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Agriculture, Ecosystems and Environment 99 (2003) 15–27

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Review

Carbon sequestration in tropical agroforestry systems

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Received 15 July 2002; received in revised form 11 February 2003; accepted 8 March 2003

Abstract

Removing atmospheric carbon (C) and storing it in the terrestrial biosphere is one of the options, which have been proposed to compensate greenhouse gas (GHG) emissions. Agricultural lands are believed to be a major potential sink and could absorb large quantities of C if trees are reintroduced to these systems and judiciously managed together with crops and/or animals. Thus, the importance of agroforestry as a land-use system is receiving wider recognition not only in terms of agricultural sustainability but also in issues related to climate change. The objective of this paper was to analyse C storage data in some tropical agroforestry systems and to discuss the role they can play in reducing the concentration of CO_2 in the atmosphere. The C sequestration potential of agroforestry systems is estimated between 12 and 228 Mg ha^{-1} with a median value of 95 Mg ha^{-1}. Therefore, based on the earth's area that is suitable for the practice (585–1215 $\times$ 10^6 ha), 1.1–2.2 Pg C could be stored in the terrestrial ecosystems over the next 50 years. Long rotation systems such as agroforests, homegardens and boundary plantings can sequester sizeable quantities of C in plant biomass and in long-lasting wood products. Soil C sequestration constitutes another realistic option achievable in many agroforestry systems. In conclusion, the potential of agroforestry for CO_2 mitigation is well recognised. However, there are a number of shortcomings that need to be emphasised. These include the uncertainties related to future shifts in global climate, land-use and land cover, the poor performance of trees and crops on substandard soils and dry environments, pests and diseases such as nematodes. In addition, more efforts are needed to improve methods for estimating C stocks and trace gas balances such as nitrous oxide (N_2O) and methane (CH_4) to determine net benefits of agroforestry on the atmosphere.

Keywords: Agroforestry; Carbon Sequestration; Global warming; Greenhouse gas; Sink

1. Introduction

The concentration of CO_2 and other greenhouse gases (GHGs) in the atmosphere has considerably increased over the last century and is set to rise further. C is accumulating in the atmosphere at a rate of 3.5 Pg (Pg $= 10^{15}$ g or billion tons) per annum, the largest proportion of which resulting from the burning of fossil fuels and the conversion of tropical forests to agricultural production (Paustian et al., 2000). Scientific evidence suggests that increased atmospheric CO_2 could have some positive effects such as improved plant productivity (Schaffer et al., 1997; Pan et al., 1998; Centritto et al., 1999a,b; Idso and imball, 2001; Keutgen and Chen, 2001). However, negative changes in the global climate (rising temperatures, higher frequency of droughts and floods) are often the most consequential processes associated

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0167-8809/$ – see front matter
doi:10.1016/S0167-8809(03)00138-5

with an increased concentration of CO_2 in the atmosphere (USDA NRCS, 2000).

The debate on the atmospheric build up of GHGs and their role in global warming culminated in the third session of the Conference of the Parties to the United Nations Framework Convention of Climate Change (UNFCCC) in 1997, in Kyoto, Japan. One of the major achievements of this conference was the signature of a protocol urging participating countries to find ways of reducing GHG concentrations in the atmosphere. In the case of C, reduction targets could be achieved through two major processes: (1) reducing anthropogenic emissions of CO_2; and (2) creating and/or enhancing C sinks in the biosphere.

Current terrestrial (plant and soil) C is estimated at 2000 ± 500 Pg, which represents 25% of global C stocks (DOE, 1999). The sink option for CO_2 mitigation is based on the assumption that this figure can be significantly increased if various biomes are judiciously managed and/or manipulated (Table 1). In this connection, agricultural lands have the potential to remove and store between 42 and 90 Pg of C from the atmosphere over the next 50–100 years.

Promoting agroforestry is one option many perceive as a major opportunity to deal with problems related to land-use and CO_2-induced global warming. In this paper agroforestry is defined as any land-use system that involves the deliberate retention, introduction or mixture of trees or other woody perennials with agricultural crops, pastures and/or livestock to exploit the ecological and economic interactions of the different components (Lundgren, 1982; Nair, 1993; Young, 1997). Historical evidence showed that agroforestry has been widely practised through the ages as a means of achieving agricultural sustainability and slowing the negative effects of agriculture such as soil degradation and desertification.

The significance of agroforestry with regards to C sequestration and other CO_2 mitigating effects is being widely recognised, but there is still paucity of quantitative data on specific systems. The objective of this paper was to review and discuss the C storage potential of a few agroforestry systems in the tropics, where widescale practice of agroforestry is more likely to occur.

2. Carbon storage in a few agroforestry practices

According to recent projections, the area of the world under agroforestry will increase substantially in the near future. Undoubtedly, this will have a great impact on the flux and long-term storage of C in the terrestrial biosphere (Dixon, 1995). Agroecosystems play a central role in the global C cycle and contain approximately 12% of the world terrestrial C (Smith et al., 1993; Dixon et al., 1994; Dixon, 1995). Soil degradation as a result of land-use change has been one of the major causes of C loss and CO_2 accumulation in the atmosphere. Agroforestry may involve practices that favour the emission of GHGs including shifting cultivation, pasture maintenance by burning,

Table 1
Categorisation of biomes and their C sequestration (CS) potential (DOE, 1999)

Biomes	Primary method to increase CS[a]	Potential CS (Pg C per year)
Agricultural lands	Management (H)	0.85–0.90
Biomass croplands	Manipulation (H)	0.50–0.80
Grasslands	Management (M)	0.50
Rangelands	Management (M)	1.20
Forests	Management (M)	1–3
Urban forests and grasslands	Creation and maintenance (M)	na[b]
Deserts and degraded lands	Manipulation (H)	0.80–1.30
Terrestrial sediments	Protection (L)	0.70–1.70
Boreal speatlands and other wetlands	Protection (L)	0.10 to −0.70
Total		5.65–10.10

[a] The primary method of carbon sequestration is rated as high (H), medium (M), and low (L) levels of sustained management intensity required over the long term. Global potential sequestration rates were estimated that might be sustained over a period of 25–50 years.

[b] Not available.

Table 2
Potential C storage for agroforestry systems in different ecoregions of the world (Dixon et al., 1993; Krankina and Dixon, 1994; Schroeder, 1993; Winjum et al., 1992)

	Ecoregion	System	$Mg\,C\,ha^{-1}$
Africa	Humid tropical high	Agrosilvicutural	29–53
South America	Humid tropical low	Agrosilvicutural	39–102[a]
	Dry lowlands		39–195
Southeast Asia	Humid tropical	Agrosilvicutural	12–228
	Dry lowlands		68–81
Australia	Humid tropical low	Silvopastoral	28–51
North America	Humid tropical high	Silvopastoral	133–154
	Humid tropical low	Silvopastoral	104–198
	Dry lowlands	Silvopastoral	90–175
Northern Asia	Humid tropical low	Silvopastoral	15–18

[a] Carbon storage values were standardised to 50-year rotation.

paddy cultivation, N fertilisation and animal production (Dixon, 1995; Le Mer and Roger, 2001). However, several studies have shown that the inclusion of trees in the agricultural landscapes often improves the productivity of systems while providing opportunities to create C sinks (Winjum et al., 1992; Dixon et al., 1993; Krankina and Dixon, 1994; Dixon, 1995).

