Review Article

Agroforestry as a strategy for carbon sequestration

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Abstract

During the past three decades, agroforestry has become recognized the world over as an integrated approach to sustainable land use because of its production and environmental benefits. Its recent recognition as a greenhouse gas–mitigation strategy under the Kyoto Protocol has earned it added attention as a strategy for biological carbon (C) sequestration. The perceived potential is based on the premise that the greater efficiency of integrated systems in resource (nutrients, light, and water) capture and utilization than single-species systems will result in greater net C sequestration. Available estimates of C-sequestration potential of agroforestry systems are derived by combining information on the aboveground, time-averaged C stocks and the soil C values; but they are generally not rigorous. Methodological difficulties in estimating C stock of biomass and the extent of soil C storage under varying conditions are compounded by the lack of reliable estimates of area under agroforestry. We estimate that the area currently under agroforestry worldwide is 1,023 million ha. Additionally, substantial extent of areas of unproductive crop, grass, and forest lands as well as degraded lands could be brought under agroforestry. The extent of C sequestered in any agroforestry system will depend on a number of site-specific biological, climatic, soil, and management factors. Furthermore, the profitability of C-sequestration projects will depend on the price of C in the international market, additional income from the sale of products such as timber, and the cost related to C monitoring. Our knowledge on these issues is unfortunately rudimentary. Until such difficulties are surmounted, the low-cost environmental benefit of agroforestry will continue to be underappreciated and underexploited.

Key words: biomass / carbon-sequestration potential (CSP) / clean development mechanism (CDM) / greenhouse gases (GHG) / socio-economics / soil carbon sequestration (SCS)

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1 Introduction

Never before in the history of human civilization has environmental issues attained so much global prominence as it does today. Hardly a day passes without some aspect of it hitting the headlines. The award of the Nobel Peace Prize 2007 to Al Gore and the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (UN) for raising global awareness about the severity of human-induced climate change was a defining moment in history. It is now widely accepted that current global-climate change, or global warming as it is commonly called, is the most serious environmental issue affecting human lives on a global scale. Global warming, the increase in temperature of the earth's near-surface air and oceans in recent decades, is believed to be brought about primarily by the increase in atmospheric concentrations of the so-called greenhouse gases (GHGs).

Carbon dioxide (CO_2) is a major GHG. The continued increase in its concentration in the atmosphere is believed to be accelerated by human activities such as burning of fossil fuels and deforestation (*IPCC*, 2007). One of the approaches to reducing CO_2 concentration in the atmosphere is carbon (C) sequestration, the process of removing C from the atmosphere and depositing it in a reservoir (UNFCCC: http://unfccc.int/essential_background/glossary/items/3666.php#C). The Land Use, Land Use Change and Forestry (LULUCF), an approach that became popular in the context of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC)—the first and so far the largest international agreement to stabilize GHG concentrations—allows the use of C sequestration through afforestation and reforestation as a form of GHG-offset activities. Forest-, crop-, and grazing-land management, and revegetation were added to the detailed list of LULUCF activities in 2001. Consequent to that and the realization of the role of trees as an important means to capture and store atmospheric CO_2 in vegetation, soils, and biomass products (see, *e.g., Malhi* et al., 2008), agroforestry became recognized as a C-sequestration activity especially under the afforestation and reforestation activities that have been approved as GHG-mitigating strategies under the Kyoto Protocol; thus, agroforestry systems attracted attention as a C-sequestration strat-

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egy from both industrialized and developing countries (*Albrecht* and *Kandji*, 2003; *Nair* and *Nair,* 2003; *Makundi* and *Sathaye*, 2004; *Sharrow* and *Ismail*, 2004; *Haile* et al., 2008; *Takimoto* et al., 2008a). This became particularly relevant to Clean Development Mechanism (CDM) under the Kyoto Protocol, which allows industrialized countries with a GHG-reduction commitment to invest in mitigation projects in developing countries as an alternative to what is generally more costly in their own countries. Since agroforestry is mostly practiced by subsistence farmers in developing countries, there is an attractive opportunity for those farmers to benefit economically from agroforestry if the C sequestered through agroforestry activities is sold to developed countries. Thus, a lot of expectation has been raised about the role of agroforestry as a strategy for C sequestration. It is therefore timely that our current understanding on the topic is evaluated and the realistic potential of agroforestry as a biological approach to C sequestration assessed. The objective of this review is to evaluate the role of agroforestry as a strategy for C sequestration and highlight its underlying scientific bases. In the light of the excellent publications that are increasingly becoming available on the mechanisms and processes of C sequestration especially in soils (*Sarkhot* et al., 2007; *Bachmann* et al., 2008; *Flessa* et al., 2008; *Kögel-Knabner* et al., 2008; *von Lützow* et al., 2008; *Marschner* et al., 2008), the focus of this paper is on application-oriented scientific developments in the subject.

