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 CO2 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 CO2 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\(_2\)O) 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 Imbhall, 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
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 widespread 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

<table>
<thead>
<tr>
<th>Biomes</th>
<th>Primary method to increase CS$^a$</th>
<th>Potential CS (Pg C per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural lands</td>
<td>Management (H)</td>
<td>0.85–0.90</td>
</tr>
<tr>
<td>Biomass croplands</td>
<td>Manipulation (H)</td>
<td>0.50–0.80</td>
</tr>
<tr>
<td>Grasslands</td>
<td>Management (M)</td>
<td>0.50</td>
</tr>
<tr>
<td>Rangelands</td>
<td>Management (M)</td>
<td>1.20</td>
</tr>
<tr>
<td>Forests</td>
<td>Management (M)</td>
<td>1–3</td>
</tr>
<tr>
<td>Urban forests and grasslands</td>
<td>Creation and maintenance (M)</td>
<td>na$^b$</td>
</tr>
<tr>
<td>Deserts and degraded lands</td>
<td>Manipulation (H)</td>
<td>0.40–1.30</td>
</tr>
<tr>
<td>Terrestrial sediments</td>
<td>Protection (L)</td>
<td>0.70–1.70</td>
</tr>
<tr>
<td>Boreal peatlands and other wetlands</td>
<td>Protection (L)</td>
<td>0.10 to −0.70</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>5.65–10.10</td>
</tr>
</tbody>
</table>

$^a$ 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)

<table>
<thead>
<tr>
<th>Ecoregion</th>
<th>System</th>
<th>Mg C ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>Humid tropical high</td>
<td>29–53</td>
</tr>
<tr>
<td></td>
<td>Humid tropical low</td>
<td></td>
</tr>
<tr>
<td>South</td>
<td>Agrosilvicultural</td>
<td>39–102a</td>
</tr>
<tr>
<td></td>
<td>Dry lowlands</td>
<td>39–195</td>
</tr>
<tr>
<td>Southeast</td>
<td>Humid tropical</td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>Agrosilvicultural</td>
<td>12–228</td>
</tr>
<tr>
<td></td>
<td>Dry lowlands</td>
<td>68–81</td>
</tr>
<tr>
<td>Australia</td>
<td>Humid tropical high</td>
<td>133–154</td>
</tr>
<tr>
<td>North</td>
<td>Silvopastoral</td>
<td>28–51</td>
</tr>
<tr>
<td>America</td>
<td>Humid tropical low</td>
<td>133–154</td>
</tr>
<tr>
<td></td>
<td>Silvopastoral</td>
<td>104–198</td>
</tr>
<tr>
<td></td>
<td>Dry lowlands</td>
<td>90–175</td>
</tr>
<tr>
<td>Northern</td>
<td>Humid tropical low</td>
<td>15–18</td>
</tr>
<tr>
<td>Asia</td>
<td>Silvopastoral</td>
<td></td>
</tr>
</tbody>
</table>

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

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 alliodora) and cacao–pоро (Erythrina poepigiana) (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 per year was 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.

2.1.1. 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 alliodora) and cacao–pоро (Erythrina poepigiana) (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 per year was 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
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 falling 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\(^{-1}\) 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.

2.4.2. Soil carbon

Several studies have shown increased SOM after a few seasons of tree planting on degraded soils and 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 4

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

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

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ mitigating options. Economic analyses showed that these costs could be easily offset by the monetary benefits from agricultural products and trading in C credits.

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 substandard 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 falls, 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$_2$O) 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$_2$O (Choudhary et al., 2002; Palm et al., 2002). N$_2$O 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 widespread use of woody legumes might result in massive release of N$_2$O gas into the atmosphere. Similarly, ungulate production and cultivation of rice paddy in agroforestry systems can produce significant quantities of CH$_4$ (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$_2$O 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. Permanent 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 CO2 mitigation through agroforestry systems.
4. Adequate understanding on issues such as pests and diseases and the emission of other GHGs, especially N2O and CH4 in agroforestry systems.
5. More powerful methods to implement cost/benefit analyses of agroforestry-based GHG mitigation and to define incentives for widespread adoption of agroforestry systems.

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