The amount of C sequestered largely depends on the agroforestry system put in place, the structure and function of which are, to a great extent, determined by environmental and socio-economic factors. Other factors influencing carbon storage in agroforestry systems include tree species and system management. Table 2 shows the carbon storage potential of agroforestry systems in different regions of the world.

2.1. *Complex agroforestry systems*

In the humid tropics (annual precipitation exceeds 2000 mm), perennial crops like coffee or cacao are commonly mixed with trees such as *Erythrina* spp., *Inga* spp. and *Cordia* spp. to diversify farm products and to exploit the benefits of tree–crop interactions. The trees play various functions, including shading crops to reduce evapotranspiration, erosion control and nutrient cycling (Beer, 1987; Szott et al., 1991a; Young, 1997). Depending on species, the shade tree can be regularly pruned for soil improvement (e.g. *Erythrina* spp.) or left to grow fully to produce firewood and timber (e.g. *Cordia* spp.).

Agroforests (also known as multistrata tree gardens or analogue forests) and homegardens are other variants of these complex systems, but involve a higher plant diversity (Fernandes and Nair, 1986; Mc Connell, 1992; Gouyon et al., 1993; Nuberg and Evans, 1993; Aumeerudy and Sansonnens, 1994; de Foresta and Michon, 1994; Salafsky, 1994; Baijukya and Piters, 1998). These complex mixtures of trees and agricultural crops are widely practised in Latin America, Southeast Asia and Equatorial Africa and are among the most sustainable cropping systems in the tropics (Beer et al., 1990; Szott et al., 1991a; Herzog, 1994).

2.1.1. *Carbon in plant biomass*

As described earlier, variability can be high within complex agroforestry systems, and productivity depends on several factors including the age, the structure and the way the system is managed. Beer et al. (1990) gave a detailed breakdown of biomass production over 10 years in two tree combinations in Costa Rica: cacao (*Theobroma cacao*)–laurel (*Cordia alliadora*) and cacao–poro (*Erythrina poeppigiana*) (Fig. 1). Based on these data, whole system C stocks were calculated by averaging the annual biomass production in the two periods defined by the authors (0–5 years and 6–10 years) and multiplying the output by 0.5 (Kürsten and Burschel, 1993). Thus, $11\,Mg\,C\,ha^{-1}$ per year was stored over 10 years in the system including $6\,Mg\,C\,ha^{-1}$ per year in the shade trees. $60\,Mg\,C\,ha^{-1}$ is clearly higher than storage values estimated by Kürsten and Burschel (1993) on similar systems ($7–25\,Mg\,C\,ha^{-1}$), even if these authors did not consider below-ground C. However, this corresponds perfectly to the C sequestration capacity of agroforestry calculated by Houghton et al. (1991) for America and Asia. Biomass estimates by Jensen (1993a,b) in Java showed that $16\,Mg\,C\,ha^{-1}$ could be stored if rice fields were transformed into homegardens.

2.1.2. *Soil carbon*

Despite the continuous harvest of crops, wood and other products, decline in soil fertility can be considered as minimal in complex agroforestry systems. The

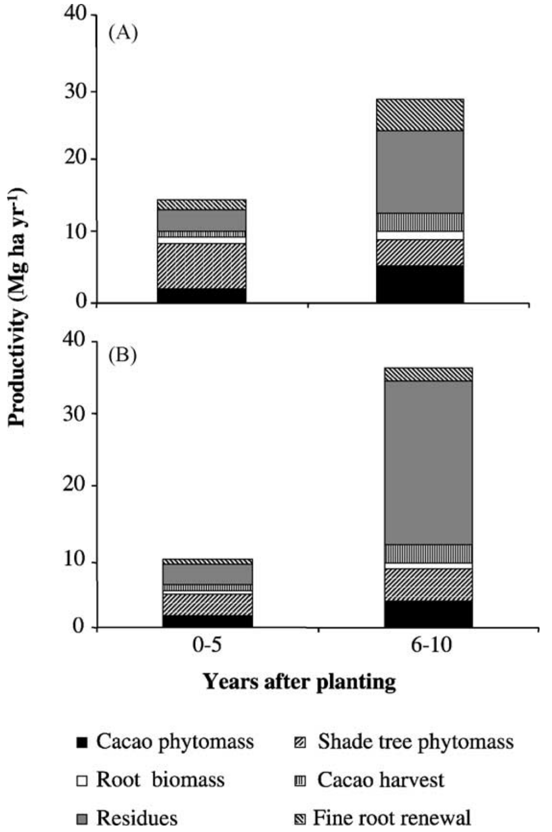

Fig. 1. Net productivity (Mg ha^{-1} per year) of the systems *T. cacao–C. alliadora* (A) and *T. cacao–E. poeppigiana* (B) in the periods 0–5 and 6–10 years after planting (data from Beer et al., 1990).

abundant litter and/or pruning biomass returned to the soil (for example in Fig. 1), combined with the decay of roots, contribute to the improvement of soil physical and chemical properties. For example in the same system studied by Beer et al. (1990), SOM in the 0–45 cm layer increased over 10 years by 42 and 16 Mg ha^{-1} in the cacao–*E. poeppigiana* and in the cacao–*C. alliadora*, respectively. This would amount to about 21 and 8 Mg C ha^{-1} sequestered, respectively.

2.2. Boundary plantings

Windbreaks and live fences are two common examples of boundary plantings. Naturally, the primary function of a windbreak (or shelterbelt) is to protect an area from wind damage. However, beside filtering and slowing winds that would otherwise affect the performance of crops or animals, windbreaks can be designed to provide multiple functions and/or products, including fruit, animal fodder, wildlife habitat, and other economic and farm products (Zhang and Brandle, 1996; Wilkinson and Elevitch, 2000). Live fences comprise two basic categories: (1) living fence posts, which are widely spaced, single lines of woody plants supporting barbed wire, bamboo or other materials; and (2) living barriers or hedges, which are thicker, more densely spaced fences that generally include a number of different species and usually do not support barbed wire.

These systems have been fairly well studied in recent years and comprehensive information on their description and essential features can be found in the literature (Budowski, 1987; Budowsky and Russo, 1993; Huxley, 1997). Boundary plantings are known to have positive effects on soil characteristics and crop production. Several reports indicated yield increases as a result of modified microclimate and improved water conditions for crops although in dry environments, competition for water may be an obstacle to a good agricultural production (Benzarti, 1999).

