Agroforestry Systems **61:** 281–295, 2004.

Carbon sequestration: An underexploited environmental benefit of agroforestry systems

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Key words: Carbon market, Kyoto Protocol, PES (payment for environmental services), Policy framework, Silvopasture, Soil carbon

Abstract

Agroforestry has importance as a carbon sequestration strategy because of carbon storage potential in its multiple plant species and soil as well as its applicability in agricultural lands and in reforestation. The potential seems to be substantial; but it has not been even adequately recognized, let alone exploited. Proper design and management of agroforestry practices can make them effective carbon sinks. As in other land-use systems, the extent of C sequestered will depend on the amounts of C in standing biomass, recalcitrant C remaining in the soil, and C sequestered in wood products. Average carbon storage by agroforestry practices has been estimated as 9, 21, 50, and 63 Mg C ha^{-1} in semiarid, subhumid, humid, and temperate regions. For smallholder agroforestry systems in the tropics, potential C sequestration rates range from 1.5 to 3.5 Mg C ha^{-1} yr^{-1}. Agroforestry can also have an indirect effect on C sequestration when it helps decrease pressure on natural forests, which are the largest sink of terrestrial C. Another indirect avenue of C sequestration is through the use of agroforestry technologies for soil conservation, which could enhance C storage in trees and soils. Agroforestry systems with perennial crops may be important carbon sinks, while intensively managed agroforestry systems with annual crops are more similar to conventional agriculture. In order to exploit this vastly unrealized potential of C sequestration through agroforestry in both subsistence and commercial enterprises in the tropics and the temperate region, innovative policies, based on rigorous research results, have to be put in place.

Introduction

Finding low-cost methods to sequester carbon is emerging as a major international policy goal in the context of increasing concerns about global climate change. Recognizing that the accumulation of carbon dioxide and other greenhouse gases in the upper atmosphere is the major reason for global climate change, the idea of mitigating it through forest conservation and management was discussed as early as in the 1970s. But it was in the 1990s that international action was initiated in this direction. In 1992, several countries agreed to the United Nations Framework Convention on Climate Change (UNFCCC), with the major objectives of developing national inventories of greenhouse gas emissions and sinks, and reducing the emission of greenhouse gases (FAO 2001). At the third meeting of the FCCC in 1997 in Kyoto, Japan, the participating countries, including the United States, agreed, through what would later become known as the Kyoto Protocol, to reduce greenhouse gas emissions to 5% or more below 1990 levels by 2012 (http://unfcc.int). The Protocol provides a mechanism by which a country that emits carbon in excess of agreed-upon limits can purchase carbon offsets from a country or region that manages carbon sinks. Although the United States' withdrawal from the treaty in 2001 has considerably weakened its implementation, the Kyoto Protocol represents a major international effort related to carbon sequestration. Initially there was no agreement as to whether forests could be considered as carbon sinks, but the potential role of forest conservation and management to decrease greenhouse gases in the atmosphere was soon recognized. Globally, forests contain more than half of all terrestrial carbon, and account for about 80% of carbon exchange between terrestrial ecosystems and the atmosphere. Forest ecosystems are estimated to absorb up to 3 Pg (3 billion tons) of carbon annually. In recent years, however, a significant portion of that has been returned through deforestation and forest fires. For example, tropical deforestation in the 1980s is estimated to have accounted for up to a quarter of all carbon emissions from human activities (FAO 2003).

Basically there are three categories of activities through which forest management can help reduce atmospheric carbon: *Carbon sequestration* (through afforestation, reforestation, and restoration of degraded lands, improved silvicultural techniques to increase growth rates, and implementation of agroforestry practices on agricultural lands); *Carbon conservation* (through conservation of biomass and soil carbon in existing forests, improved harvesting practices such as reduced impact logging, improved efficiency of wood processing, fire protection and more effective use of burning in both forest and agricultural systems); and *Carbon substitution* (increased conversion of forest biomass into durable wood products for use in place of energy-intensive materials, increased use of biofuels such as introduction of bioenergy plantations, and enhanced utilization of harvesting waste as feedstock such as sawdust for biofuel) (Bass et al. 2000). Of the three, carbon conservation is regarded as having the greatest potential for rapid mitigation of climate change, whereas carbon sequestration takes place over a much longer period of time. Agroforestry has been recognized to be of special importance as a carbon sequestration strategy because of its applicability in agricultural lands as well as in reforestation programs (Cairns and Meganck 1994; Ruark et al. 2003).

Some tropical countries have recently started programs of incentives to encourage tree plantation development, especially on degraded areas. For example, in Costa Rica, Payment for Environmental Services (PES) contributes, since 1996, to promoting plantations through the assignment of differential incentives for already established plantations and for new reforestation. Carbon, water, and biodiversity are the major components of the program. Funding for these incentives comes from a special tax on gasoline, and from external sources (J. J. Campos A. and R. Ortiz: pers. comm., February 1999). In 2003, agroforestry systems were added to the list of systems receiving incentives in Costa Rica. Similarly, the Dutch government has been engaged in a 25-year program to finance reforestation projects covering 2500 km^2 in South America, in order to offset carbon emissions from coal-fired stations in The Netherlands (Myers 1996).

Many observers believe that the Clean Development Mechanism (CDM) offered by the Kyoto Protocol could reduce rural poverty by extending payments to low-income farmers who provide carbon storage through land-use systems such as agroforestry (Smith and Scherr 2002). Consequent to the realization of the potential of agroforestry practices such as silvopasture and riparian buffers in providing environmental benefits including carbon sequestration, methods for their valuation and development of policies to motivate the general public to pay for such benefits are under way in industrialized nations too (Alavalapati et al. 2004). Nevertheless, the potential of agroforestry as a strategy for carbon sequestration has not yet been fully recognized, let alone exploited. A major difficulty is that empirical evidence is still lacking on most of the mechanisms that have been suggested to explain how agroforestry systems could bring about reductions in the buildup of atmospheric CO_2. In this paper we review the current status of understanding on carbon storage potential for agroforestry systems and examine how this potential could be exploited for the benefit of landowners and the society at large.

Carbon Sequestration by tree-based systems

The basic premise of carbon sequestration potential of land-use systems, including agroforestry systems, is relatively simple: it revolves around the fundamental biological/ecological processes of photosynthesis, respiration, and decomposition (Nair and Nair 2003). Essentially, carbon sequestered is the difference between carbon ‘gained’ by photosynthesis and carbon ‘lost’ or ‘released’ by respiration of all components of the ecosystem, and this overall gain or loss of carbon is usually represented by net ecosystem productivity. Most carbon enters the ecosystem via photosynthesis in the leaves, and carbon accumulation is most obvious when it occurs in aboveground biomass. More than half of the assimilated carbon is eventually transported below ground via root growth and turnover, root exudates (of organic substances), and litter deposition, and therefore soils contain the major stock of C in the ecosystem. Inevitably, practices that increase net primary productivity (NPP) and/or return a greater portion of plant materials to the soil have the potential to increase soil carbon stock. Since the literature on C sequestration in agroforestry systems is rather scanty compared with that of tree-plantation systems, and considering that C sequestration potential of both plantations and agroforestry systems is based mainly on the attributes of the tree component, we will first review the situation with respect to tree plantations and then attempt to relate the lessons to agroforestry systems.

