.6a

Leguminosae comprised a combination of *Parkia multijuga*, *Dinizia excelsa* and *Dalbergia nigra*.

TABLE 10. SOC and N pools in the 0-20 cm soil layer of Typic Troposamments in control and 4.5 year old plantations of *Albizia lebbek* in Puerto Rico (calculated from Parrotta, 1992).

	SOC		Nitrogen		Sequestration ratio (kg/ha/yr)	
Treatment	Concentration (%)	Pool (Mg C/ha)	Concentration (%)	Pool (Mg N/ha)	SOC	N
Plantation	1.70 (1.04)	35.4	0.095 (1.04)	1.98	1022	89
Control (grasses)	1.44 (1.07)	30.8	0.074 (1.07)	1.58	–	–

Number in parenthesis is soil bulk density in Mg/m^3

lebbek was 1022 kg/ha/yr, which is a very high rate. Several experiments in South America have shown variable response of SOC to replacement of native forest by plantations. In the Cerrado region of Brazil, Zinn et al. (2002) observed that conversion of native forest to plantations decreased the SOC pool at 0-60 cm depth by 11 Mg/ha in *Pinus* over twenty years and 9 Mg/ha under *Eucalyptus* in seven years. The magnitude of SOC depletion was more in soils with low than high clay content. Significant SOC losses under plantation were also reported by Madeira et al. (1989) and Fonseca et al. (1983). In contrast, no effect on the SOC pool under plantation was reported by Lepsch (1980) and Prosser et al. (1993), and increase in the SOC pool was observed by Sanginga and Swift (1992) and Althoff et al. (1996). Such contradictory results for *Pinus* have been reported by Bernhard-Reversat (1996) and Turner and Lambert (2000).

There is a wide range of factors that affect the response of SOC to conversion of native forest to plantation. Important among these are: soil type (clay content and mineralogy), drainage conditions, antecedent SOC pool, species, management and especially the availability of nitrogen and other nutrients. The effect of establishing tree plantations on soil C storage differs among tree species, which differ in biomass production, tissue nutrient concentrations and their effects on soil quality. There is generally 20-100% more SOC under N-fixers than non-N fixers or 0.05-0.12 kg/m^2/yr more C under N-fixers. Resh et al. (2002) attributed this difference to greater retention of older soil C under N-fixing trees. Some plantation species may also grow better under the enhanced CO_2-fertilization effect, assumed to be 0.5-2 Pg C/yr or the equivalent to 8-33% of the annual global fossil fuel emissions (Davidson and Hirsch, 2001).

The effect of tree plantations on SOC sequestration also depends on the management. Poorly managed plantations may as well be a source rather than a sink for CO_2. In Nigeria, Aweto (1995) observed a decline in SOC pool under plantation compared with natural forest in southern Nigeria. The rate of decline in the SOC pool in kg C/ha/yr for 0-20 cm layer was 392 in teak, 492 in gmelina, 627 in cashew, 720 in rubber, 1890 in oil palm and 1144 in coffee. Aweto concluded that "plantations appear to have the potential of contributing towards global warming–a threat they are supposed to mitigate." Once again, the term $(A - KC)$ was negative under plantations, as the vegetation cover was less dense, plants were less diverse, and the biomass C returned to the soil was less than would have occurred under natural forest. For the $(A - KC)$ term to be positive under plantation, the rate of biomass production and return must be more than the natural forest, as was reported for *Pinus caribaea* in Puerto Rico (Cuevas et al., 1991). If plantations in southern Nigeria were established on degraded cropland they could become a sink for CO_2.

Therefore, identification of degraded soils and choice of site-adapted species for a short-rotation plantation is an important strategy for C sequestration. The data in Table 11 show unused/fallow land and some degraded cropland and pastureland in the Brazilian Amazon which can be converted to tree plantations. There also exists a potential for tree plantations in the unused and degraded lands in the Cerrados (Table 12). Similarly degraded soils and ecosystems exist in Latin America, sub-Saharan Africa, and tropical and sub-tropical regions of Asia. Such

TABLE 11. Temporal trends in deforested area and its use in Brazilian Amazonia (adapted from Margulis, 2004).

	Land Use Change (%)				
	1970	1975	1980	1985	1995
Total area deforested (UNITS)	3.0	4.0	6.2	7.7	9.5
Cropland	0.3	0.6	1.0	1.2	1.1
Planted pastures	0.7	1.4	2.6	3.8	6.6
Unused and fallow	2.0	2.0	2.6	2.7	1.8

Original forested area = 419 million hectares (Mha).
Deforested area: 1978 (15.2 Mha); 1990 (41.5 Mha); 2000 (60.3 Mha).

TABLE 12. Trends in land use in the Brazilian Cerrados (adapted from Margulis, 2004).

Land use (Mha)	1975	1996	Average annual growth (%)
Agricultural area	110.8	124.3	0.5
Anthropic area	34.7	64.5	3.0
Fallow area	0.36	0.67	7.4
Productive area not in use	10.8	4.6	−3.9

Anthropic area = crops, planted pastures, reforested, fallow, and productive land not in use.

lands need to be identified as potential sites for terrestrial C sequestration via the judicious management of fast-growing plantations.

Root Crop Based Systems

Cassava (*Manihot esculenta*), yam (*Dioscorea* spp.), sweet potato (*Ipomea batata*) and taro (*Xanthosomas esculenta*) are examples of important root crops for the TFEs. Severe erosion under cassava can deplete the SOC pool. In Colombia, Ruppenthal et al. (1997) reported SOC loss by erosion under cassava at 15-110 kg C/ha/yr with grass barriers, 38-670 kg C/ha/yr with intercropping, 64-330 kg C/ha/yr with flat planting and 4346-7257 kg C/ha/yr with unplanted bare fallow. Root crops require effective 'root room' for tubers to grow; they also respond positively to mulching because of an effective erosion control, water conservation and temperature moderation (Lal, 1975; Hahn et al., 1979). Including restorative cover crops in the rotation cycle and growing root crops as an agroforestry system are important strategies for enhancing the SOC pool, improving soil quality and increasing productivity. In addition, the application of fertilizers and integrated nutrient management can enhance the SOC pool (Jin et al., 1999) in root crop systems.