2.2.1. Carbon in plant biomass

Most of the data on border hedge productivity come from Latin America, where research on agroforestry systems has been fairly comprehensive. Baggio and Heuveldop (1984) studied the potential of *Calliandra calothyrsus* as a live fence species in Costa Rica. At 10 months, the total biomass produced was 3–4 Mg dry matter per km of fence (2 Mg C sequestered per km). This would represent about 20 Mg C ha^{-1} considering an average width of 1 m for the fences. However, for a better evaluation of the C sequestration potential of these agroforestry systems, the whole cycle (the lifetime of the hedges) needs to be considered. Biomass production in boundary plantings can be highly variable-dependent on environmental and soil characteristics, tree spacing, pruning frequency and management. For example, live fences of *Gliricidia sepium* monitored on a 4-year cycle produced a total biomass of 7 Mg km^{-1} per year (35 Mg C ha^{-1} per year) when pruned every 4 months and 9.5 Mg km^{-1} per year (50 Mg C ha^{-1} per year) when pruned every 6 months. Similar figures (30 and 55 Mg C ha^{-1} per year, respectively) could be calculated for *Erythrina* *bertroana* in the same study (Romero et al., 1991). In a C sequestration trial in Mexico, live fence trees were reported to store 24–36 Mg C ha^{-1} during a cycle of 25–30 years (de Jong et al., 1995).

2.2.2. Soil carbon

Although a high amount of litterfall and root biomass can be produced in every line of trees, the contribution of hedgerows or windbreaks in the build-up of soil C may not be very significant at a field level because of the relatively small proportion of land covered by the trees. Rao et al. (1998) suggested that the effect of boundary plantings is limited to 10 m on both sides of the tree lines. If this analysis is applied here, a 50% increase in the C stocks around a 100 m tree line would only translate into a 10% C increase per hectare. However, boundary plantings can contribute to the improvement of the soil conditions and indirectly enhance carbon sequestration by improving crop productivity and reducing erosion-induced soil losses.

2.3. Hedgerow intercropping

Hedgerow intercropping (HI) refers to the agroforestry systems where crops are grown between rows of regularly coppiced woody species. In the tropics, no distinction is usually made between HI and alley cropping, which in other climates, means growing crops in large alleys delimited by uncoppiced, free growing trees (Rao et al., 1998). Initially developed to restore the fertility of degraded soils in the humid and sub-humid tropics, HI has later been adopted in other regions (Xu et al., 1993a,b) not only to ameliorate soils, but also to provide other products (e.g. fodder) and services (e.g. erosion control).

2.3.1. Carbon in plant biomass

There have been mixed results from HI experiments in various parts of the world. Analysis of biomass production from published literature showed strong variations (1–37 Mg ha^{-1}) depending on climate, soil type and system management (Kang, 1993; Evensen et al., 1994; Viswanath et al., 1998; Kang et al., 1999). However, C storage is only temporary in HI systems since the biomass is continuously harvested for prunings (or fodder) and firewood.

2.3.2. Soil carbon

In many areas of the tropics, regular addition of prunings and root turnover over the years have contributed to the build up of SOM and nutrient stocks in the soil (Lehmann et al., 1998; Rao et al., 1998; Kumar et al., 2001). In a 12-year HI trial on a Nigerian Alfisol, *G. sepium* and *Leucaena leucocephala* increased surface soil organic carbon (SOC) by 15% (2.38 Mg C ha^{-1}) compared to sole crops (Kang et al., 1999). A 12% increase in SOC (0.23 Mg C ha^{-1}) has also been observed after 5 years of HI with *Inga edulis* in a Typic Paleudult in Peru (Alegre and Rao, 1996).

To assess the potential of *L. leucocephala* for improving soil chemical properties in a high base status soil, SOC in the 0–15 cm layer of an HI was compared with that of a continuous cropping system after 5 years. The measures were 1.23% in the hedgerows (the same level as in the start of trial), 0.94% in the alleys and 0.59% (Kang, 1997). Assuming bulk density values of 1.4 for the continuous cropping system, 1.3 for the alleys and 1.2 for the hedgerows, it could be concluded that 6–10 Mg C ha^{-1} were stored through HI.

2.4. Improved fallows

In this review, the definition of improved fallows (IF) is restricted to the agroforestry systems in which one (pure) or a few (mixed) tree species are planted as a substitute to natural fallow, to achieve the benefits of the latter in a shorter time (Prinz, 1986; Young, 1997). Rao et al. (1998) distinguished two categories of IF: (1) the short-duration fallows with fast growing leguminous trees or shrubs seeking to replenish soil fertility; and (2) the medium-to-long-duration fallows with diverse species and aimed at rehabilitating degraded and abandoned lands as well as exploiting tree products such as poles and firewood. As in the case of natural fallows, land availability is one of the major factors that determine farmers' decision about the duration of the improved fallow. Medium-to-long-term planted fallows are realistic only in areas with low population density such as the southern African region (Zambia, Malawi), where fallowing with *Sesbania sesban* is gaining popularity as an alternative to the traditional bush fallows. In recent years, IF has also been widely tested and recommended in western Kenya to improve the productivity of degraded soils, but their duration is shortened by land scarcity. However with the existence of two rainy seasons per year in this area, shorter-duration fallows are feasible and have shown good promise. In the following sections, biomass data in IF and changes in soil C will be discussed, drawing mainly from examples in the Philippines and western Kenya.

2.4.1. *Carbon in plant biomass*

Biomass production in planted fallows depends on several factors including the environmental conditions, the soil type, the magnitude of land degradation and the length of the fallow period. In the Philippines, there are various types of IF using *L. leucocephala*. One of the best known is the Naalad system, an indigenous agroforestry practice that was developed in central Philippines more than a century ago. A comprehensive study on the production and C sequestration potential of *L. leucocephala* during the fallow phase of the Naalad system was carried out by Lasco and Suson (1999) using a 6-year-old model fallow. Above-ground *Leucaena* biomass increased from 4 Mg ha^{-1} in the first year to 64 Mg ha^{-1} in the sixth year (end of the fallow). C in the understory, soils and woody debris was estimated at 25% of the above-ground C. Overall, the authors calculated an average C storage of 16 Mg ha^{-1} over the 6-year period.

Table 3 summarises biomass data from some improved fallow trials in western Kenya. The duration of the fallow was the major factor explaining the differences in biomass production although variations related to plant species, local environmental conditions and soil characteristics could be observed. Above-ground biomass varied between 7 and 43.4 Mg ha^{-1}, resulting in carbon storages of 4–22 Mg ha^{-1}. Below-ground biomass was also relatively high, especially in the 18- and 22-month fallows. The 18-month fallow of *Tephrosia candida* produced the most significant root biomass (33.2 Mg ha^{-1}). In conclusion, planting fallow trees for 12–22 months in western Kenya resulted in C inputs ranging from 1.35 to 16.5 Mg ha^{-1} in the soil.