Carbon sequestration by tree plantations

Conceptually trees are considered to be a terrestrial carbon sink (Houghton et al. 1998). Therefore, managed forests can, theoretically, sequester carbon both *in situ* (biomass and soil) and *ex-situ* (products). According to FAO (2000) estimates, forest plantations cover 187 million ha worldwide, a significant increase from the 1995 estimate of 124 million ha. The reported new annual planting rate is 4.5 million ha globally, with Asia and South America accounting for 89‰. The main fast-growing, short-rotation species are of the genera *Eucalyptus* and *Acacia.* Pines and other coniferous species are the main medium-rotation utility species, primarily in the temperate and boreal zones. There is strong variation in the carbon sequestration potential among different plantation species, regions and management. Variations in environmental conditions can affect carbon sequestration potential even within a relatively small geographic area. In addition, management practices such as fertilization can easily increase carbon sequestration of species such as eucalypts (Koskela et al. 2000). Various estimates are available on C sequestration rates of common plantation species of varying rotation ages (Schroeder 1992; FAO 2000; FAO 2001; FAO 2003).

Use of native species for reforestation is minimal, and exotic tree species predominate both in industrial and in rural development plantations worldwide (Evans, 1999). Plantations using indigenous species are restricted for the most part to small- and medium-sized farms where reforestation is practiced in degraded portions of the land, often using species in response to government incentives (Piotto et al. 2003). The relative efficiency of native and exotic species in terms of their carbon accumulation potential has been investigated in a few studies. In experimental plantings in Central America, for example, values of C sequestration in aboveground biomass for ten native tree species were comparable to exotic species growing under similar conditions (Table 1). Proper design and management of such agroforestry (or, farm forestry) plantations can increase biomass accumulation rates, making them effective carbon sinks (Shepherd and Montagnini, 2001). Montagnini and Porras (1998) and Shepherd and Montagnini (2001) compared three mixed plantations with monocultures of each tree included to find out the benefits or disadvantages in terms of biomass accumulation and soil fertility maintenance for mixed stands versus monocultures in Central America. Mixtures of three to four tree species had C accumulation rates similar or larger than those of the fastest-growing species included in the mixture. With relatively short or medium rotation times of 15 to 25 years and relatively high standing volumes at harvest of 250 to 300 m^3 ha^{-1}, planting of these species is attractive for smallholders of the region. Fuelwood from thinning and pruning would be an additional source of farm income and thus an incentive for tree planting. In fact, the species involved in the experiment currently account for the majority of small farm reforestation in the region, and interest has recently developed for mixed designs that include some of the fastest growing trees with good timber value (*Terminalia amazonia*, *Vochysia guatemalensis* and *Hieronyma alchorneoides*) (Montagnini et al. 1995; Montagnini and Mendelsohn, 1996).

The idea that planting trees could be an easy (and often cheap) way to absorb emissions of carbon dioxide as well as its feasibility, has, however, been challenged. Based on experiments conducted in loblolly pine (*Pinus taeda*) forests in North Carolina, Oren et al. (2001) reported that after an initial growth spurt, trees grew more slowly and did not absorb as much excess carbon from the atmosphere as expected. In two experiments with loblolly pine trees exposed to increased atmospheric CO_2, CO_2-induced biomass-carbon increment without added nutrients was undetectable at a nutritionally poor site, and the stimulation at a nutritionally moderate site was transient, stabilizing at a marginal gain after three years. However, a large synergistic gain from higher CO_2 and nutrients was detected with nutrients added, the gain being larger at the poor site than at the moderate site. Based on these findings, the authors concluded that assessment of future carbon sequestration should consider the limitations imposed by soil fertility as well as interactions with nitrogen deposition. Schlesinger and Lichter (2001) examined decomposing leaves and roots on the floor of the experimental pine forest plots

Table 1. Carbon content in above ground biomass of 10 plantation-tree species at 10 years of age at la Selva, Costa Rica.

Plantation species	Stand density (trees ha^{-1})	Carbon content (Mg ha^{-1})			
		Foliage	Branch	Stem	Total
Balizia elegans	764	0.6	2.5	17.3	20.5
Calophyllum brasiliense	551	5.8	10.8	29.7	46.3
Dipteryx panamensis	670	5.3	15.4	82	102.6
Genipa americana	278	1.1	4.8	17.5	23.3
Hieronyma alchorneoides	660	2.4	13.5	43.8	59.7
Jacaranda copaia	596	0.8	1.6	42.5	44.9
Terminalia amazonia	462	4.7	14.6	63.2	82.5
Virola koschnyi	610	2	4.1	31	37
Vochysia ferruginea	556	2.7	5.7	30.6	39.1
Vochysia guatemalensis	551	2.2	5.2	55.5	62.8

Source: F. Montagnini (unpublished data).

and found the total amount of litter increased in a carbon-dioxide-enriched atmosphere, but so did the rate at which it was broken down, resulting in the release of carbon back to the atmosphere rather than being incorporated into the soil. Although these findings certainly do not imply that tree planting is not important, they suggest that planting trees *per se* may not necessarily enhance C sequestration or serve as an adequate substitute for reducing heat-trapping greenhouse gas emissions, and the relationship between tree planting and C sequestration is not as straight forward and simple as it is often portrayed.

The role of traditional forestry practices such as natural forest management in C sequestration is also unclear. As Harmon (2001) points out, there are two contrasting views, and consequently some confusion prevails. On the one hand, young (or newly planted) forests are generally believed to be better than older ones for C sequestration because of their faster growth, higher dry-matter accumulation rates, and fewer dead trees or decomposing parts. On the other hand, replacements of older forests with younger ones are reported to result in net release of C into the atmosphere (e.g., Schulze et al. 2000) through decomposition of dead and dying material from the old forests that are replaced by new plantings. This apparent confusion disappears when we acknowledge that in the former scenario, only the living plants of the ecosystem are considered as the long-term store of carbon, whereas in the latter, a more holistic view of the whole system is considered. It is essential that such a holistic view is considered in the discussion on C sequestration potential of mixed systems such as agroforestry, in which C dynamics in pools such as detritus and soil are quite different from those in sole stands of trees or crops.

Based on the above, it seems prudent to surmise that three factors are needed to determine the amount of carbon sequestered: (1) the increased amount of carbon in standing biomass, due to land-use changes and increased productivity; (2) the amount of recalcitrant carbon remaining below ground at the end of the tree rotation; and (3) the amount of carbon sequestered in products created from the harvested wood, including their final disposition (Johnsen et al. 2001).

Carbon sequestration by agroforestry systems

Claims on C sequestration potential of agroforestry systems are based on the same premise as for tree plantations: the tree components in agroforestry systems can be significant sinks of atmospheric C due to their fast growth and high productivity. By including trees in agricultural production systems, agroforestry can, arguably, increase the amount of carbon stored in lands devoted to agriculture, while still allowing for the growing of food crops (Kursten 2000). The discussion on planted forests presented in the earlier section has shown that: (1) soil fertility may be a limiting factor in realizing carbon sequestration potential of planted forests; (2) mixed stand of plants might be more efficient than sole stands in carbon sequestration; and (3) C sequestration estimates should be based on a holistic view of the long-term carbon storage potential of all components in the system including detritus, soil, and forest products. Agroforestry systems score highly in all these points: soil fertility improvement is a distinct possibility in agroforestry systems, especially under low-fertility conditions of the tropics (Nair et al. 1999); agroforestry systems entail mixed stands of species; and, a holistic rather than compartmental consideration of systems is a key concept of agroforestry (Nair 2001). In most agroforestry systems, the tree component is managed, often intensively, for its products such as pruning of hedgerows in tropical alleycropping, and harvest of commercial, mostly nontimber, products. Such harvested materials often are returned to the soil (as in alleycropping and improved fallow systems for soil fertility improvement). In addition, the amount of biomass and therefore carbon that is harvested and 'exported' from the system is relatively low in relation to the total productivity of the tree (as in the case of shaded perennial systems). Therefore, unlike in tree plantations and other monocultural systems, agroforestry seems to have a unique advantage in terms of C sequestration. Many of these assumptions have, however, been not systematically tested and validated.