2 Agroforestry

Agroforestry has been defined in various ways. The World Agroforestry Centre (www.icraf.cgiar.org) defines it as "a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels." The Association for Temperate Agroforestry, AFTA (http://www.aftaweb.org) defines it as "an intensive land management system that optimizes the benefits from the biological interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock." Several other definitions are also available. In essence, they all refer to the practice of the purposeful growing of trees and crops, and/or animals, in interacting combinations, for a variety of benefits and services (*Nair* et al., 2008).

The concept of agroforestry stems from the expected role of on-farm and off-farm tree production in supporting sustainable land-use and natural-resource management. This concept is based on the premise that land-use systems that are structurally and functionally more complex than either crop or tree monocultures result in greater efficiency of resource (nutrient, light, water) capture and utilization and greater structural diversity that entails tighter nutrient cycles. While the above- and belowground diversity provides more system stability and resilience at the site-level, the systems provide connectivity with forests and other landscape features at the landscape and watershed levels (*Nair* et al., 2008).

Today, agroforestry is recognized as an integrated applied science that has the potential for addressing many of the land-management and environmental problems found in both developing and industrialized nations. A large number of traditional as well as improved agroforestry systems has been recognized from different parts of the world (Appendix 1). Numerous and diverse agroforestry systems can be found in the tropics, partly because of their favorable climatic conditions and partly because of the socio-economic factors such as human-population pressure, more availability of labor, smaller land-holding size, complex land tenure, and less proximity to markets (*Nair*, 2007; *Nair* et al., 2008).

Unlike the production emphasis of agroforestry in the tropics, environmental protection and, to some extent, monetary return, are the main motivating factors for agroforestry in the industrialized nations. Alley cropping, forest farming, riparian buffer strips, silvopasture, and windbreaks are the five major agroforestry practices recognized in North America (AFTA: www.aftaweb.org). Other temperate-zone agroforestry systems include the ancient tree-based agriculture involving a large number of multipurpose trees such as chestnuts (*Castanea* spp.), oaks (*Quercus* spp.), carob (*Ceratonia siliqua*), olive (*Olea europa*), and figs (*Ficus* spp.) in the Mediterranean region (*Nair* et al., 2008; *Rigueiro-Rodríguez* et al., 2008). The dehesa system, grazing under oak trees with strong linkages to recurrent cereal cropping in rangelands, is also a very old European practice (*Rigueiro-Rodríguez* et al., 2008).

3 Carbon-sequestration potential of agroforestry systems

Carbon sequestration involves the net removal of CO_2 from atmosphere and storage in long-lived pools of C. Such pools include the aboveground plant biomass; belowground biomass such as roots, soil microorganisms, and the relatively stable forms of organic and inorganic C in soils and deeper subsurface environments, and the durable products derived from biomass (*e.g.*, timber). Agroforestry systems are believed to have a higher potential to sequester C than pastures or field crops (*Sanchez*, 2000; *Roshetko* et al., 2002; *Sharrow* and *Ismail*, 2004; *Kirby* and *Potvin*, 2007). This conjecture is based on the notion that tree incorporation in croplands and pastures would result in greater net aboveground as well as belowground C sequestration (*Palm* et al., 2004; *Haile* et al., 2008).

A large number of estimates of C sequestration and C losses in different land-use systems are available. For agroforestry alone, CAB Abstracts (http://www.cabi.org) lists 266 papers, most of which were published during the past 15 y, under the keywords "agroforestry" and "carbon sequestration." These estimates are derived by combining information on the aboveground, time-averaged C stocks (half of the system's C stock at its maximum age or rotation length in the case of plantations) and the soil C values of the system.