2.4.2. *Soil carbon*

Several studies have shown increased SOM after a few seasons of tree planting on degraded soils (Table 4). The examples used here mainly came from Togo and Kenya and include several fallow species and different soil types. Considering the changes in bulk density induced by the improved fallow practice and the sampling depth, SOC accretions were estimated between 0.73 and 12.46 Mg ha^{-1}.

The influence of the soil type on the build-up of soil C was investigated in some IF in western Kenya. C stocks in the top 20 cm were measured after 18 months of improved fallow with 4 tree species, on two sites characterised by different soils: Teso (clay content = 50 g kg^{-1}) and Lubao (clay content = 400 g kg^{-1}). Continuous maize/bean intercropping, which is the normal land-use system in the area, was used as control. The results of the experiment indicated that tree biomass was lower in the sandy soil than in the finer-textured soil (Fig. 2). In the sandy soil, *Tephrosia vogelii* and *T. candida* induced no significant changes in the C stocks while the latter increased by about 2 Mg ha^{-1} in the *Crotalaria paulina* and *Crotalaria grahamiana* fallows. In the finer-textured soil, there was an increase of C stocks in all the IF, with the extent of accretion (2.5–3.74 Mg ha^{-1}) being positively correlated with the biomass produced by the fallow.

Table 3
Above- and below-ground biomass production (Mg ha^{-1}) in some improved fallow trials in western Kenya (Boye, 2000; Ndufa, 2001; Nybert, 2001; Impala, 2001)[a]

Fallow tree	Above-ground	Below-ground	Fine roots	R/S[a]
12-month-old fallows				
C. grahamiana	8.5	2.7	–	0.32
C. calothyrsus	21.0	7.0	–	0.33
Cajanus cajan	8.5	3.9	–	0.46
Senna spectabilis	7.0	4.8	–	0.69
S. sesban	14.2	7.3	–	0.51
T. vogelii	10.8	4.0	–	0.37
18-month-old fallows				
C. grahamiana	24.7	10.9	6.4	0.44
C. paulina	19.8	13.6	3.7	0.69
T. candida	31.0	33.2	3.6	1.07
22-month-old fallows				
C. calothyrsus	27.0	15.5	2.8	0.57
S. sesban	36.9	10.8	2.4	0.29
Grevillia robusta	32.6	17.7	2.8	0.54
Eucalyptus saligna	43.4	19.1	2.4	0.44

[a] Root/shoot ratio.

Table 4
SOC increase in a few tropical soils following IF with different tree species in the sub-humid tropics

Fallow species	Age (years)	Country	Soil type	Sampling depth (cm)	SOC increase (Mg ha^{-1})	Source
Acacia auriculiformis	5	Togo	Ferric Acrisol	0–10	3.41	Drechsel et al. (1991)
Albizzia lebbek	5	Togo	Ferric Acrisol	0–10	5.21	Drechsel et al. (1991)
Azadirachta indica	5	Togo	Ferric Acrisol	0–10	12.46	Drechsel et al. (1991)
C. cajan	1	Kenya	Deep red loam	0–30	0.73	Onim et al. (1990)
Cassia siamea	5	Togo	Ferric Acrisol	0–10	5.20	Drechsel et al. (1991)
C. grahamiana	1.5	Kenya	Arenosol	0–20	1.69	Impala (2001)
C. grahamiana	1.5	Kenya	Ferralsol	0–20	3.60	Impala (2001)
C. paulina	1.5	Kenya	Arenosol	0–20	2.15	Impala (2001)
C. paulina	1.5	Kenya	Ferralsol	0–20	2.94	Impala (2001)
L. leucocephala	1	Kenya	Ferralsol	0–30	8.34	Onim et al. (1990)
S. sesban	1	Kenya	Ferralsol	0–30	3.10	Onim et al. (1990)
T. candida	1.5	Kenya	Ferralsol	0–20	3.74	Impala (2001)
T. vogelii	1.5	Kenya	Ferralsol	0–20	2.58	Impala (2001)

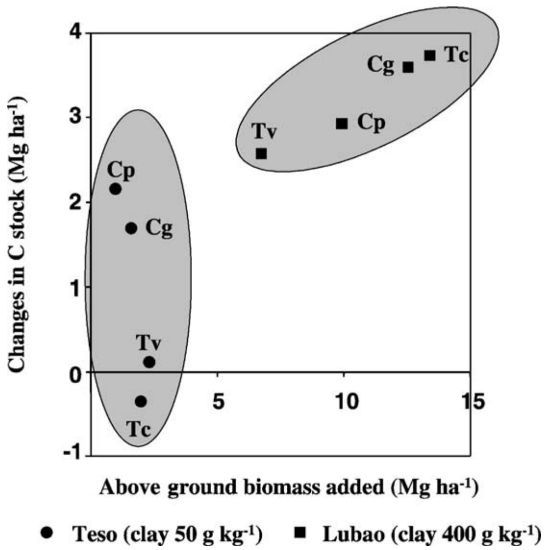

Fig. 2. Changes in carbon stocks in the 0–20 cm soil layer after 18-month-old IF in western Kenya (Cg: *C. grahamiana*; Cp: *C. paulina*; Tc: *T. candida*; Tv: *T. vogelii*).

3. Potential of agroforestry for carbon sequestration

It is clear from the above section that most if not all agroforestry systems have the potential to sequester C. With adequate management of trees in cultivated lands and pastures, a significant fraction of the atmospheric C could be captured and stored in plant biomass and in soils. However, increasing C stocks in a given period of time is just one step; the fate of those stocks is what ultimately determines sequestration. In agroforestry systems C sequestration is a dynamic process and can be divided into phases. At establishment, many systems are likely to be sources of GHGs (loss of C and N from vegetation and soil). Then follow a quick accumulation phase and a maturation period when tons of C are stored in the boles, stems, roots of trees and in the soil. At the end of the rotation period, when the trees are harvested and the land returned to cropping (sequential systems), part of the C will be released back to the atmosphere (Dixon, 1995). Therefore, effective sequestration can only be considered if there is a positive net C balance from an initial stock after a few decades (Feller et al., 2001).

Realistically, C storage in plant biomass is only feasible in the perennial agroforestry systems (perennial-crop combinations, agroforests, windbreaks), which allow full tree growth and where the woody component represents an important part of the total biomass. One comparative advantage of these systems is that sequestration does not have to end at wood harvest. C storage can continue way beyond if boles, stems or branches are processed in any form of long-lasting products (Roy, 1999). For the estimation of these effects, a decomposition rate of wood products of between 1 and 2% has been suggested for the tropics (Findlay, 1985; Roy, 1999). Alternatively the wood can serve as fuel, in which case an important part of the plant-stored C returns to the atmosphere. While C sequestration per se may be insignificant in the latter scenario, producing firewood from arable or grazed land may still present interesting opportunities in CO_2 mitigation through: (1) the protection of existing forests and other natural landscapes; (2) the conservation of soil productivity; and (3) the reduction of fossil energy consumption by using wood as energy sources (Kürsten and Burschel, 1993; Cooper et al., 1996; Kürsten, 2000). Adequate understanding of these secondary effects of agroforestry with regards to CO_2 mitigation will require more research.