Focusing on the tree component of agroforestry, some attempts have been made to estimate the global contribution of agroforestry as a sink for C. Based on tree growth rates and wood production, and assuming ratios of tree-stem biomass to C content of 1:2 (i.e., 50% of stemwood is assumed to be C), average carbon storage by agroforestry practices has been estimated to be 9, 21, 50, and 63 Mg C ha^{-1} in semiarid, subhumid, humid, and temperate regions (Schroeder 1994). The higher levels reported for temperate ecozones reflect the longer cutting cycles in these regions, with a resulting longer-term storage. At a global scale, it has been estimated that agroforestry systems could be implemented on 585 to 1275×10^6 hectares of technically suitable land, and these systems could store 12 to 228 Mg C ha^{-1} under the prevalent climatic and edaphic conditions (Dixon 1995).

In addition, agroforestry systems can have an indirect effect on C sequestration if they can help to decrease pressure on natural forests, which are the largest sink of terrestrial C. Within tropical regions, it has been estimated that one hectare of sustainable agroforestry could potentially offset 5 to 20 hectares of deforestation (Dixon 1995). Based on this assumption, projects promoting agroforestry in farmland surrounding 'islands' of natural forests have been attempted in Kenya and Madagascar (Young 1997). There are some examples of cases where promotion and implementation of agroforestry systems has been successful in this regard: in Sumatra, Indonesia, farmers who integrated rice (*Oryza sativa*) production with tree crops and home gardens exerted much less pressure on adjacent forest, in comparison with farmers dedicated to rice only (ICRAF 1995). Agroforestry systems can, however, be either sinks or sources of C and other greenhouse gases. Some agroforestry systems, especially those that include trees and crops (agrisilviculture) can be C sinks and temporarily store C, while others (e.g. ruminant-based agrosilvopastoral systems) are probably sources of C and other greenhouse gases. Especially in tropical regions, agroforestry systems can be significant sources of greenhouse gases: practices such as tillage, burning, manuring, chemical fertilization, and frequent disturbance can lead to emissions of CO_2, CH_4 and N_2O from soils and vegetation to the atmosphere. Silvopastoral systems, when practiced in an unsustainable manner, can result in soil compaction and erosion with losses of C and N from soils. Ruminant-based agrosilvopastoral systems and rice paddy agrosilvicultural systems are well documented sources of CH_4 (Dixon 1995).

On the other hand, agroforestry systems, especially if well managed and if they include soil conservation practices, can contribute to increasing short-term C storage in trees and soils, as will be shown in some examples that follow. Finally, whether agroforestry systems can be a sink or a source of C depends on the land-use systems that they replace: if they replace natural primary or secondary forests, they will accumulate comparatively lower biomass and C, but if they are established on degraded or otherwise treeless lands, their C sequestration value is considerably increased.

Agroforestry and soil carbon

Measurements of carbon stocks in soil are not very accurate, due to sampling and measurement problems (Koskela et al. 2000). For the past 20 years, scientists have been attempting to calculate the global carbon stocks of tropical forests, as well as the changes in these stocks as changes in land use occur. Recently, satellite data and remote sensing have been used to characterize ground cover, providing more accurate estimates in changes of vegetation each year throughout the tropics than ever before (Loveland and Belward 1997).

According to the estimates of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2000), tropical forests are by far the largest carbon stock in vegetation, while boreal forests represent the largest

C stock in soils (www.ipcc.ch). Tropical savannas store about one third of C in vegetation as do tropical forests, but savannas also have large C stocks in soils, similar to those of temperate grasslands. Croplands worldwide have the smallest C stocks in vegetation, with intermediate values for soils. Where agroforestry lies in these ranges depends on the proportion of trees included in the production system, as well as on the soil management and conservation practices used by each agroforestry system.

Globally, 1.5 to 3 times more C occurs in soils than in vegetation (Dixon 1995). Soils are the largest pool of terrestrial carbon, estimated at 2200 Pg; tropical topsoils contain about 13% of world soil carbon (Young 1997). However small on a global sense, the potential positive role of agroforestry in increasing soil carbon cannot be disregarded, especially considering other indirect effects on carbon and soil nutrients, as for example when proper agroforestry practices can help reducing soil erosion losses.

Estimates of C sequestration in agroforestry systems

Two issues need to be addressed in the discussion on C sequestration potential of agroforestry systems, and, unfortunately both seem to be rather insurmountable at the moment. First, the area under different agroforestry systems (existing or potential) is not known, and, second, a holistic picture of the *in situ* and *ex-situ* C storage and dynamics in different agroforestry systems is not yet determined. In the following sections, we attempt to discuss these issues in the light of available information.

Tropical systems

Available estimates of C sequestration potential of agroforestry systems are mostly for tropical regions. Based on a preliminary assessment of national and global terrestrial C sinks, Dixon (1995) identified two primary beneficial attributes of agroforestry systems in terms of C sequestration: (1) direct near-term C storage (decades to centuries) in trees and soils; and (2) a potential to offset immediate greenhouse gas emissions associated with deforestation and subsequent shifting cultivation. Following that, some projections have been made on the role of agroforestry in reducing the C emission from tropical deforestation. Based on its project known as ‘Alternatives to Slash and Burn’, ICRAF (International Centre for Research in Agroforestry) and its collaborators around the humid tropics concluded that the greatest potential for C sequestration in the humid tropics is above ground, not in the soil: through the establishment of tree-based systems on degraded pastures, croplands, and grasslands, the time-averaged C stocks in the vegetation would increase as much as 50 Mg C ha^{-1} in 20 years, whereas the soil stocks would increase only 5 to 15 Mg C ha^{-1} (Palm et al. 2000). A projection of carbon stocks for smallholder agroforestry systems in the tropics indicated C sequestration rates ranging from 1.5 to 3.5 Mg C ha^{-1} yr^{-1} and a tripling of C stocks in a twenty-year period, to 70 Mg C ha^{-1} (Watson et al. 2000). The total carbon emission from global deforestation, estimated at 17 million ha yr^{-1}, is 1.6 Pg yr^{-1}.

Lack of reliable estimates on the extent of area under agroforestry systems in different ecological zones is a serious problem in projecting the extent to which agroforestry practices could counter carbon emission from deforestation. The difficulty is compounded by the fact that carbon sequestered in agroforestry systems varies with a number of site- and system-specific characteristics, including climate, soil type, tree-planting densities, and tree management. Nevertheless the IPCC Report (Watson et al. 2000) estimates the area currently under agroforestry worldwide as 400 million hectares with an estimated C gain of 0.72 Mg C ha yr^{-1}, with potential for sequestering 26 Tg C yr^{-1} by 2010 and 45 Tg C yr^{-1} by 2040 1 Tg = 10^{12} g or 1 million tons. That report also estimates that 630 million hectares of unproductive cropland and grasslands could be converted to agroforestry worldwide, with the potential to sequester 391 Tg C yr^{-1} by 2010 and 586 Tg C yr^{-1} by 2040. The report further argues that agroforestry can sequester carbon at time-averaged rates of 0.2 to 3.1 Mg C ha^{-1}. (Time averaged C stock is half the C stock at the maximum rotation length, and is a scale usually used to adjust C stocks of systems with varying ages and rotation lengths to a common base.) These studies recognize that agroforestry improvement practices generally have a lower carbon uptake potential than land conversion to agroforestry practices because existing agroforestry systems have much higher carbon stocks than degraded croplands and grasslands that can be converted into agroforestry.