3.1 Aboveground (vegetation) carbon sequestration

Estimates of aboveground C-sequestration potential (CSP) are based on the assumption that 45% to 50% of branch and

30% of foliage dry weight constitute C (*Shepherd* and *Montagnini*, 2001; *Schroth* et al., 2002). A summary of aboveground C-sequestration rates in some major agroforestry systems around the world is presented in Tab. 1. The table indicates that the estimates of CSP in agroforestry systems are highly variable, ranging from 0.29 to 15.21 Mg ha^{-1} y^{-1}. As can be expected, these values are a direct manifestation of the ecological production potential of the system, depending on a number of factors including site characteristics, land-use types, species involved, stand age, and management practices. Agroforests in the arid, semiarid, and degraded sites have a lower CSP than those in fertile humid sites; and the temperate agroforestry systems have relatively lower vegetation CSP than the tropical ones (Tab. 1). Based on published data on aboveground and time-averaged soil C stocks in forests, agroforestry systems, and croplands/pastures under slash-and-burn systems in the humid tropics of Brazil and Cameroon, *Mutuo* et al. (2005) concluded that the more intensive continuous cropping and short-term fallow systems in subhumid tropics that have relatively short growing cycles or rotation periods have lower CSP in vegetation unlike the slash-and-burn systems of the humid tropics.

3.2 Belowground (soil) carbon sequestration

Soils play a vital role in the global C cycle. The soil C pool comprises soil organic C (SOC) estimated at 1550 Pg (1 petagram = 10^{15} g = 1 billion ton) and soil inorganic C approx. 750 Pg both to 1 m depth (*Batjes*, 1996). This total soil C pool of 2,300 Pg is three times the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg; a reduction in soil C pool by 1 Pg is equivalent to an atmospheric enrichment of CO_2 by 0.47 ppmv (*Lal*, 2001). Thus, any change in soil C pool would have a significant effect on the global C budget. The historical amount of CO_2-C emitted into the atmosphere from the terrestrial ecosystems is estimated to be approx. 136 ± 55 Pg, of which soils account for approx. 78 ± 12 Pg (*Lal*, 2007). Loss of organic C from the tropical soils not only increases the atmospheric CO_2 content, but also reduces the fertility of those soils that are generally nutrient-poor.

The Soil Science Society of America (SSSA) recognizes that C is sequestered in soils in two ways: direct and indirect (*Soil Science Society of America*, 2001): "Direct soil C sequestration occurs by inorganic chemical reactions that convert CO_2 into soil inorganic C compounds such as calcium and magnesium carbonates." Indirect plant C sequestration occurs as plants photosynthesize atmospheric CO_2 into plant biomass. Some of this plant biomass is indirectly sequestered as SOC during decomposition processes. The amount of C sequestered at a site reflects the long-term balance between C uptake and release mechanisms. Because those flux rates are large, changes such as shifts in land cover and/or land-use practices that affect pools and fluxes of SOC have large implications for the C cycle and the earth's climate system.

Table 1: Mean vegetation (above- and belowground) carbon-sequestration[a] potential of prominent agroforestry systems[d].

Agroforestry/land-use system[b]	Age[c] (y)	Mean vegetation C (Mg ha^{-1} y^{-1})	Source
Fodder bank, Ségou, Mali, W African Sahel	7.5	0.29	*Takimoto* et al. (2008b)
Live fence, Ségou, Mali, W African Sahel	8	0.59	*Takimoto* et al. (2008b)
Tree-based intercropping, Canada	13	0.83	*Peichl* et al. (2006)
Parklands, Ségou, Mali, W African Sahel	35	1.09	*Takimoto* et al. (2008b)
Agrisilviculture, Chattisgarh, Central India	5	1.26	*Swamy* and *Puri* (2005)
Silvopasture, W Oregon, USA	11	1.11	*Sharrow* and *Ismail* (2004)
Silvopastoralism, Kurukshetra, India	6	1.37	*Kaur* et al. (2002)
Silvopastoralism, Kerala, India	5	6.55	*Kumar* et al. (1998a)
Cacao agroforests, Mekoe, Cameroon	26	5.85	*Duguma* et al. (2001)
Cacao agroforests, Turrialba, Costa Rica	10	11.08	*Beer* et al. (1990)
Shaded coffee, SW Togo	13	6.31	*Dossa* et al. (2008)
Agroforestry woodlots, Puerto Rico	4	12.04	*Parrotta* (1999)
Agroforestry woodlots, Kerala, India	8.8	6.53	*Kumar* et al. (1998a)
Home and outfield gardens	23.2	4.29	*Kirby* and *Potvin* (2007)
Indonesian homegardens, Sumatra	13.4	8.00	*Roshetko* et al. (2002)
Mixed species stands, Puerto Rico	4	15.21	*Parrotta* (1999)