Restoring degraded croplands and pastures is an effective way of storing C in the soil. Pre-cultivation C stocks on the present area of cultivated land are estimated at 222 Pg (Paustian et al., 1997). From a practical viewpoint, this may be considered as an upper limit for soil C sequestration, although instances of increased C stocks relative to those of native soils have been achieved after intensive management of specific biomes (Paustian et al., 1997). There is strong evidence that soil C levels can be considerably increased at a global scale if management options that improve land productivity are pursued. For such options to be successful, they will have to increase inputs (primary production) while reducing losses through the processes of decomposition, leaching and erosion (Fig. 3). The use of plant residues, mulching and animal manure, combined with conservation practices such as zero tillage (Christensen et al., 1994; Salinas-Garcia et al., 1997; Dao, 1998; Potter et al., 1998; Allmaras et al., 2000; Feller et al., 2001), have been shown to increase soil C. Agroforestry trees also improve land cover in agricultural fields in addition to providing C inputs (root biomass, litter and prunings) to the soil. This has often reduced soil erosion, which is a crucial process in the soil C dynamics. It has been speculated that the most significant increases in C stocks occur in fine-textured soils, where C is better protected through soil aggregation (Ingram and Fernandes, 2001). But, one must be aware of the fact that soils have a finite sink capacity of 0.4–0.6 Pg C per year over 50–100 years (Paustian et al., 2000; Ingram and Fernandes, 2001). If above-ground and soil C are considered together, 1.1–2.2 Pg C could be sequestered annually over 50 years, which, as estimates suggest, would offset about 10–15% of the current annual C emissions (Dixon, 1995). Looking at this contribution, it becomes clear that agroforestry alone cannot solve the current climatic problems, but can only be one among a range of strategies. However, the implementation of agroforestry projects could be justified for many other reasons. First, increasing soil C greatly benefits agricultural productivity and sustainability. Second, given the improbability of obtaining any single mitigating method, adding modest contributions together appears to be a more realistic way of achieving CO_2 reduction targets (Paustian et al., 1997). Third, the financial cost of C sequestration through agroforestry appears to be much lower (approximately \$1–69/Mg C, median \$13/Mg C) than through other CO_2 mitigating options. Economic analyses showed that these costs could be easily offset by the monetary benefits from agricultural products and trading in C credits.

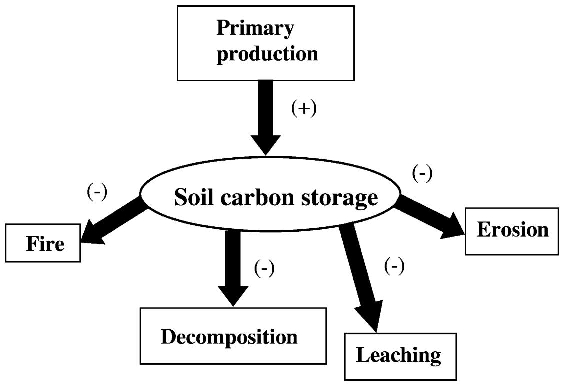

Fig. 3. Schematic diagram showing the major processes controlling the soil carbon storage (modified from Wang and Hsieh, 2002).

4. Limitations and uncertainties for carbon sequestration

It has been long believed that when trees or shrubs replace pastures or grasslands, there is an automatic increase of C stocks. Today, it is becoming increasingly clear that this does not happen all the time. For example, in a study conducted by Jackson et al. (2002) in the United States, it was shown that the invasion of grasslands by shrubs increased C in vegetation although to a much lower extent than expected. On the other hand, soil C increased only on the drier sites and actually decreased in the wetter sites. As a result, the net C balance was marginally positive for the dry sites but negative for the wetter sites. Such findings suggest that the current land-based methods of

C assessment may have led to an overestimation of C sinks in many areas of the globe (Jackson et al., 2002; Goodale and Davidson, 2002). These inaccuracies will be compounded further if we consider that changes in C fluxes are likely to occur in the next 50 years as a result of shift in global climate, land-use and land cover. The magnitude and direction these changes will take remain largely unknown (Wang and Hsieh, 2002).

Similarly, degraded soils and wastelands occupy a large proportion of the earth's area and there is general belief that converting them into agroforestry would be a major global opportunity to absorb a significant portion of the atmospheric CO_2 (Dixon, 1995). However, cultivating trees or crops in sub-standard soils still remains a challenge to growers and agriculturists. On infertile soils (for example acid soils) or in semi-arid areas, trees usually perform poorly, making such environments little suitable for agroforestry (Matthews et al., 1992; Akyeampong, 1999). Consequently if biomass production is not adequate, positive changes in soil properties are unlikely to occur in agroforestry systems. There have been many reports indicating unchanged, or even declining, SOM levels after HI on substandard soils and in dry environments (Szott et al., 1991b; Mathuva et al., 1998; Samsuzzaman et al., 1999; Akyeampong, 1999). Moreover, in dry environments, the tree–crop competition for water usually results in low crop yields, which makes HI unattractive for dryland farmers.

As shown in this review and many other studies, improved fallow is a promising technology for increasing C stocks in degraded soils. But, a major problem with implementing sequential agroforestry systems in general is that farmers have to forego growing crops during the fallow phase, which can stretch on one or more cropping seasons. Although IF can ameliorate soil conditions in a much shorter time than natural fallows, they are still not very realistic in areas with high population density. Pests and diseases are other key issues that deserve to be addressed more adequately if the improved fallow technology is to spread and reach a wider number of farmers in the tropics. Various species of damaging insects (Melaku et al., 1996; Pandit and Pradhan, 1996; Sileshi et al., 2000) and plant–parasitic nematodes (Desaeger and Rao, 1999; Desaeger and Rao, 2000a,b; Kandji et al., 2001) have been associated with fallow trees. These represent a major threat to the development of agroforestry in the tropics.

5. Other GHGs

If carbon fluxes in agroforestry systems are well documented, this is not the case for other trace gases such as nitrous oxide (N_2O) and methane (CH_4). Legumes play a prominent role in agroforestry and are effective in improving the nutrient status of nitrogen-depleted soils. Recent studies have shown that nitrogen (N) inputs derived from agroforestry practices such as IF can exceed the agronomic requirements of subsequent crops. This may result in volatilisation of excess N in the form of N_2O (Choudhary et al., 2002; Palm et al., 2002). N_2O is one of the most important trace gases and has a global warming potential (GWP) 200–300 times higher than that of CO_2 (Jaques, 1992). Thus, there is growing concern that the widescale use of woody legumes might result in massive release of N_2O gas into the atmosphere. Similarly, ungulate production and cultivation of rice paddy in agroforestry systems can produce significant quantities of CH_4 on a global scale (Dixon, 1995). More research will, therefore, be needed to clearly understand the implications of agroforestry vis-à-vis the emission of trace gases. The success of agroforestry in addressing issues related to climate change will be determined, among other factors, by the trade-offs between C sequestration and the emission of other GHGs such as N_2O and CH_4 to the atmosphere.