Annual crop–tree combinations

(a) Alleycropping

Tropical alleycropping systems, the cultivation of arable crops between tree hedgerows, represent a low end with respect to potential for C storage. As trees are periodically pruned to deposit their mulch in the alleys, C is only stored in the stem left after pruning. Therefore, pruning frequency, which can be as high as once every other month during the growing season, greatly affects the C storage capacity of the system. From data from a study of two alleycropping systems from Turrialba, Costa Rica, Koskela et al. (2000) estimated the annual 'labile' C stocks (C stored in tree leaves, branches, and crops), and compared them with the 'permanent' C stocks in tree stems. In the two systems, the perennial carbon stocks were higher than the labile stocks. However, significant decreases in soil C were detected in both systems after three to five years, thus greatly decreasing the overall value of the alleycropping system as a C sink. Some results from alleycropping experiments report on increases in soil organic carbon when prunings are returned to the soil; these increases are thought to be due to higher density of roots in alleycropping systems in comparison with adjacent plots with conventional agriculture (Schroeder 1994).

(b) Other annual crop–tree combinations

Lott et al. (2000a, 2000b) examined the biomass of agroforestry systems involving the intercropping of maize (*Zea mays*) with grevillea (*Grevillea robusta*) trees, popular in agroforestry systems in the highlands of Kenya. Their study site was the semiarid savanna area of Machakos, Kenya. Plots of sole grevillea, and sole maize were compared with agroforestry plots with both maize and grevillea intercropped for two years. The expectation was that grevillea would utilize ('capture') water and nutrient sources from deeper soil layers while the maize would rely on water and nutrients in the topsoil. However, the grevillea appeared to compete with the maize for scarce water and nutrients, resulting in lower biomass for the agroforestry system as compared to the sole grevillea or sole maize crops. Sole grevillea accumulated 1.2 times the biomass of the grevillea in the agroforestry system. The sole maize plots accumulated between two to twelve times the biomass of the maize in the agroforestry plots.

Perennial crop–tree combinations

(a) Cacao under shade trees

Koskela et al. (2000) compared labile and perennial C stocks in shaded cacao (*Theobroma cacao*) systems in Turrialba, Costa Rica, based on data from a study by Beer et al. (1990) (Table 2). The shade trees were *Erythrina poeppigiana*, a nitrogen-fixing tree that was pruned periodically for mulch, and *Cordia alliodora,* a non-nitrogen- fixing, timber tree that does not need pruning. In both systems, soil C stocks increased through time: in the cacao-*Cordia* system, soil C stocks increased by 75% in 10 years, and in the cacao *Erythrina* system they increased by 65%. C sequestration in perennial plant biomass was similar for both systems: an average of 4.28 Mg C ha^{-1} yr^{-1} for the cacao-*Cordia* system, and 3.08 Mg C ha^{-1} yr^{-1} in the cacao-*Erythrina* system (Beer et al. 1990). In spite of the relatively high values for C sequestration in perennial plant tissue and soil, the C stocks in vegetation were about 50% of those found in mature forests in the region. Similarly, in cacao agroforests of southern Cameroon, soil C was higher than in secondary forest, with values reaching 62% of the carbon stock found in primary forest (Duguma et al. 2001).

(b) Multistrata agroforestry in Central Amazonia

Schroth et al. (2002) compared three multistrata agroforestry plots with five monoculture plantations and fourteen-year-old local secondary forests at the EMBRAPA (Brazilian National Agricultural System) research station, near Manaus, Brazil. Monocultures included peach palm (*Bactris gasipaes*) grown for fruit, cupuacu (*Theobroma grandiflorum*) – also for fruit, rubber (*Hevea brasiliensis* grafted with *Hevea pauciflora*), and orange (*Citrus sinensis*). The multistrata systems contained different mixtures of peach palm for fruit, peach palm for heart of palm, rubber, cupuacu, Brazil nut (*Bertolletia excelsa*), annatto (*Bixa orellana*), coconut palms (*Cocos nucifera*) and orange, as well as intercrops of papaya (*Carica papaya*), cassava (*Manihot esculenta*), maize and cowpea (*Vigna unguiculata*). In general, it was found that the trees in the multistrata systems tended to be larger in canopy volume than those in the monocultures. None of the systems reached the biomass of the secondary forest that they had replaced: the most productive plot only contained about two-thirds of the biomass of the natural regrowth. The primary forest contained more than four times the amount of total

Table 2. Carbon stocks in two cacao (*Theobroma cacao*) – shade tree systems under humid tropical conditions in Turrialba, Costa Rica.

System	Perennial C stock (Mg C ha^{-1})		Labile C stock (Mg C ha^{-1} yr^{-1})	
	Soil	Tree and cacao	Litter	Tree and cacao
Cordia alliodora + cacao				
Initial	98	–	–	–
5th year	138	18.6	2.6	3.0
10th year	171	42.8	8.8	3.0
Erythrina poeppigiana + cacao				
Initial	115	–	–	–
5th year	152	7.8	4.1	4.4
10th year	190	30.8	9.6	5.6

The perennial carbon stocks in vegetation comprise the cacao branches and stems, tree stems, an estimated 85% of roots (coarse root proportion), and tree branches in the *Cordia* + cacao system. The labile carbon stocks in vegetation comprise the leaves, an estimated 15% of roots (fine root proportion), and tree branches in the *Erythrina* + cacao system
Source: Adapted from Beer et al. (1990) by Koskela et al. (2000).

biomass than that of the most productive plot: peach palm for fruit.

Other perennial crop–tree combinations

Other studies of biomass and C sequestration by perennial crop-tree combinations also show that agroforestry systems accumulate considerably more C than the monocultures of annual crops; but lower than that accumulated by natural forests in the region. For example, results from studies in Cameroon showed that total biomass in cacao agroforests (304 Mg/ha) was much greater than in food crop fields (85 Mg ha^{-1}), and ranked third after the biomass in primary forest (541 Mg $^{-1}$ha), and long-term fallow (460 Mg/ha) (Duguma et al. 2001). In Sumatra, Indonesia, annual aboveground C stocks accumulation rates during the establishment phase after slash-and-burn land clearing were 1, close to 2, and 3.5 Mg C ha^{-1} for sun coffee (*Coffea* sp.), shade coffee and fallow regrowth, respectively. It was estimated that in Sumatra, conversion of all sun-coffee to shade coffee systems could increase average landscape level C stocks by 10 Mg C/ha during a 20-year period, or 0.5 Mg C ha^{-1} yr^{-1} (van Noordwijk et al. 2002).

As is to be expected, while comparing the annual crop-tree combinations (including alleycropping) with the perennial crop-tree combinations, agroforestry systems with perennial crops may be important carbon sinks, while intensively managed agroforestry systems with annual crops are more similar to conventional agriculture. However, even the perennial crop-tree combinations do not attain C sequestration rates comparable to the natural forests that grow in the region.