[a] Though reported as carbon-sequestration potential, the values are based on C-stock estimates.
[b] Values for similar systems (in terms of location and age) were pooled wherever possible regardless of species.
[c] "Age" of the system, though not clearly defined, is assumed to be the number of years since establishment of the tree component in the system.
[d] These systems were selected from many reports of this nature to provide a broad spectrum of agroforestry systems (live fences to multistrata systems) in different geographical regions.

Soil organic C contains a variety of fractions that differ in decomposability and are very heterogeneous in structure. The turnover of SOC is intimately linked with organic-matter quality (*Ågren* et al., 1996; *Martens*, 2000). Distinctive components of SOC have different residence times, ranging from labile to stable forms (*Carter*, 1996). This concept has led to the suggestion that SOC can be viewed as having an active, labile pool (mean residence times [MRTs] approx. 1–2 y), a slow pool (MRTs approx. 25 y), and a passive, recalcitrant pool (MRTs approx. 100–1000 y) (*Parton* et al., 1987; *Jenkinson*, 1990; *Schimel* et al., 1994; *Torn* et al., 2005). Further, protection of SOC by silt and clay particles is well established (*Sorensen*, 1972; *Ladd* et al., 1985; *Feller* and *Beare*, 1997; *Hassink*, 1997; *von Lützow* et al., 2006, 2007). It is also known that aggregation increases in less disturbed systems and that organic material within the soil aggregates, especially the microaggregates, has lower decomposition rate than that located outside the aggregates (*Elliott* and *Coleman*, 1988; *Six* et al., 2000).

The literature on soil C-sequestration (SCS) potential of agroforestry systems is scanty in spite of the rather plentiful reports on the potential role of agricultural soils to sequester C. Recent studies on SCS, summarized in Tab. 2, indicate that the estimates vary greatly, just as for vegetation CSP, among the different land-use practices. A general trend of increasing SCS in agroforestry compared to other land-use practices (with the exception of forests) is discernible from these studies. Overall, the land-use systems can be ranked in terms of their SOC content in the order: forests > agroforests > tree plantations > arable crops. Understandably, the large differences in SCS values among the land-use systems are a reflection of the biophysical and socio-economic characteristics of the system parameters and/or methodological artifacts. However, such site-quality attributes are not adequately reported in most studies listed in Tab. 2.

From a study of silvopastoral systems with slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*), and an adjacent

Table 2: Some recent reports on soil carbon-sequestration potential under agroforestry systems[a].