GLOBAL POTENTIAL OF SOC SEQUESTRATION IN TFES

There are three strategies of SOC sequestration in TFEs: (i) establishing of tree plantations on degraded and agriculturally marginal soils, (ii) incorporating planted fallows in the rotation cycle, and (iii) using agroforestry techniques. Afforestation, the establishment of tree plantations after ≥ 50 years without forest, has a large potential for SOC sequestration in the tropics (Table 13). The area that must be afforested with tropical plantations to sequester 1 Pg C/yr by 2054 is estimated to be 250 Mha (Pacala and Socolow, 2004). High rates of SOC sequestration at 0.8-4.0 Mg C/ha/yr have been reported for secondary forest succession on land that had been cultivated for 100-300 years in Puerto Rico (Lugo and Sanchez, 1986). Bouwman and Leemans (1995) estimated that afforestation stored 50 Mg of SOC in 30 years. Johnson (1992) reported a > 35% increase in soil C following the afforestation and reforestation of cultivated soils. Brown and Lugo (1990) reported SOC increase of 1-2 Mg C/ha/yr in the wet tropical zone. The data by Parrotta et al. (1992) show SOC sequestration rate of 1022 kg C/ha/yr (Table 10). The rates of SOC sequestration are generally lower in the dry tropics than in the wet tropics. Deans et al. (1999) reported SOC accumulation under 18-year plantation of *Acacia senegal* in northern Senegal at the rate of 0.03%/yr under the tree canopy and 0.02%/yr in the open ground, corresponding to SOC sequestration rates of 420 and 280 kg C/ha/yr for a soil bulk density of 1.4 Mg/m^3. In contrast, Bashkin and Binkley (1998) reported no or little net increase in net SOC sequestration following afforestation.

The CO_2 fertilization effect also has the potential to increase SOC sequestration. However, the positive response to CO_2 fertilization may be limited by the availability of N and other essential nutrients (Schlesinger and Lichter, 2001; Oren et al., 2001). The data in Table 14 show an estimate of the potential of SOC sequestration in TFEs. Thus, the total potential of SOC sequestration in these ecosystems is 200 to

TABLE 13. Land area in tropical regions potentially available for afforestation and adoption of recommended management practices for soil carbon sequestration (adapted from Grainger, 1988; Schroeder, 1992).

Land use	Africa	Asia	Latin America	Total
	------------------------------------Mha-------------------------------			
Logged forests	39.0	53.6	44.0	136.6
Forest fallows	59.3	58.8	84.8	202.8
Deforested watersheds	3.1	56.5	27.2	86.9
Desertified drylands	740.9	748.0	162.0	1650.9
Total	842.3	916.9	318.0	2077.2

TABLE 14. The potential of soil organic carbon sequestration in the TFE of the humid tropics.

Land use	Area (Mha)	Rate of SOC sequestration (kg C/ha/yr)	Potential of SOC sequestration (Tg C/yr)
Agroforestry	500	100-300	50-150
Plantations	250	500-1,000	125-250
No-till mulch farming	50	100-200	5-10
Improved pastures	200	100-500	20-100
Total	1,000		200-510

500 Tg C/yr. The sink capacity may be filled over two to five decades, provided that the restorative land use is followed on a continuous basis. Whereas the rates of SOC sequestration used in these computations are supported by the literature reviewed, the projections of land areas that can be converted to improved and restorative management strategies are based on the estimates by Grainger (1988) and Schroeder (1992). Granger (1988) estimated that tropics contain over 2 Bha of degraded and depleted lands. Of these, 758 Mha were once forested and include 137 Mha of logged tropical moist forests, 203 Mha of forest fallows, 87 Mha of deforested watershed areas and 331 Mha of rainfed/irrigated cropland (Granger, 1988). These areas are suitable for afforestation and adoption of recommended management practices.

CONCLUSIONS

Sustainable management of tropical biomass is essential to terrestrial C sequestration and improving soil and environment quality. Avoiding deforestation through prudent management for land already cleared is important. Appropriate land uses for enhancing the terrestrial C pool include: planted fallows, plantations, site-adapted pastures with deep root systems, and agroforestry systems. The rate of SOC sequestration in TFEs may be 100 to 1000 kg C/ha/yr. High rates may be obtained on clayey soils with favorable soil moisture regimes in farming systems that involve minimal soil disturbance, ensure a continuous supply of biomass to the soil surface, and maintain favorable nutrient balance within the soil and ecosystem. Establishing species adapted to the soil-specific conditions, which produce a large quantity of biomass and have a deep and prolific root system, supports high rates of SOC sequestration. Formation of stable micro-aggregates or organo-mineral complexes is another important mechanism of protection of SOC against microbial processes. The SOC encapsulated within aggregates is not easily decomposed. Site-specific choice of an appropriate farming system depends on soil properties, climate, terrain, and socio-economic, ethnic and cultural factors. Tree-based systems, with planted fallows as shade and mulching, are important components that will contribute to achieving the sustainable use of soil and water resources in TFEs. Soil fertility enhancement through nutrient management is also important to SOC sequestration. Realizing the total potential of SOC sequestration (200-500 Tg C/yr) will necessitate implementation of appropriate policies that encourage adoption of restorative land uses and quantification of changes in the SOC pool over time, so that C credits can be traded in domestic and international markets.

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