Temperate-zone systems

One of the most quoted estimates, which perhaps was also the basis for most of the subsequent calculations, is the report of Dixon et al. (1994), which states that the potential carbon storage with agroforestry in temperate areas ranges from 15 to 198 Mg C ha^{-1} with a modal value of 34 Mg C ha^{-1}. Most of the subsequent reports that are available on temperate systems are from North America. Garrett and McGraw (2000) acknowledge that reliable statistics of areas under alleycropping practice in North America are not available, but suggest that more than 45 million ha of nonfederal cropland in the United States with erodibility index (EI)[1] greater than 8 (USDA-SCS 1989) could potentially benefit from the use of alleycropping. They further argue that in the Midwest, where alleycopping adoption is greatest, an area of more than 7.5 million ha has EI greater than 10 (Noweg and Kurtz 1987), and approximately 3.6 million ha of this land that is recommended for forestry planting would

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[1] Erodiblity Index (EI) is calculated based on the parameters used in the Universal Soil Loss Equation. In practical terms, soils with an EI < 5 are only slightly susceptible to erosion, and those with EI > 8 are highly susceptible. An EI between 8 and 15 indicates that crop land bare of cover could erode eight or more times the tolerance value and EI of 15 and higher suggests that erosion could occur at 15 or more times the tolerance value (see End Note 1, Garrett et al., this volume).

be ideal for alleycropping. Furthermore, across the United States, approximately 7 million ha of pastureland has high potential for conversion to cropland and could be alley-cropped. Another 16 million ha have medium potential for conversion, and a total of 25 million ha has high or medium potential for conversion, all of which could be alley-cropped. Thus, the estimated area suitable, or that could soon be available, for alleycropping in the United States is approximately 80 million ha of land. Based on the estimated average total soil C sequestration potential of 142 Tg C yr^{-1} from 154 million ha of total U.S. crop lands (Lal et al. 1999), the potential for C sequestration through alleycropping could be 73.8 Tg C yr^{-1}.

Discussing the area under silvopastoral systems, Clason and Sharrow (2000) argue that, given the widespread co-occurrence of grazing and forestry across North America, the joint production of livestock and tree products is by far the most prevalent form of agroforestry found in the United States and Canada. But, areas are generally classified as forest, rangeland, and pasture, implying a single dominant form of land; area statistics do not deal with multiple product systems such as forested rangelands, grazed forests, and pasture with trees. According to Brooks (1993), forests currently occupy approximately 314 million ha of land in the United States and 436 million ha in Canada, of which only 70% and 60%, respectively, are timber-producing areas. Considerable amounts of forage may be available for grazing under trees in mature open canopied forest stands, such as semiarid conifer forests and savannas of western United States. Based on inventories made on 11-year-old Douglas-fir (*Pseudotsuga menziesii*)/ perennial ryegrass (*Lolium perenne*)/ subclover (*Trifolium subterraneum*) silvopastoral agroforestry system in western Oregon, United States, Sharrow and Ismail (2004) reported that the agroforests (silvopastures) were more efficient in accreting C than tree plantations or pasture monocultures. They attributed this to the advantages of silvopastures in terms of higher biomass production and active nutrient cycling patterns of both forest stands and grasslands, compared to those of pastures or timber stands alone. Even close-canopied forests may produce considerable amounts of vegetation following timber harvests or fire, which could remain unexploited if not grazed by ruminant livestock. Based on these considerations, Clason and Sharrow (2000) conclude that about 70 million ha, more than a quarter of all forest land in the United States, is grazed by livestock, which is also 13% of the total grazing land in the country (USDA 1996). At the average estimated total soil C sequestration potential for U.S. grazing lands of 69.9 Tg C yr^{-1} (Follett et al. 2001), the potential for silvopastoral systems could be around 9.0 Tg C yr^{-1}. Estimates of areas under other agroforestry practices (windbreaks, riparian forest buffer, and forest farming) are even more difficult to make. The (U.S.) National Agroforestry Center estimates that protecting the 85 million ha of exposed cropland in the North Central United States by planting 5% of the field area to windbreaks would sequester over 58 Tg C (215 Tg CO_2) in 20 years, or an average of 2.9 Tg C yr^{-1}. (National Agroforestry Center, 2000, *USDA National Agroforestry Center Resources.* www.unl.edu/nac.) Similarly, planting windbreaks around the 300 000 unprotected farms in the region would result in 120 million trees (at the rate of 400 trees/home), storing 3.5 Tg C in 20 years or 0.175 Tg C yr^{-1}. Planting live snow-fences along roads would be another opportunity. All together, a conservative estimate of the C sequestration potential of a reasonable windbreak-planting program could be around 4 Tg C yr^{-1}.

Riparian buffers and short-rotation woody crops (SRWC) are other notable agroforestry opportunities for C sequestration. The U.S. Department of Agriculture (USDA) has committed to planting 3.2 million km (2 million miles) of conservation buffers (US Dept of Energy 1999). If one-fourth of these buffers were 30 m-wide forested riparian buffers, C removal would exceed 30 Tg C in 20 years or 1.5 Tg C yr^{-1}. In the Pacific Northwest, 10-year-old irrigated plantations of SRWC are estimated to remove 222.3 Mg of C ha^{-1} or an average of 22.3 Mg C yr^{-1}. Although statistics on these practices and others such as forest farming are unavailable, for discussion purposes, a modest amount of 2.0 Tg C yr^{-1} could be presented as the C sequestration potential of these agroforestry practices. Based on these assumptions, Nair and Nair (2003) estimated that the total C sequestration potential through agroforestry practices in the United States could amount to 90 Tg C yr^{-1} (Table 3). One report estimates that 57×10^6 ha of marginal or degraded land is considered suitable for establishment of trees in Canada (Thevathasan and Gordon in press); but how much of this land area will actually be converted to tree-planting and agroforestry is uncertain.

Table 3. Estimated C sequestration potential through agroforestry practices in the USA by 2025.

Agroforestry Practice	[1]Estimated area	[#]Potential C sequestration Tg C yr^{-1}, sum of above- and belowground storage
Alleycropping	80×10^6 ha	73.8
Silvopasture	70×10^6 ha	9.0
Windbreaks	85×10^6 ha[@]	4.0
Riparian Buffer	0.8×10^6 km of 30-m-wide forested riparian buffers	1.5
Short rotation woody crops (SRWC), forest farming, etc.	2.4×10^6 km conservation buffer including SRWC	2.0
Total		90.3

[1] Area that is currently under or could potentially be brought under the practice

[@] Area of exposed cropland, 5% of which to be planted to windbreaks

[#] The time frame during which these estimates will be appropriate depends on how fast these potentially feasible practices are implemented. Assuming their implementation by 2010, the estimated C sequestration benefits could be appropriate for 2025; potential benefits thereafter will depend on expansion or shrinkage of areas under the different practices.

Source: Nair and Nair (2003).

Exploiting C sequestration potential of agroforesty for the benefit of landowners: Payment for environmental services

The Kyoto Protocol triggered a strong increase in investment in plantations as carbon sinks, although the legal and policy instruments and guidelines for management are still debated (FAO 2000). A number of countries have already prepared themselves for the additional funding for the establishment of human-made forests. In an initiative claimed to be the first of its kind, in 1997 Costa Rica established tradable securities of carbon sinks that could be used to offset emissions and to utilize independent certification insurance. According to a FAO report, in 2000 greenhouse gas mitigation funding covered about 4 million hectares of forest plantations worldwide (FAO 2000). The recognition of afforestation and reforestation as the only eligible land use under the CDM of the Kyoto Protocol is expected to lead to a steep increase in forest plantation establishment in developing countries.

Can environmental services pay for agroforestry promotion? We present some examples from both the tropical region and North America to illustrate the current trend in this direction.

Tropical region

In Costa Rica, in 1997, $14 million was invested for the Payment for Environmental Services (PES), which resulted in the reforestation of 6 500 ha, the sustainable management of 10 000 ha of natural forests, and the preservation of 79 000 ha of private natural forests (R. Nasi, S. Wunder, and J. J. Campos A.: pers. comm, March 2002). Eighty percent of this funding originated nationally from a tax on fossil fuels; the other 20% came from the international sale of carbon from public protected areas and contributed with $2 million. Recently, the World Bank provided a $32.6 million loan to Costa Rica to fund the PES trough a Project called ‘Ecomarkets’. It came along with a grant from the Global Environment Facility (GEF) of approximately $8 million. These schemes only considered reforestation or forest conservation. Starting in 2003, PES in Costa Rica also includes agroforestry systems, with payments calculated based on the number of individual trees present in the farm.