Agroforestry system/species	Location	Age (y)	Soil depth (cm)	Soil C (Mg ha^{-1})	Reference/comments
Mixed stands, *Eucalyptus* + *Casuarina, Casuarina* + *Leucaena*, and *Eucalyptus* + *Leucaena*	Puerto Rico	4	0–40	61.9, 56.6, and 61.7	*Parrotta* (1999)
Agroforest (*Pseudotsuga menziesii* + *Trifolium subterraneum*)	W Oregon, USA	11	0–45	95.89	*Sharrow* and *Ismail* (2004)
Agrisilviculture (Gmelina arborea + eight field crops)	Chhattisgarh, Central India	5	0–60	27.4	*Swamy* and *Puri* (2005)
Tree-based intercropping: hybrid poplar + *Hordeum* vulgare	Ontario, Canada	13	0–20	78.5	*Peichl* et al. (2005)
Silvopastoral system: *Acacia mangium* + *Arachis pintoi*	Pocora, Atlantic coast, Costa Rica	10–16	0–100	173	*Amézquita* et al. (2005)
Silvopastoral system: *Brachiaria brizantha* + *Cordia alliodora* + *Guazuma ulmifolia*	Esparza, Pacific coast, Costa Rica	10–16	0–100	132[a]	*Amézquita* et al. (2005) stable C =14 Mg ha^{-1}
Alley cropping *Leucaena*–4 m	W Nigeria	5	0–10	13.6	*Lal* (2005)
Alley cropping: hybrid poplar + wheat, soybeans (*Glycine max.*), and maize rotation	S Canada	13	0–40	1.25	*Oelbermann* et al. (2006)
Alley cropping system: *Erythrina poeppigiana* + maize and bean (*Phaseolus vulgaris*)	Costa Rica	19	0–40	1.62	*Oelbermann* et al. (2006)
Shaded coffee, *Coffea canephora* var. robusta + *Albizia adianthifolia*	SW Togo	13	0–40	97.27	*Dossa* et al. (2008)
Agroforest (home and outfield gardens)	Ipetí-Embera, Panama		0–40	45.0 ±2.3	*Kirby* and *Potvin* (2007)
Faidherbia albida parkland	Ségou, Mali	35	0–100	33.3	*Takimoto* et al. (2008b)
Live fence (*Acacia nilotica, A. senegal, Bauhinia rufescens, Lawsonia inermis*, and *Ziziphus mauritiana*)	Ségou, Mali	8	0–100	24	*Takimoto* et al. (2008b)
Fodder bank (*Gliricidia sepium, Pterocarpus lucens*, and *P. erinaceus*)	Ségou, Mali	6–9	0–100	33.4	*Takimoto* et al. (2008b)
Tree-based pastures: slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*)	Florida, USA	8–40	0–125	6.9 to 24.2	*Haile* et al. (2008)
Gliricidia sepium + maize (*Zea mays*)	Zomba, Malawi	10	0–200	123	*Makumba* et al. (2007)

[a] Footnotes to Tab. 1 apply to Tab. 2 as well.

open pasture with bahiagrass at four sites, representing Spodosols and Ultisols, in Florida, USA, *Haile* et al. (2008) reported that SOC across four sites in whole soil at different depth classes up to 120 cm below surface was higher under silvopasture by an overall average of 33% near trees and 28% in the alleys between tree rows as compared to adjacent open pasture. Using stable–C isotope signatures, the C contents within three fraction-size classes (250–2000, 53–250, and <53 μm) of each soil layer were traced to the plant sources (C3 *vs.* C4 plant). Silvopasture accumulated higher C3-derived SOC in the macro-sized fraction (250–2000 μm), retained more C3-derived SOC in micro-sized fraction (53–250 μm) and the silt + clay fraction (<53 μm) of soil compared to open pastures. Slash pine trees (C3 plants) seemed to have contributed more C in the silt- + clay-sized fractions than bahiagrass (C4 plants), particularly in lower soil layers, at all sites (*Haile*, 2007). The results suggest that most of SOC in deeper soil profiles and the relatively stable C were derived from tree components (C3 plants) in the pasture systems, and therefore the tree-based pasture system has greater potential for C sequestration compared with the treeless system.

The impact of any agroforestry system on soil C sequestration depends largely on the amount and quality of input provided by tree and nontree components of the system and on properties of the soils themselves, such as soil structure and their aggregations. For example, in the establishment of silvopastoral systems, when trees are allowed to grow in grass-dominated land such as an open pasture, some functional consequences are inevitable, most notably alterations in above- and belowground total productivity, modifications to rooting depth and distribution, and changes in the quantity and quality of litter inputs (*Connin* et al., 1997; *Jackson* et al., 2000; *Jobbágy* and *Jackson*, 2000). These changes in vegetation component, litter, and soil characteristics modify the C dynamics and storage in the ecosystem—which in turn may lead to alterations of local and regional climate systems (*Schlesinger* et al., 1990; *Ojima* et al., 1999). Humification (conversion of biomass into humus), aggregation (formation of organo-mineral complexes as secondary particles), translocation of biomass into subsoil by deep roots, and leaching of soil inorganic C into groundwater as bicarbonates are processes that lead to SOC sequestration (*Lal*, 2001). All these processes are operational in tree-based land-use systems. But not many studies are available on the mechanisms and processes associated with C dynamics and storage in tree-based systems such as silvopasture, despite their local, if not regional, significance (*Jackson* et al., 2000).