6. Conclusions

This review gave a description of a few agroforestry systems practised in the tropics in relation to their C sequestration potential. The analysis of C stocks from various parts of the world showed that significant quantities of C (1.1–2.2 Pg) could be removed from the atmosphere over the next 50 years if agroforestry systems are implemented on a global scale. C storage depends on several factors including climatic, edaphic, and socio-economic conditions. Perennial systems like homegardens and agroforests can store and conserve considerable amounts of C in living biomass and also in wood products. C sequestration in soils is also realistic with most agroforestry practices including short-rotation systems such as IF and HI. However, it is apparent that C storage in agroforestry systems and its eventual consequences on the global climate are fraught with a number of uncertainties. Consequently, there is still some work to be done to improve our understanding of C sequestration and GHG mitigation. Data and research needs include:

(1) Standardised methodologies for estimating above- and below-ground C stocks to improve the reliability of data.
(2) Consideration of other C stocks often left out in estimates; these include deep soil C (especially when trees are involved) and C in durable wood products.
(3) Predictive models to accommodate future climate and land-use changes and their implications for CO_2 mitigation through agroforestry systems.
(4) Adequate understanding on issues such as pests and diseases and the emission of other GHGs, especially N_2O and CH_4 in agroforestry systems.
(5) More powerful methods to implement cost/benefit analyses of agroforestry-based GHG mitigation and to define incentives for widescale adoption of agroforestry systems.

Acknowledgements

The authors sincerely thank the European Commission, Directorate Research, for its support through the Impala Project no. ICA4-CT-2000-30011. Special thanks also to Drs. Christian Feller and Louis Verchot for their valuable comments on the draft of this paper.

References

Akyeampong, E., 1999. Suitability of six hedgerow species for alley cropping on an acid infertile soil in Burundi. Trop. Agric. 76, 83–87.

Alegre, J.C., Rao, M.R., 1996. Soil and water conservation by contour hedging in the humid tropics of Peru. Agric. Ecosyst. Environ. 57, 17–25.

Allmaras, R.R., Schomberg, H.H., Douglas Jr., C.L., Dao, T.H., 2000. Soil organic carbon sequestration potential of adoption conservation tillage in US croplands. J. Soil Water Conserv. 55, 365–373.

Aumeerudy, Y., Sansonnens, B., 1994. Shifting from simple to complex agroforestry systems: an example for buffer zone management from Kerinci (Sumatra, Indenosia). Agrofor. Syst. 28, 113–141.

Baggio, A., Heuveldop, J., 1984. Initial Performance of *Calliandra calothyrsus* Meissm. in Live Fences for the Production of Biomass. Martinus Nijhoff, The Hague, The Netherlands, pp. 19–29.

Baijukya, F.P., Piters, B.D.S., 1998. Nutrient balances and their consequences in the banana-based land use systems of Bukoba district, northwest Tanzania. Agric. Ecosyst. Environ. 71, 147–158.

Beer, J., 1987. Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea, cacao and tea. Agrofor. Syst. 5, 3–13.

Beer, J., Bonnemann, A., Chavez, W., Fassbender, H.W., Imbach, A.C., Martel, I., 1990. Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliadora*) or poro (*Erythrina poeppigiana*) in Costa Rica. V. Productivity indices, organic material models and sustainability over ten years. Agrofor. Syst. 12, 229–249.

Benzarti, J., 1999. Temperature and water-use efficiency by lucerne (*Medicago sativa*) sheltered by a tree windbreak in Tunisia. Agrofor. Syst. 43, 95–108.

Boye, A.G., 2000. A simulator study of soil erosion under different land-use systems in western Kenya. Master Thesis. University of Copenhagen, 112 pp.

Budowski, G., 1987. Living fences in tropical America, a widespread agroforestry practice. In: Gholz, H.L. (Ed.), Agroforestry: Realities, Possibilities and Potentials. Martinus Nijhoff, Dordrecht, The Netherlands, pp. 169–178.

Budowsky, G., Russo, R.O., 1993. Live fence posts in Costa Rica: a compilation of the farmer's beliefs and technologies. J. Sustain. Agric. 3, 65–87.

Centritto, M., Lee, H.S.J., Jarvis, P.G., 1999a. Interactive effects of elevated [CO_2] and drought on cherry (*Prunus avium*) seedlings. I. Growth, whole-plant water use efficiency and water loss, whole-plant water use efficiency and water loss. New Phytol. 141, 129–140.

Centritto, M., Magnani, F., Lee, H.S.J., Jarvis, P.G., 1999b. Interactive effects of elevated [CO_2] and drought on cherry (*Prunus avium*) seedlings. II. Photosynthetic capacity and water relations. New Phytol. 141, 141–153.

Choudhary, M.A., Akramkhanov, A., Saggar, S., 2002. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. Agric. Ecosyst. Environ. 93, 33–43.

Christensen, N.B., Lindeman, W.C., Salazar-Sosa, E., Gill, L.R., 1994. Nitrogen and carbon dynamics in no till and stubble mulch tillage system. Agron. J. 86, 298–303.

Cooper, P.J.M., Leakey, R.R.B., Rao, M.R., Reynolds, L., 1996. Agroforestry and the mitigation of land degradation in the humid and sub-humid tropics of Africa. Expl. Agric. 32, 235–290.

Dao, T.H., 1998. Tillage and crop residue effects on carbon dioxide evolution and carbon storage in a Paleustoll. Soil Sci. Soc. Am. J. 62, 250–256.

de Foresta, H., Michon, G., 1994. Agroforests in Sumatra: where ecology meets economy. Agrofor. Today 6, 12–13.

de Jong, B.H.J., Montoya-Gomez, G., Nelson, K., Soto-Pinto, L., Taylor, J., Tipper, R., 1995. Community forest management and carbon sequestration: a feasibility study from Chiapas, Mexico. Interciencia 20, 409–416.

Desaeger, J., Rao, M.R., 1999. The root-knot nematode problem in sesbania fallows: scope for managing it in western Kenya. Agrofor. Syst. 47, 273–288.

Desaeger, J., Rao, M.R., 2000a. Parasitic nematode populations in natural fallows and improved cover crops and their effects on subsequent crops in Kenya. Field Crops Res. 65, 41–56.

Desaeger, J., Rao, M.R., 2000b. Infection and damage potential of *Meloidogyne javanica* on *Sesbania sesban* in different soil types. Nematology 2, 169–178.