Can this example from Costa Rica be extended to other tropical regions? Some examples exist, involving private enterprises and development agencies. In Guatemala, cacao and other shaded crops have been proposed for financing to the farmers through payment of environmental services such as carbon sequestration (Parrish et al. 2003). For example, TechnoServe, a non-profit organization, is undertaking a project supported by the Ford Foundation and the U.S. Agency for International Development, USAID, which investigates the use of carbon trading to promote sustainable coffee cultivation by smallholder producers in Central America. Based on data compiled from a Guatemalan coffee cooperative, they are determining the range of prices for sequestered carbon to be used in the delineation of the carbon trading and financing instrument; they are possibly extending the scheme to other agricultural commodities such as cocoa (Newmark TE 2003, *Carbon sequestration and cocoa production: financing sustainable development by trading carbon emission credits.* http://natzoo.si.edu/smbc/Research/Cacao/newmark.htm.).

Also in Guatemala, a private company, AES Thames, has already invested more than $2 million to establish agroforestry and woodlot systems to help offset CO_2 emissions from its coal-fired power plant (Dixon 1995). Through a grant to CARE, an NGO (non-governmental organization), AES is assisting 40 000 farmers to plant trees during a ten-year period. By managing the agroforestry systems for farm and community use, the project is expected to reduce deforestation in eastern Guatemala.

In Paraguay, another subsidiary of the AES corporation has committed more than $2 million to the Nature Conservancy, an NGO, for land purchase and agroforestry to help offset CO_2 emissions from a coal-fired cogeneration facility. The long-term project goals are to promote sustainable agroforestry systems, preserving existing tropical forest (biosphere reserves) and creating a sustainable watershed management system in the Paraguayan-Brazilian border (Dixon 1995). In Chiapas, southern Mexico, the Scolel Té community forestry project, with funding from the British Department for International Development (DFID) is developing model planning and administrative systems by which the farmers can gain access to carbon markets (FAO 2001; Tipper 2002). Smallholder farmers and local communities identify reforestation, agroforestry and forest restoration activities that are both financially beneficial and intended to sequester or conserve carbon. Offsets are sold through a trust fund managed by a local NGO. Carbon has been sold to various purchasers, including the International Automobile Federation. Approximately 300 farmers, having an average holding size of one hectare each, are involved. The average C sequestration potential is 26 Mg ha^{-1} at a cost of $12 per Mg. The baseline used is the mean carbon storage potential of the previous land use, assuming that the land use would have continued in the absence of project intervention. Cacho et al. (2003) have documented the details of five C sequestration projects that are currently being implemented involving smallholders in Latin America and Indonesia (Cacho OJ, Marshall GR, and Milne M, 2003, Smallholder agroforestry projects: Potential for carbon sequestration and poverty alleviation, ESA Working Paper 03-06; www.fao.org/es/esa)

A number of development agencies in Kenya are currently considering the potential of establishing a carbon credit payments scheme for small landholders in the buffer zone surrounding Mt. Kenya National Park, an International Biosphere Reserve and a World Heritage Site (KWS, 2002, *Background of Mt. Kenya National Park.* HTML: http://www.kws.org/mtkenya.htm#Background Kenya Wildlife Service. Nairobi, Kenya.). The park is located in south-central Kenya and surrounded by Nyeri, Embu, Kirinyaga and Meru Districts. These districts serve as important agricultural production centers of food and cash crops in Kenya. Based on a landscape-level study at the Manupali watershed in the Philippines, Shivley et al. in press calculated that carbon storage via land use modification costs $3.30 per ton on fallowed land and $62.50 per ton on land that otherwise supports high-value cropping. Carbon storage through agroforestry was found to be less costly than via a pure tree-based system, which is a strong argument in favor of agroforestry rather than forestry *per se* in reforestation projects. These are some examples of how systems for payment of environmental services to farmers can be carried out as mitigation projects by private companies, in alliance with NGOs or development agencies. These projects do not consist of just agroforestry but they are integrated with other forestry and conservation projects.

Agroforestry and other planted and/or managed systems may have advantages over natural forest management in terms of C sequestration in situations where land and tree tenure are contentious issues related to the question of compensating for the opportunity cost for forest conservation. For example, Tomich et al. (2002) reported that in Indonesia, C offsets through ‘agroforestation’ seemed more feasible than forest conservation because property rights over timber from planted trees would be easier to establish and enforce than property rights over timber from natural forests.

North America

An interesting recent development in North America and other industrialized temperate regions of the world is the increasing recognition of the value of environmental services provided by sustainable land management systems such as agroforestry. Silvopasture, for example, is becoming an increasingly popular agroforestry practice in southern United States (Clason and Sharrow 2000; Workman et al. 2003). Environmental benefits provided by this practice include water quality improvement, soil conservation, carbon sequestration, wildlife habitat protection, and aesthetics (Alavalapati and Nair 2001; Workman et al. 2003). Environmental economists argue that internalizing the environmental benefits through compensation schemes could potentially influence ranchers' and other landowners' decision to adopt silvopasture. Valuation of environmental improvement associated with forestry and agricultural practices has been studied extensively (Cooper and Kleim 1996; Bateman and Willis1999). Shrestha and Alavalapati (in press) studied the public willingness to pay (WTP) for improvements in water quality, carbon sequestration, and wildlife habitat through silvopasture in the Lake Okeechobee watershed, Florida, using the random parameter logit model. The study showed that the WTP for a moderate level of improvement in these environmental attributes amounted to \$137.97 per household per year, out of which carbon sequestration alone accounted for 42.07% (\$58.05). With 1.34 million households in the watershed, the total WTP for environmental improvement would be \$924.4 million. With the cost of silvopastural practice as perceived by ranchers at \$23.02 per ha per year, the annual opportunity cost of silvopasture adoption on 1.06 million hectares of ranchland in the watershed would be \$24.41 million. Using the total WTP as a trust fund, its annual returns could be used to compensate ranchers for the environmental services provided by silvopasture. This is just an example of the scope and nature of public policy that will need to be developed for supporting agroforestry adoption for environmental services including carbon sequestration.

Another interesting development worth mentioning in this context is the development of the so-called Carbon Markets. Such markets can only develop under a 'cap and trade' system, in which the total amount of carbon emissions is limited by a mandatory cap, and carbon-emitting industries are allowed to meet their targets with some combination of carbon emission reduction technologies and the purchase of carbon offsets on open financial exchanges (V. A. Sample, JG Gray Distinguished Lecture, Univ. of Florida, 23 April 2003). The concept is based on the highly successful sulfur dioxide (SO_2) cap-and-trade mechanism aimed at combating acid rain, established in the United States by the 1990 Clean Air Act amendments. Under these amendments, the US Environmental Protection Agency (EPA) issued permits to utilities for a certain level of SO_2, and the right to trade these permits with other utilities. Ten years later, the market in SO_2 permits had grown to \$3 billion, overall SO_2emissions by the utility industry as a whole were significantly *lower* than EPA targets, and the reduction had been accomplished at about one tenth of the predicted cost.

The 2001 withdrawal of the United States from participation in the Kyoto Protocol has significantly slowed progress toward developing a corresponding cap-and-trade system for carbon dioxide (CO_2) emissions in the United States and internationally. With the United States being the source of about one-quarter of the world's carbon emissions, no such system is likely to be effective in reducing global atmospheric carbon without U.S. participation. This has not stopped individual states within the United States from acting, however. More than half the states have adopted voluntary or mandatory programs for reducing carbon emissions. Other countries see opportunity in the U.S. retreat from the Kyoto Protocol, particularly those in Europe that are well along in developing their own emissions trading systems. The director of CO2e.com, a London brokerage firm, observed 'Now that the Americans are out, Europe can dominate the emissions trading market. It entitles the Europeans to write the rules for global trading.' (O. Pohl, *New York Times*, 10 April 2003).