3.3 Methodological difficulties

3.3.1 Lack of standard methods and procedures

The methodologies and approaches used for C-sequestration potential of land-use systems are unfortunately not rigorous. As stated before, C sequestration refers to removing C from the atmosphere and depositing it in a reservoir (UNFCCC: http://unfccc.int/essential background/glossary/items/3666.php#C). Ideally, CSP should be reported as rates (mass per units of area and time). But the available data are reported mostly as stocks. For soil C, this is understandable, given that time-sequence studies on soil C involving time intervals of several years are rare in land-use systems in general and nonexistent in agroforestry systems. Vegetation C pools are sometimes linked to rotation length of trees especially in the case of plantations and therefore could be considered as rates; yet many of them are estimated from and listed as C stocks. Considering that the studies from which these datasets are reported were not part of any unified or coordinated research project, the lack of uniformity and rigor is understandable. With the available information, it is also difficult to standardize these datasets. In spite of these deficiencies, we are using these datasets not only to present the "state of affairs," but in the hope that researchers will be encouraged to be aware of the need for more methodological uniformity in future studies.

Available reports on C-stock assessments involve computations of aboveground biomass from field measurements and satellite-image interpretation and estimates of belowground biomass derived from aboveground computations (*FAO*, 2004). Broadly, they include the following:

– direct on-site measurements of biomass, soil C, or C flux;
– indirect remote-sensing techniques;
– modeling.

These estimates are derived by combining information on the aboveground, time-averaged C stocks, and the soil C values of the system.

A major challenge facing C-stock estimation is accurate estimation of tree biomass. One of the main technical issues is the determination of the inventory and monitoring of stocks of C sequestered in current and potential land uses and management approaches; but a standard set of methods and procedures is not available for this. Aboveground biomass is typically estimated using allometric equations developed for trees in the natural forests. But, they generally lack accuracy either because of their very location-specific or much "generalized" nature (*Kumar* et al., 1998a). The size of individual tree canopies in an agroforestry setting also could be different from that in a forest or single-species stand. In addition, the crown and root architecture and tree-management practices are different; the resultant variations in structure could result in erroneous estimates, especially if generalized regression equations are used.

Belowground-biomass studies in agroforestry systems are even more problematic. Fine-root dynamics are one of the least understood aspects of plant life (*Strand* et al., 2008). Information on C stocks of belowground vegetation components are not usually reported, and those that have been reported lack the required scientific rigor. Available reports, however, suggest that as much as 33% of the global annual net primary productivity (NPP) is used for fine-root production, which therefore is a major input to soil organic matter (SOM) pool (*Nair* et al., 1999). *Woomer* and *Palm* (1998) reported that roots in tropical agroforestry systems can have a time-averaged C stock ranging from approx. 6 Mg C ha^{-1} for shifting cultivation to approx. 20 Mg C ha^{-1} for tree fallows in the top 0–50 cm soil depth. Root biomass is often estimated from root-to-shoot ratios (R : S; ranging from 0.18 to 0.30 for tropical, temperate, and boreal forests; *Cairns* et al., 1997).

Direct methods and approaches used to quantify the amount of C in forests are generally based on permanent sample plots laid out in statistically sound designs (*Montagnini* and *Nair*, 2004). But indirect methods of estimation such as remote sensing and modeling are subject to the problem with simplified "average" values that are often used as the bases for further computations. In GHG mitigation projects, for example, it is not uncommon to find differing "definitions" and interpretations of source and sink categories and uncertainties about the basic processes leading to emissions and/or removals. To estimate the effects of harvest on C stocks, accurate information is required on three items: preharvest biomass, the fraction of this biomass harvested or damaged, and the fraction of the harvested biomass removed; much of these, however, are not available (*de Jong*, 2001).

Another point of uncertainty arises from the stand age. Older stands are generally considered to accumulate more C than younger ones; there is, however, no consensus on this. *Woomer* et al. (2000) argued that C-accumulation rates (vegetation, soil, and litter) for different land-use systems were not based so much on the time a system re-grew, as on the land-use type. Fallows established after initial cropping accumulated C stocks similar to that of the original forest after approx. 20 y, but bush fallows and multistrata agroforests accumulated approx. 60% of initial forest C stocks in approx. 30 y, and pasture/grassland after slash-and-burn resulted in continued gradual decline. Conversely, a logistic model of biomass accumulated during the first 15 y after abandonment in shifting cultivation fallows showed that biomass production reached maximum after 6 y at 47 Mg dry matter (d.m.) ha^{-1} (*Jepsen*, 2006).

