Chapter 10
Carbon Sequestration in Agroforestry Systems

Abstract Agroforestry systems have great potential as carbon (C) sinks, through C sequestration both above- and belowground. The C-sequestration potentials of tropical agroforestry systems are highly variable. The variation may be caused by (i) the estimates of C-sequestration potential of agroforestry systems that are not rigorous, (ii) lack of widely and easily adoptable methodologies for estimating the soil C potential under different conditions, and (iii) the natural variability of soil C stock in agroforestry systems in different agroecological zones. Reported data on soil C sequestration are also highly variable, partly because the term "carbon sequestration potential" can have different meanings depending on the context. Various agroforestry practices and technologies such as alley cropping/intercroping, silvopasture, riparian buffers, parklands, forest framing, homegardens, woodlots, windbreaks, and other similar land-use systems can be valued as carbon sinks in both tropical and temperate regions. The C sequestration potential of agroforestry systems justifies the plea made for its inclusion in the United Nations-based REDD (Reducing Emissions from Deforestation and Forest Degradation) programme for tropical developing regions, aimed at reducing emissions of greenhouse gases. An accurate estimation of C changes is necessary to improve the implementation of REDD + (i. e., conservation and sustainable management of forests, and enhancement of C stocks, on top of REDD) mechanisms, which use financial incentives to promote and popularize the use of any method that would reduce emissions of greenhouse gases.

10.1 Introduction

The potential of agroforestry systems to act as carbon (C) sinks is becoming more and more emphasized, especially with the advent of REDD (Reducing Emissions from Deforestation and Forest Degradation), which is a United Nations-based collaborative initiative to reduce greenhouse gas emission through reduced deforestation and forest degradation in the tropical regions. For more details on REDD and agroforestry, please see chapter 20. Atmospheric C sequestration involves C uptake through photosynthesis and storage in long-living pools such as timber and the soil. Agroforestry systems store C in plant biomass and in the soils. Carbon sequestration has long been an underexploited benefit of agroforestry (Montagnini and

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Nair 2004), and this environmental service is becoming increasingly recognized and valued (Schroeder 1994; Albrecht and Kandji 2003; Nair et al. 2009a; Kumar and Nair 2011).

However, some agroforestry systems may act as C sources, because of the complexity of C trade-offs between agroforestry components, and because of the interactions between major greenhouse gases (GHG), e. g., methane, carbon dioxide nitrogen dioxide, in agroforestry systems. Agroforestry systems also release carbon dioxide and nitrogen into the atmosphere, making it possible to have a negative C-balance (i. e., the difference between C sequestered and C released to the atmosphere). Indeed, agrisilvicultural systems are usually C sinks, while ruminant-based silvopastoral systems are largely sources of greenhouse gases (Dixon 1995). The difference in the C sink–source relationship between agroforestry systems reflects the difference in the practices that are carried out between systems, and in the species composition of these systems. The difference in the C sink-source relationship is also a reflection of complexity of agroforestry systems (e.g., soil properties, system components, climate, land cultivation history, farming practices, and socioeconomic context). This chapter will discuss the potential of agroforestry systems to sequester atmospheric C, including brief discussion on methods for estimating C stocks in agroforestry systems and specific agroforestry practices that could help establish agroforestry systems to be C sources, and end with a brief introduction of REDD in agroforestry, which is discussed in more detail in Chapter 20.

10.2 The Potential for C Sequestration in Agroforestry Systems

Agroforestry systems have the potential to sequester C while maintaining crop production (Schoeneberger 2009; Kumar and Nair 2011), and constitute a promising option for environmental management. Potential secondary environmental benefits include food security and secure land tenure in developing countries, increasing farm income, restoring and maintaining aboveground and belowground biodiversity, creating corridors between protected forests, maintaining watershed hydrology, and soil conservation (Pandey 2002). Agroforestry systems can sequester C in standing biomass, in wood products and in the soil, mostly through increased soil organic matter content.