On 16 January 2003, the Chicago Climate Exchange (CCX) opened for business, and it is poised to become the first financial market in the United States to begin trading carbon credits like any other commodity (P. Behr and E. Pianin: Firms Start Trading Program for Greenhouse Gas Emissions. *Washington Post*, 17 January 2003, p.A14. Additional information available at: *www.chicagoclimatex.com*). The goal of the CCX is to implement a voluntary, private cap-and-trade pilot program for reducing and trading greenhouse gas emissions.

What might all these mean for private forest landowners in the industrialized nations? Many questions still remain to be answered and details to be addressed. Clearly, however, major U.S. and international forest products companies have determined that generating and selling carbon credits has a potential to significantly add to the income stream from their forestry operations, and improve their financial bottom line.

Conclusions

The value of forests and trees in sequestering carbon and reducing carbon dioxide emission to the atmosphere is being recognized increasingly the world over. Forest plantations and agroforestry systems are thus recognized to have the potential to regain some of the carbon lost to the atmosphere in the clearing of primary or secondary forests. Although neither regrowth nor plantations can come close to replacing the full amount of carbon that was present in the primary forest, plantations and agroforestry systems have the added benefit of providing valuable products and food to local people. The rotation ages for plantations and trees in agroforestry systems play a large role in the amount of carbon they can sequester. In mixed plantations or agroforestry systems, since rotation lengths vary within the system according to the species, a complete clearing of the plot (which would increase the release of soil carbon) is less likely. Consideration of how the biomass from managed plots is used should also play a role in the carbon equation. If used for wood, about 25% of the carbon from that rotation can be considered sequestered for an additional span of five or more years. If used for fuelwood, most of the carbon can be considered returned to the atmosphere within the year.

As the concept of 'carbon credits' being paid by fossil fuel emitters to projects that sequester or reduce carbon output becomes more common, many nations and organizations will seek to find inventive ways to sequester carbon. The clearing of primary forest releases more carbon than natural regrowth or fast-growing plantations could recover in 25 years or more. Therefore, protection of primary forest should be top priority when looking at ways to reduce carbon emission from the tropics. The most important role that agroforestry and plantations may play is to offset destruction of primary forest by providing the necessary wood products from land that has already been cleared. If this can be done in a manner that provides competitive biomass accumulation rates to that of natural regrowth and is sustainable in terms of soil fertility, then plantations and agroforestry systems could play a substantial role in CO_2 mitigation in the tropics. The recent trends in economic valuation of the ecosystem services of forests and trees, and the development of private capital markets to actually monetize the value of those services to the benefit of forest landowners, point to exciting opportunities and new developments in this area.

In the face of carbon markets, C storage becomes an additional output that landowners might consider in their management decisions. This would change the dynamics of their agroforestry systems in terms of the rotation age of trees, crop-tree mixture, and silviculture and other management practices. With the introduction of carbon payments, agroforestry systems that are otherwise less profitable may become more attractive or vice-a-versa. This suggests that research addressing both biophysical and socioeconomic issues of carbon sequestration is needed.

References

Alavalapati J.R.R., Shrestha R.K., Stainback G.A. and Matta J.R. 2004. Agroforestry development: An environmental economic perspective. (This volume).

Alavalapatti J.R.R. and Nair P.K.R 2001. Socioeconomic and institutional perspectives of agroforestry: an overview. pp. 52–62. In: World Forests, Markets and Policies, Vol. 2 in the series World Forests, Kluwer, Dordrecht, The Netherlands.

Bass S., Dubois O., Mouracosta P., Pinard M., Tipper R. and Wilson C. 2000. Rural Livelihood and Carbon Management. IIED Natural Resources Paper No. 1. International Institute for Economic Development. London, UK.

Bateman I.J. and Willis K.G. (eds) 1999. Valuing Environmental Preferences: Theory and Practice of Contingent Valuation Method in the US, EU, and Developing Countries. Oxford University Press, New York.

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

Brooks D.J. 1993. U.S. forests in a global context. USDA For. Serv. Gen. Tech. Rep. RM-228. US For. Serv. Rocky Mountain For. and Range Exp. Stn, Ft. Collins, CO.

Cairns M.A. and Meganck R.A. 1994. Carbon sequestration, biological diversity, and sustainable development: integrated forest management. Environ Manag 18: 13–22.

Clason T.R. and Sharrow S.H. 2000. Silvopastoral practices. pp. 119–147. In: Garrett H.E., Rietveld W.J. and Fisher R.F. (eds) North American Agroforestry: An Integrated Science and Practice. Am. Soc. Agronomy, Madison, WI.

Cooper J.C. and Kleim R.W. 1996. Incentive payments to encourage farmer adoption of water quality protection practices. Am J Agr Econ 78: 54–64.

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

Dixon R.K., Winjum J.K., Andrasko K.J., Lee J.J. and Schroeder P.E. 1994. Integrated systems: assessment of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration. Climatic Change 30: 1–23.

Duguma B., Gockowski J. and Bakala J. 2001. Smallholder cacao *(Theobroma cacao* Linn.) cultivation in agroforestry systems of West and Central Africa: challenges and opportunities. Agroforest Syst 51: 177–188.

Evans J. 1999. Planted forests of the wet and dry tropics: their variety, nature, and significance. New Forestry 17: 25–36.

FAO 2000. Global Forest Resources Assessment 2000. Main Report. FAO, Rome, Italy 512 pp.

FAO 2001. State of the world's forests 2001. Food and Agriculture Organization of the United Nations. Rome, Italy, 181 pp.

FAO 2003. State of the World's Forests 2003. Food and Agriculture Organization of the United Nations. Rome, Italy, 126 pp.

Follett R.F., Kimble J.M. and Lal R. (eds) 2001. The Potential of U. S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publ., Boca Raton, FL.

Garrett H.E. and McGraw R.L. 2000. Alley cropping practices. pp. 149–188. In: H.E. Garrett, W.J. Rietveld and R.F. Fisher (eds) North American Agroforestry: An Integrated Science and Practice, Am. Soc. Agronomy, Madison, WI.

Harmon ME (2001) Carbon sequestration in forests: addressing the scale question. J Forest 99 (4): 24–29.

Houghton R.A., Davidson E.A. and Woodwell G.M. 1998. Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance. Global Biogeochem Cy 12: 25–34.

ICRAF 1995. International Centre for Research in Agroforestry. Annual Report, 1995. ICRAF, Nairobi, 288 pp.

IPCC 2000. Special Report on Land Use, Land Use Change and Forestry. Summary for Policy Makers. Geneva, Switzerland. 20 pp.

Johnsen K.H., Wear D., Oren R.., Teskey R.O., Sanchez F., Will R., Butnor J., Markewitz D., Richter D., Rials T., Allen H.L., Seiler J., Ellsworth D., Maier C., Katul G. and Dougherty P.M. 2001. Meeting global policy commitments: Carbon sequestration and southern pine forests. J Forest 99 (4): 14–21.

Koskela J., Nygren P., Berninger F. and Luukkanen O. 2000. Implications of the Kyoto Protocol for tropical forest management and land use: prospects and pitfalls. Tropical Forestry Reports 22. University of Helsinki, Department of Forest Ecology. Helsinki. 103 pp.

Kursten E. 2000. Fuelwood production in agroforestry systems for sustainable land use and CO_2 mitigation. Ecol Eng 16: S69–S72.

Lal R., Kimble J.M., Follett R.F. and Cole C.V. (eds) 1999. The Potential of U. S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publ, Boca Raton, FL.