Dixon, R.K., 1995. Agroforestry systems: sources or sinks of greenhouse gases? Agrofor. Syst. 31, 99–116.

Dixon, R.K., Andrasko, K.J., Sussman, F.A., Lavinson, M.A., Trexler, M.C., Vinson, T.S., 1993. Tropical forests: their past, present and potential future role in the terrestrial carbon budget. Water Air Soil Pollut. 70, 71–94.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. Science 263, 185–190.

DOE, 1999. Carbon Sequestration: State of the Science. US Department of Energy (DOE), Washington, DC.

Drechsel, P., Glaser, B., Zech, W., 1991. Effects of four multipurpose tree species on soil amelioration during tree fallow in central Togo. Agrofor. Syst. 16, 193–202.

Evensen, C.I., Dierolf, T.S., Yost, R.S., 1994. Growth of four tree species managed as hedgerows in response to liming on acid soil in west Sumatra, Indonesia. Agrofor. Syst. 27, 207–222.

Feller, C., Albrecht, A., Blanchart, E., Cabidoche, Y.M., Chevallier, T., Hartmann, C., Eschenbrenner, V., Larre-Larrouy, M.C., Ndandou, J.F., 2001. Soil carbon sequestration in tropical areas: general considerations and analysis of some edaphic determinants for Lesser Antilles soils. Nutr. Cycl. Agroecosyst. 61, 19–31.

Fernandes, E.C.M., Nair, P.K.R., 1986. An evaluation of the structure and functions of tropical homegardens. Agric. Syst. 21, 279–310.

Findlay, W.P.K., 1985. Preservation of Timber in the Tropics. Marinus/Junk Publishers, Dordrecht, 273 pp.

Goodale, C.L., Davidson, E.A., 2002. Uncertain sinks in the shrubs. Nature 418, 593–594.

Gouyon, A., de Foresta, H., Levang, P., 1993. Does 'jungle rubber' deserve its name? An analysis of rubber agroforestry systems in southeast Sumatra. Agrofor. Syst. 22, 181–206.

Herzog, F., 1994. Multipurpose shade trees in coffee and plantations in Côte d'Ivoire. Agrofor. Syst. 27, 259–268.

Houghton, R.A., Unruh, J.D., Lefebre, P.A., 1991. Current Land Use in the Tropics and Its Potential for Sequestering Carbon. The Woods Hole Research Centre, Woods Hole, MA, 25 pp.

Huxley, P., 1997. Glossary for Agroforestry. ICRAF, Kenya.

Idso, S.B., Kimball, B.A., 2001. CO_2 enrichment of sour orange trees: 13 years and counting. Environ. Exp. Bot. 46, 147–153.

Impala, 2001. First annual report of IMPALA Project, covering the period October 2000–December 2001, Nairobi, Kenya, 68 pp.

Ingram, J.S.I., Fernandes, E.C.M., 2001. Managing carbon sequestration in soils: concepts and terminology. Agric. Ecosyst. Environ. 87, 111–117.

Jackson, R.B., Banner, J.L., Pockman, W.T., Walls, D.H., 2002. Ecosystem carbon loss with woody plant invasion of grasslands. Nature 418, 623–626.

Jaques, A.P., 1992. Canada's Greenhouse gas emissions: estimates for 1990. Report Environmental Protection Series (EPS) 5/AP/4, 78 pp.

Jensen, M., 1993a. Soil conditions, vegetation structure and biomass of a Javanese homegarden. Agrofor. Syst. 24, 171–186.

Jensen, M., 1993b. Productivity and nutrient cycling of a Javanese homegarden. Agrofor. Syst. 24, 187–201.

Kandji, S.T., Albrecht, A., Ogol, C.K.P.O., 2001. Diversity of plant–parasitic nematodes and their relationships with some soil physico-chemical properties in improved fallows in western Kenya. Appl. Soil Ecol. 18, 143–157.

Kang, B.T., 1993. Alley cropping: past achievements and future directions. Agrofor. Syst. 23, 141–155.

Kang, B.T., 1997. Alley cropping—soil productivity and nutrient recycling. For. Ecol. Manage. 91, 75–82.

Kang, B.T., Caveness, F.E., Tian, G., Kolawole, G.O., 1999. Long-term alley cropping with four species on an Alfisol in southwest Nigeria—effect on crop performance, soil chemical properties and nematode population. Nutr. Cycl. Agroecosyst. 54, 145–155.

Keutgen, N., Chen, K., 2001. Responses of citrus leaf photosynthesis, chlorophyll fluorescence, macronutrient and carbohydrate contents to elevated CO_2. J. Plant Physiol. 158, 1307–1316.

Krankina, O.N., Dixon, R.K., 1994. Forest management options to conserve and sequester terrestrial carbon in the Russian Federation. World Resour. Rev. 6, 88–101.

Kumar, B.M., George, S.J., Suresh, T.K., 2001. Fodder grass productivity and soil fertility changes under four grass + tree associations in Kerala, India. Agrofor. Syst. 52, 91–106.

Kürsten, E., 2000. Fuelwood production in agroforestry systems for sustainable land use and CO_2 mitigation. Ecol. Eng. 16, 69–72.

Kürsten, E., Burschel, P., 1993. CO_2-mitigation by agroforestry. Water Air Soil Pollut. 70, 533–544.

Lasco, R.D., Suson, P.D., 1999. A *Leucaena leucocephala*-based indigenous fallow system in central Philippines: the Naalad system. Int. Tree Crops J. 10, 161–174.

Le Mer, J., Roger, P., 2001. Production, oxidation, emission and consumption of methane by soils: a review. Eur. J. Soil Biol. 37, 25–50.

Lehmann, J., Poidy, N., Schroth, G., Zech, W., 1998. Short-term effects of soil amendment with three legume biomass on carbon and nitrogen in particle size separates in central Togo. Soil Biol. Biochem. 30, 1545–1552.

Lundgren, B., 1982. Introduction [Editorial]. Agrofor. Syst. 1, 3–6.

Mathuva, M.N., Rao, M.R., Smithson, P.C., Coe, R., 1998. Improving maize yields in semi-arid highlands of Kenya: agroforestry or fertilisers? Field Crops Res. 55, 57–72.

Matthews, R.B., Lungu, S., Volk, J., Holden, S.T., Solberg, K., 1992. The potential of alley cropping in improvement of cultivation systems in the high rainfall areas of Zambia. II. Maize production. Agrofor. Syst. 17, 241–261.

Mc Connell, D.J., 1992. The Forest Garden Farms of Kandy, Sri Lanka. FAO Farm Systems Management, Series 3, FAO, Rome.

Melaku, W., Tsedeke, A., Anteneh, T., 1996. Getting to know the enemy—Mesoplatys beetles and sesbania. Agrofor. Today 8, 17–18.