The C that is captured by plants through photosynthesis is stored in long-living C pools including the aboveground plant standing biomass such as timber, and belowground plant biomass such as roots. Carbon pools in agricultural systems also include fruits, soil microorganisms, and any form of organic and inorganic C in soils. Because plants store C in their biomass, it is obvious that the greater the plant size, the greater the amount of C sequestered. For that reason, the introduction of trees in agricultural landscapes will likely increase the C sequestration potential in agricultural systems. Consequently, efforts are increasingly made to bring to light the C sequestration potential of agroforestry systems, as they are tree-based agricultural systems.

Agroforestry systems can sequester large quantities of C in the soil, plant biomass, and wood products (Albrecht and Kandji 2003). Various estimations of C sequestration potential in the tropics have given different figures. In humid areas, agroforestry systems can sequester up to 50 Mg C ha^{-1}, and smallholder agroforestry in the tropics can sequester between 1.5 and 3.5 Mg C ha^{-1} $year^{-1}$ (Montagnini and Nair 2004). Albrecht and Kandji (2003) reported that tropical agroforestry systems have C sequestration potential ranging between 12 and 228 Mg C ha^{-1} with a median value of 95 Mg C ha^{-1}. According to Mutuo et al. (2005), the potential of agroforestry systems in the humid tropics to sequester C in plant biomass may be over 70 Mg C ha^{-1}, plus up to 25 Mg C ha^{-1} can be sequestered in the top 20 cm of the soil. In a review by Oelbermann et al. (2004), it was indicated that the potential for aboveground components in agroforestry systems in Costa Rica to sequester C is estimated to be 2.1×10^9 Mg C $year^{-1}$. The study revealed that a 10-year-old *Erythrina poeppigiana* system can sequester C at a rate of 0.4 Mg C ha^{-1} $year^{-1}$ in coarse roots, and 0.3 Mg C ha^{-1} $year^{-1}$ in tree trunks (Oelbermann et al. 2004).

C sequestration rates are highly variable between agroforestry systems in the tropics. Indeed, the rate of C sequestration ranged between 0.22 Mg C ha^{-1} $year^{-1}$ in *Faidherbia albida*-based plantations in Senegal and 5.8 Mg C ha^{-1} $year^{-1}$ in rotational woodlots in Tanzania (Luedeling et al. 2011). Estimation of C stocks in agroforestry systems varies with the area under consideration. Total C stocks in coffee agroforestry systems amounted to 127 ± 6.6 (SE) and to 93 ± 7.75 (SE) Mg C ha^{-1} in the western highlands of Guatemala (Schmitt-Harsh et al. 2012) and in the central valley of Costa Rica (Häger 2012), respectively. Annual organic C input to the soil from branches and leaves was estimated to be 1.4 Mg C ha^{-1}, and approximately 3.0 Mg C ha^{-1} from crop residues (Oelbermann et al. 2004). Takimoto et al. (2008) estimated that biomass C stock in agroforestry systems in the West African Sahel ranged from 0.7 to 54 Mg C ha^{-1} using allometric equations. The same study revealed that soil C stock determined in three layers (0–10, 10–40 and 40–100 cm) ranged from 28.7 to 87.3 Mg C ha^{-1}, indicating that more C is stored in the soil than in aboveground plant biomass. Shaded-perennial-crop-based agroforestry systems have great potential for soil C sequestration. In the weathered Oxisols of Bahia, Brazil, soil C stock in shaded cocoa (*Theobroma cacao* L.) -based agroforestry systems was estimated as 302 Mg ha^{-1} to 1 m depth in 2009 (Gama-Rodrigues et al. 2010).

Agroforestry practices affect the amount of potential C captured in a system. Traditional parkland agroforestry systems have larger C stock than the improved systems (Takimoto et al. 2008). In sub-Saharan Africa, Vagen et al. (2005) reported that an improved fallow system can increase attainable soil C sequestration rates from 0.1 to 5.3 Mg ha^{-1} $year^{-1}$. Also, organic coffee agroforestry systems (i. e., on which farmers applied between 0 and 10,500 kg of organic fertilizers ha^{-1} annually) stored more C (109.1 ± 29 (SD) Mg ha^{-1}) than conventional (i. e., on which farmers applied between 600 and 3,300 kg of synthetic nitrogen-phosphorus-potassium fertilizers ha^{-1} $year^{-1}$) coffee agroforestry systems (76.1 ± 18 Mg ha^{-1}) between November 2008 and April 2011 on Alfisols in Costa Rica (Häger 2012).