Lott J.E., Howard S.B., Ong C.K. and Black C.R. 2000a. Long-term productivity of a *Grevillea robusta*-based overstorey agroforestry system in semi-arid Kenya. I. Tree growth. Forest Ecol Manag 139: 175–186.

Lott J.E., Howard S.B., Ong C.K. and Black C.R. 2000b. Long-term productivity of a *Grevillea robusta*-based overstorey agroforestry system in semi-arid Kenya. II. Crop growth and system performance. Forest Ecol Manag 139: 187–201.

Loveland T.R. and Belward A.S. 1997. The IGBP-DIS global 1 km land cover data set, DISCover ® first results. Int J Remote Sens 18: 3289–3295.

Montagnini F. 2001. Strategies for the recovery of degraded ecosystems: experiences from Latin America. Interciencia 26(10): 498–503.

Montagnini F., González E., Rheingans R. and Porras C 1995. Mixed and pure forest plantations in the humid neotropics: a comparison of early growth, pest damage and establishment costs. Commonw Forest Rev 74: 306–314.

Montagnini F. and Mendelsohn R. 1996. Managing forest fallows: improving the economics of swidden agriculture. Ambio 26: 118–123.

Montagnini F. and Porras C. 1998. Evaluating the role of plantations as carbon sinks: an example of an integrative approach from the humid tropics. Environ Manag 22: 459–470.

Myers N. 1996. The world's forests: problems and potential. Environ Conserv 23(2): 156–168.

Nair P.K.R. 2001. Agroforestry. pp. 375–393. In: Our Fragile World: Challenges and Opportunities for Sustainable Development, Forerunner to The Encyclopedia of Life Support Systems. UNESCO, Paris, France & EOLSS, UK.

Nair P.K.R., Buresh R.J., Mugendi D.N. and Latt C.R. 1999. Nutrient cycling in tropical agroforestry systems: Myths and science. p. 1–31. In: Buck L.E., Lassoie J.P. and Fernandes, E.C.M. (eds), Agroforestry in Sustainable Agricultural Systems. CRC Press, Boca Raton, FL, USA.

Nair P.K.R. and Nair V.D. 2003. Carbon Storage in North American Agroforestry Systems. pp. 333–346. In: J. Kimble, L.S. Heath, R.A. Birdsey and R. Lal (eds) The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect. CRC Press, Boca Raton, FL, USA.

Noweg T.A. and Kurtz W.B. 1987. Eastern black walnut plantations: an economically viable option for conservation of reserve lands within the corn belt. North J Appl Forest 4: 158–160.

Oren R., Ellsworth D.S., Johnsen K.H., Phillips N., Ewers B., Maler C., Schaefer K.V.R., McCarthy H., Hendrey H., McNutty S.G. and Katul G.G. 2001. Soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere. Nature 411: 469–471.

Palm C.A. and 17 others 2000. Carbon sequestration and trace gas emissions in slash-and-burn and alternative land-uses in the humid tropics. Final Report, Alternatives to Slash and Burn (ASB) Climate Change Working Group, Phase II. ICRAF, Nairobi, Kenya.

Parrish J., Reitsma R. and Greensberg R. 2003. Cacao as crop and conservation tool. http://nationalzoo.si.edu/conservationandscience/migratorybirds/research/cacao/parrish.cfm.

Piotto D., Montagnini F., Ugalde L., and Kanninen M. 2003. Performance of forest plantations in small and medium sized farms in the Atlantic lowlands of Costa Rica. Forest Ecol Manag 175: 195–204.

Ruark G.A., Schoeneberger M.M. and Nair P.K.R. 2003. Agroforestry–Helping to Achieve Sustainable Forest Management. UNFF (United Nations Forum for Forests) Intersessional Experts Meeting on the Role of Planted Forests in Sustainable Forest Management, 24–30 March 2003, New Zealand. www.maf.govt.nz/unff-planted-forestry-meeting

Schlesinger W.H. and Lichter J. 2001. Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO_2. Nature 411: 466–468.

Schroeder P. 1992. Carbon storage potential of short rotation tropical tree plantations. Forest Ecol Manag 50: 31–41.

Schroeder P. 1994 Carbon storage benefits of agroforestry systems. Agroforest Syst 27: 89–97.

Schroth G., D'Angelo S.A., Teixeira W.G., Haag D. and Lieberei R. 2002. Conversion of secondary forest into agroforestry and monoculture plantations in Amazonia: consequences for biomass, litter and soil carbon stocks after 7 years. Forest Ecol Manag 163: 131–150.

Schulze E.D., Wirth C. and Heimann M. 2000. Managing forests after Kyoto. Science 289: 2058–2059.

Sharrow S.H. and Ismail S. 2004. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agroforest Syst 60: 123–130.

Shepherd D. and Montagnini F. 2001. Carbon Sequestration Potential in mixed and pure tree plantations in the humid tropics. J Trop For Sci 13: 450–459.

Shivley G.E., Zelek C.A., Midmore D.J. and Nissen T.M. Carbon sequestration in a tropical landscape: An economic model to measure its incremental cost. Agroforest Syst (in press).

Shrestha R.K. and Alavalapati J.R.R. Valuing environmental benefits of silvopasture practices: A case study of the Lake Okeechobe Watershed in Florida. Ecol Econ (in press).

Smith J. and Scherr S.J. 2002. Forest Carbon and Local Livelihoods: Assessment of Opportunities and Policy Recommendations. CIFOR Occasional Paper 37, Centre for International Forestry Research, Jakarta, Indonesia.

Thevathasan N.V. and Gordon A.M. Enhancing greenhouse gas (GHG) sinks in agroecosystems through agroforestry based land-use practices in Canada. Forest Chron (in press).

Tipper R. 2002. Helping indigenous farmers to participate in the international market for carbon services: the case of Scolel Té pp. 222–233. In: Pagliola S., Bishop J. and Landell-Mills N. (eds), Selling Forest Environmental Services. Market-based Mechanisms for Conservation and Development. Earthscan, London.

Tomich T.P., de Foresta H., Dennis R., Ketterings Q., Murdiyarso D., Palm C., Stolle F., and van Noordwijk M. 2002. Carbon offsets for conservation and development in Indonesia? Am Alt Agr 17: 125–137.

USDA 1996. Grazing lands and people: A national program statement and guidelines for the cooperative extension service. USDA Ext. Serv., Dec. 1996. USDA, Washington, DC.

USDA–SCS 1989. Soil, Water, and Related resources on Nonfederal Land in the United States: Analysis of Conditions and Trends. Misc. Publ. 1482, Second RCA Appraisal, USDA Soil Cons. Serv., Washington DC.

US Dept of Energy 1999. Carbon Sequestration: State of Science. Draft Report. Ch. 4: Carbon Sequestration in Terrestrial Ecosystems. USDE, Washington, DC.

van Noordwijk M., Rahayu S., Hairiah K., Wulan Y.C., Farida A. and Verbist B. 2002. Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampug, Indonesia): from allometric equations to land use change analysis. Science in China Series C-Life Sciences 45: 75–86 Suppl. S OCT 2002. Science in China Press, Beijing.

Watson R.T., Noble I.R., Bolin B., Ravindranath N.H., Verardo D.J. and Dokken D.J. (eds) 2000. Land Use, Land-Use Change, and Forestry. Intergovernmental Panel on Climate Change (IPCC), Special report. Cambridge Univ. Press. New York.

Workman S.W., Bannister M.E. and Nair P.K.R. 2003. Agroforestry potential in the southeastern United States: Perceptions of landowners and extension professionals. Agroforest Syst 59: 73–83.

Young A. 1997. Agroforestry for Soil Management. 2nd Ed. C.A.B. International. Wallingford, UK, 320 pp.