Nair, P.K.R., 1993. An Introduction to Agroforestry. Kluwer Academic Publishers, Dordrecht, The Netherlands, 499 pp.

Ndufa, J.K., 2001. Nitrogen and soil organic matter benefits to maize by fast-growing pure and mixed species legume fallows in western Kenya. Doctoral Thesis. University of London, 323 pp.

Nuberg, I.K., Evans, D.G., 1993. Alley cropping and analog forests for soil conservation in the dry uplands of Sri Lanka. Agrofor. Syst. 24, 247–269.

Nybert, G., 2001. Carbon and nitrogen dynamics in agroforestry systems. Temporal patterns of some important soil processes. Doctoral Thesis. Swedish University of Agricultural Sciences, Umeå, Sweden.

Onim, J.F.M., Mathuva, M., Otieno, K., Fitzhugh, H.A., 1990. Soil fertility changes and response of maize and beans to green manures of leucaena, sesbania and pigeonpea, sesbania and pigeonpea. Agrofor. Syst. 12, 197–215.

Palm, C.A., Alegre, J.C., Arevalo, L., Mutuo, P.K., Mosier, A.R., Coe, R., 2002. Nitrous oxide and methane fluxes in six different land use systems in the Peruvian Amazon. Global Biogeochem. Cycles. 16 (4) 1073, doi:10.1029/2001GB001855.

Pan, Q., Wang, Z., Quebedeaux, B., 1998. Responses of the apple plant to CO_2 enrichment: changes in photosynthesis, sorbitol, other soluble sugars, and starch. Aust. J. Plant Physiol. 25, 293–297.

Pandit, N.C., Pradhan, S.K., 1996. Bionomics of the sunnhemp flea-beetle, *Longitarsus belgaumensis* Jac. (Coleoptera: Chrysomelidae). Indian J. Entomol. 57, 219–223.

Paustian, K., Andrén, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., van Noordwijk, M., Woomer, P.L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use Manage. 13, 1–15.

Paustian, K., Six, J., Elliott, E.T., Hunt, H.W., 2000. Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48, 147–163.

Potter, K.N., Torbert, H.A., Jones, O.R., Matocha, J.E., Morisson Jr., J.E., Unger, P.W., 1998. Distribution and amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47, 197–205.

Prinz, D., 1986. Increasing the productivity of smallholder framing systems by introduction of planted fallows. Plant Res. Dev. 24, 31–56.

Rao, M.R., Nair, P.K.K., Ong, C.K., 1998. Biophysical interactions in tropical agroforestry systems. Agrofor. Syst. 38, 3–50.

Romero, F., Chana, C., Montenegro, J., Sanchez, L.A., Guevara, G., 1991. Productividad de *Gliricidia sepium* y *Erythrina bertroana* en cercas vivas manejadas bajo tres frecuencias de poda en la zona atlantica de Costa Rica. Agroforestria, No. 6, Turrialba, Costa Rica, 4 pp.

Roy, C., 1999. Options techniques et socio-économiques des émissions de CO_2 et d'augmentation des stocks de carbone. CR Acad Agric. France 85, 311–320.

Salafsky, N., 1994. Forest gardens in the Gunung Palung region of West Kalimantan, Indonesia: defining a locally-developed, market-oriented agroforestry system. Agrofor. Syst. 28, 237–268.

Salinas-Garcia, J.R., Hons, F.M., Matocha, J.E., 1997. Long term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61, 152–159.

Samsuzzaman, S., Garrity, D.P., Quintana, R.U., 1999. Soil property changes in contour hedgerow systems on sloping land in the Philippines. Agrofor. Syst. 46, 251–272.

Schaffer, B., Whiley, A.W., Searle, C., Nissen, R.J., 1997. Leaf gas exchange, dry matter partitioning, and mineral element concentrations in mango as influenced by elevated atmospheric carbon dioxide and root restriction. J. Am. Soc. Hort. Sci. 122, 849–855.

Schroeder, P., 1993. Agroforestry systems: integrated land use to store and conserve carbon. Climate Res. 3, 53–60.

Sileshi, G., Maghembe, J.A., Rao, M.R., Ogol, C.K.P.O., Sithanantham, S., 2000. Insects feeding on *Sesbania* species in natural and agroforestry systems in Southern Malawi. Agrofor. Syst. 49, 41–52.

Smith, T.M., Cramer, W.P., Dixon, R.K., Leemans, R., Neilson, R.P., Solomon, A.M., 1993. The global terrestrial carbon cycle. Water Air Soil Pollut. 70, 19–38.

Szott, L.T., Fernandes, E.C.M., Sanchez, P.A., 1991a. Soil–plant interactions in agroforestry systems. In: Jarvis, P.G. (Ed.), Agroforestry: Principles and Practices. Elsevier, Amsterdam, pp. 127–152.

Szott, L.T., Palm, C.A., Sanchez, P.A., 1991b. Agroforestry in acid soils of the humid tropics. Adv. Agron. 45, 275–301.

USDA NRCS (United States Department of Agriculture Natural Resources Conservation Service), 2000. Growing carbon: a new crop that helps agricultural producers and the climate too. Available from the Soil and Water Conservation Society. http://www.unl.edu/nac.

Viswanath, S., Kaushik, P.K., Prakasam, U., 1998. Biomass production and survival of *Sesbania sesban* in alley cropping. Forest, Farm and Community Tree Research Reports, vol. 3, pp. 59–61.

Wang, Y., Hsieh, Y.-P., 2002. Uncertainties and novel prospects in the study of the soil carbon dynamics. Chemosphere 49, 791–804.

Wilkinson, K.M., Elevitch, C.R., 2000. Multipurpose windbreaks: design and species for Pacific Islands. Agroforestry Guides for Pacific Islands #4. Permanent Agriculture Resources, Holualoa, Hawaii, USA. http://www.agroforestry.net.

Winjum, J.K., Dixon, R.K., Schroeder, P.E., 1992. Estimating the global potential of forest and agroforest management practices to sequester carbon. Water Air Soil Pollut. 64, 213–228.

Xu, Z.H., Myers, R.J.K., Saffigna, P.G., Chapman, A.L., 1993a. Nitrogen cycling in leucaena (*Leucaena leucocephala*) alley cropping in semi-arid tropics. II. Response of maize growth to addition of nitrogen fertilizer and plant residues. Plant and Soil 148, 73–82.

Xu, Z.H., Saffigna, P.G., Myers, R.J.K., Chapman, A.L., 1993b. Nitrogen cycling in leucaena (*Leucaena leucocephala*) alley cropping in semi-arid tropics. I. Mineralization of nitrogen from leucaena residues. Plant and Soil 148, 63–72.

Young, A., 1997. Agroforestry for Soil Management, 2nd ed. CAB International, Wallingford, UK, 320 pp.

Zhang, H., Brandle, J.R., 1996. Windbreak effect on biomass and grain mass accumulation of corn: a modelling approach. Agron. J. 88, 607–613.