Large quantities of C can also be stored belowground. In India, Lal (2004) estimated the organic C pool sequestered in the soil at 21 billion tons in the first 30 cm,

Table 10.1 Summary of soil carbon stock under tropical agroforestry systems (Adapted from Nair et al. 2009 and Raji and Ogunwole 2006)

Agroecological zones	Major Agroforestry systems	Reported values of C stock (Mg ha^{-1})[a]
Humid lowlands	Shaded perennial systems	21–35
	Alley cropping	10–25
	Improved fallows	135–149
	Homegardens	108–119
	Tree intercropping	27–78
	Silvopasture	96–173
	Woodlots	61–75
Tropical highlands	Shaded perennial systems	21–97
	Silvopastoral systems	132–173
Arid and semiarid lowlands	Silvopastoral systems	
	Fodder banks	33
	Live fences	5.20–24
	Grazing systems	12.64–33
	Tree intercropping systems	
	Crop dominated	20–70
	Fodder dominated	25–80
	Fuelwood dominated	30–90
	Shelterbelts	39.09

[a] The soil depths and the methods used for different studies were highly variable. The listed range of values for each system is compiled from multiple literature sources. Specific literature references are therefore not given for each; literature citations can be found in Nair et al. (2009b) and Raji and Ogunwole (2006)

and 63 billion tons in the first one and a half meters. In the same study, organic C was estimated to be 196 billion tons in the first m of the soil. India's total potential of soil C sequestration was estimated to be between 39 and 49 Tg (1 Tg ~ 10^6 Mg) C $year^{-1}$ (Lal 2004).

Differences in C sequestration estimates may also exist because the estimates are not rigorous or standardized, as "the extent of C sequestered in any agroforestry system will depend on a number of site-specific biological, climatic, soil, and management factors" (Nair et al. 2009a). Generalizations based on such data are unrealistic and widely and easily adoptable methodologies are not available for estimating soil carbon sequestration potential under different conditions (Nair et al. 2009b). Amounts of soil carbon C stock will also vary by agroforestry system and agroecological zone (Tables 10.1 and 10.2). An emphasis should be placed on the development of widely acceptable and rigorous standard methods for estimating carbon sequestration in agroforestry systems (Nair 2012). Several difficulties hampered the accuracy of past estimates. The estimation of tree biomass used to quantify C sequestration is based on species-specific allometric equations (Tamang et al. 2012), which, when available, were developed for trees in natural forests, and may be location-specific. In addition, the size of the tree canopy in agroforestry systems can be different from that of the same tree species in a natural forest, creating a bias in C sequestration estimates.

Table 10.2 Indicative values of soil carbon stock and sequestration potential under major agroforestry systems in the tropics[a] (Nair et al. 2009b)

Major ecological regions and agroforestry systems	System characteristics *E*: existing; *N*: new plantings; *TD*: tree density (trees ha^{-1}); age: years (yr)	Soil carbon (Mg C ha^{-1})[b]		Time frame for realizing the potential (yr)[c]
		Stock to 50 cm depth	Potential for sequestering additional C to 100 cm soil depth	
Humid lowlands				
Shaded perennial systems	E > 15 yr	100–200	20–30	10
	N/young < 5-yr-old	70–150	100–200	
Alley cropping	E > 5 yr	20–45	25–75	> 5
	N or young < 5 yr	20–70	30–120	> 10
Improved fallows		60–100	80–150	
Homegardens	Low TD < 750 trees ha^{-1}	60–90	70–150	> 20
	Medium TD > 750 trees ha^{-1}	70–120	100–180	> 20
Silvopasture (grazing systems)	E, TD low < 50 ha^{-1}	20–80	50–100	> 20
Silvopasture (fodder bank)	E > 10-yr-old	60–95	30–60	
	N or young < 10 yr	75–95	50–100	
Woodlots	E > 10 yr	80–100	40–60	> 20
	N young or < 8 yr	50–80	50–150	
Tropical highlands				
Shaded perennial systems	E > 15-yr-old	100–200	20–50	10
Alley cropping	E > 5 yr	30–60	40–70	
	N or young < 5 yr	20–70	40–120	> 10
Homegardens	Low TD < 250 trees ha^{-1}	50–80	70–150	> 20
	Medium TD > 250 trees ha^{-1}	70–150	100–200	
Silvopasture (grazing systems)	E, TD low, > 20 trees ha^{-1}	70–120	80–150	> 20
	E, TD high	80–150	90–160	
Silvopasture (fodder bank)	E > 10 yr	60–100	30–70	> 20
	N young or < 8 yr	75–110	60–150	
Woodlots	E > 10 y-r-old	80–100	40–70	> 20
	N young or < 5 yr	50–80	60–170	
Arid and semiarid lands (mostly lowlands)				
Intercropping systems	Parklands, W Afr Sahel E ~ 50 trees ha^{-1}	30–40	5–10	> 25
?	Parklands, enrichment planting	20–30	30–50	> 25
Silvopasture, semiarid regions	E ~ 50 trees ha^{-1}	30–40	5–10	> 15
Grazing systems	N: planting trees in existing grazing lands	20–30	30–50	> 10
Fodder bank	N		30–100	
Fuelwood	N			

[a] The values are "best guess" estimates based on literature data (from nearly 150 reviewed papers and reports) and the authors' experience. Detailed literature citations are included in Nair et al. (2009)

[b] The soil stock values are reported mostly from the upper soil layers, to less than 50 cm depth. Therefore the estimates are for 0–50 cm soil depth. These, as well as the values for sequestration, will vary enormously depending on a large number of site- and system-specific factors[b]

[c] The values proposed as potential for sequestering additional C (column 4) are for up to 1 m depth considering the substantial amounts of the roots and the SOC (Soil Organic Carbon) in deeper soil layers. It is assumed that the existing systems have only limited potential in SCS (Soil Carbon Sequestration) unless they are significantly modified by management interventions such as (new) tree planting and fertilization; but the potential could be substantial in new agroforestry initiatives. It is also recognized that fairly long periods of time (column 5) are required to realize the potential for additional C sequestration in soils

Methodological issues involved in the direct and indirect estimation of C sequestration include: the accuracy of direct estimation of C stock, remote sensing and modeling, the influence of stand age on C accumulation, the influence of tree species and management practices on soil C sequestration, and information on stocks of organic C in deep soil layers. Many studies on belowground C sequestration focused on soil surface layers, but C sequestration in deep soil layers may be more important than in surface layers. Nair et al. (2009c) reported that tree-based systems store more C than treeless systems in soil layers as deep as 1 m. Issues related to C sequestration estimates in agroforestry systems are further discussed in Nair et al. (2009b).

The composition of an agroforestry system also influences the net soil C gains or losses. When estimating C stocks in a nitrogen-fixing trees and crop intercropping system, particular attention should be given to the effects of nitrous oxide, carbon dioxide, and methane emissions on net C gain and on the mitigation of GHG. Indeed, Kim (2012) reported that previous estimates of C stocks in a gliricidia-maize intercropping system in Malawi were incorrect, as the authors overlooked soil C loss as carbon dioxide emissions and the beneficial impacts of the reduction of nitrous oxide emissions from this agroforestry system on GHG mitigation. The C loss as soil carbon dioxide emissions amounted to be 64 % of the sequestered soil C (76 ± 8.6 Mg C ha^{-1} in the 0–2 m soil layer) for 7 years in the gliricidia-maize intercropping system, and the annual net gain of soil C was estimated to be 3.5 Mg C ha^{-1} $year^{-1}$ (Kim 2012). Also, the gliricidia-maize intercropping system reduced nitrous oxide emissions, thereby mitigating GHG by an equivalent of 3.5–4.1 Mg CO_2 ha^{-1} $year^{-1}$ (Kim 2012).

Another reason for the differences in the soil C sequestration data is that the term *carbon sequestration potential* has different meanings depending on its usage. Ingram and Fernandes (2001) drew on existing agroecosystem research concepts to define three levels of production, namely "potential", "attainable" and "actual". The authors suggested that the term "$attainable_{max}$" be used as the preferred term for carbon sequestration in mineral soils.

Systems also have an indirect effect by helping decrease pressure on natural forests by reducing the amount of land cleared for agricultural purposes. Dixon (1995) reported that 1 ha of sustainable agroforestry could provide enough goods and services to potentially offset 5–20 ha of deforestation. Proper design and management of agroforestry systems can lead to C sequestration (Montagnini and Nair 2004), whether it is sequestered in the ground biomass of plants, the soil or in wood products.

10.3 Agroforestry and REDD

Technologies for soil conservation using agroforestry practices can increase the storage of C in the soil, while adoption of agroforestry systems may reduce pressure on forests, indirectly increasing C sequestration (Montagnini and Nair 2004).

Agroforestry practices also contribute to C sequestration in wood products, standing biomass, roots, and soil organic matter. This role of agroforestry in C sequestration justifies the calls made for its inclusion in programs to reduce emissions of greenhouse gases (Schoeneberger 2009). Deforestation and forest degradation account for a large part of the emissions of greenhouse gases.

The United Nations-based REDD Programme, supported by The World Bank, uses financial incentives to promote and popularize the use of any method that would reduce emissions of greenhouse gases. Any strategy for reducing deforestation or promoting afforestation is eligible to be included in this program. The REDD initiative is based on the concept that developed countries should pay developing countries not to cause deforestation, and these payments should be based on the amount of C emitted by developed countries, and on the amount of C sequestered in developing countries, most of which are located in the tropics. The REDD initiative could be an opportunity for poor farmers in the tropics who practice sustainable land-use systems such as agroforestry to benefit from carbon payments. However, the financial evaluation of environmental services needs to be refined in order to be accepted by the international community (Schoeneberger 2009). As pointed out by Melick (2008), several practical questions are associated with the implementation of REDD: (i) Can forest changes and degradation be measured and monitored? Rigorous and standardized methods to estimate carbon sequestration potential in some land use systems, such as agroforestry, are not yet available (Nair et al. 2009b, c; Nair 2012); (ii) Can REDD schemes be implemented in the social, economic, and political climates of forested developing countries, most of which have problems with poor governance, low transparency, and corruption?; (iii) Will benefits from carbon payments reach forest communities? This last problem could be overcome by dealing directly with communities owning forests. For example, a system of community forests is being implemented in the Congo basin. Village communities organize themselves as legal entities, and are allowed by forest authorities to manage the surrounding forests delineated on the basis of a sustainable management plan of forest resources.

Agroforestry and other tree-based systems (woodlots, afforestation) can contribute to REDD + under certain forest definitions and for achieving REDD + in landscapes (Minang et al. 2011). In the context of REDD + agroforestry has the potential for reducing degradation by supplying timber and fuelwood that would otherwise be sourced from adjacent or distant forests, thereby reducing deforestation and pressure on natural forests. As pointed out by Minang et al. (2011), enabling market infrastructure, policies on tree rights and ownership, and safeguards would be necessary for agroforestry and other tree-based systems in the landscape to effectively contribute to the goals of REDD + and Nationally Appropriate Mitigation Actions (NAMAs).

The development of a carbon market in the tropics would certainly have an effect on the adoption of land use systems promoting afforestation and reforestation. Antle et al. (2007) developed a model to simulate the impact of carbon contracts for the adoption of agroforestry in the tropical highlands of Peru. The analysis of this model indicated that participation in carbon contracts could increase the adoption of terraces and other agroforestry practices, and the rate of adoption depends on the accumulation of C and other key factors affecting land productivity, such as the slope of the land. However, an accurate estimation of C change is necessary for better implementation of REDD mechanisms. Also needed are internationally accepted REDD standards and national and international policies on climate change (Melick 2008). Agreements for C emissions and forest protection have begun in Indonesia, as part of the REDD process (Akiefwanati et al. 2010). For REDD implementation to be successful, more awareness of REDD mechanisms is needed on the part of policy-makers, with increased support from scientists, Non-Governmental Organizations, as well as stakeholders involved in the Clean Development Mechanism (CDM) implementation.

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