3.3.2 Area under agroforestry

The first step in planning for capitalizing on the potential benefits of any land-use system and designing development plans for its sustainable utilization is to have an unambiguous estimate of the area under the system at a given period of time. The lack of such an estimate is a major difficulty, not only in estimating its CSP but in any activity aimed at the development and utilization of the services and products of agroforestry. Simply put, area statistics of agroforestry systems are not available although agroforestry systems abound in many parts of the world, particularly in the tropics. *Montagnini* and *Nair* (2004) noted that with no reliable estimates on the extent of area and the gross variability expected in terms of tree species, stocking levels, and soil attributes, it is an "almost insurmountable" task to estimate C stocks in agroforestry.

A major difficulty in estimating the area under agroforestry is lack of proper procedures for delineating the area influenced by trees in a mixed stand of trees and crops. In simultaneous systems, the entire area occupied by multistrata systems such as homegardens and shaded perennial systems and intensive tree-intercropping situations can be listed as agroforestry. However, most of the agroforestry systems are rather extensive, where the components, especially trees, are not planted at regular spacing or density; for example, the parkland system and extensive silvopastures. The problem is more difficult in the case of practices such as windbreaks and boundary planting where although the trees are planted at wide distances between rows (windbreaks) or around agricultural or pastoral parcels (boundary planting), because the influence of trees extends over a larger than easily perceivable extent of areas. In the case of windbreaks a rule of thumb is that the area protected (against wind erosion) by the windbreak extends laterally to 10 times the height (H) of trees in the central core of windbreaks. The problem has a different

Table 3: Summary of the estimates on the extent of agroforestry practices in the world and their carbon-sequestration potentials.

Region/practice	Estimated area (million ha)	Potential for C sequestration (Pg C y^{-1}; sum of above- and below-ground storage)	Source	Remarks
Africa, Asia, and the Americas: silvopastoral, agrosilvopastoral, and agrosilvopastoral.	585–1215	1.1–2.2	*Dixon* (1995)	over a 50 y period; an additional 630 Mha of crop- and grasslands that are currently fallow or marginal lands could be converted into agroforestry, primarily in the tropics
World: all agroforestry systems	400	0.026	*Watson* et al. (2000)	estimate for 2010; C gain of 0.72 Mg C ha^{-1} y^{-1}
USA: alleycropping, silvopasture, windbreaks, and riparian buffers	235.2	0.09	*Nair* and *Nair* (2003)	excludes the conservation buffer including the short-rotation woody crops on which area estimates are not available
South- and southeast Asian homegardens	8.0	0.064	*Kumar* (2006)	S India, Indonesia, Sri Lanka, and Bangladesh; based on *Roshetko* et al. (2002), estimate of mean C-sequestration potential of 107.2 Mg ha^{-1} for homegardens of average age 13.4 y
European silvoarable agroforestry	65.2		*Reisner* et al. (2007)	*Juglans* spp., *Prunus avium, Populus* spp., *Pinus pinea*, and *Quercus ilex* Target regions = 40% of the European arable land

dimension of difficulty when it comes to sequential tropical systems such as improved fallows and shifting cultivation. In such situations, the beneficial effect of trees and other woody vegetation (in the fallow phase) on the crops that follow them (in the cropping phase) is believed to last for a variable length of time (years). Obviously, it is a daunting task to determine the area under agroforestry; nevertheless, it is something that needs to be done if substantial progress has to be made in realizing the benefits of agroforestry for C sequestration.

Some attempts have, however, been made to estimate the area and C stocks and area under agroforestry in the world; these are summarized in Tab. 3. The C-stock estimates are mostly artifacts of estimates of forestry systems or their subsets. For example, the total aboveground biomass (AGB) in the world's forests has been estimated as 421 Tg (teragram = 10^{12} g = million ton) distributed over a total area of 3,869 Mha; 95% of this is in natural forest and 5% in plantation forest (*FAO*, 2007). Moreover, a recent assessment of LULUCF mitigation options suggests that the global potential for biologically feasible afforestation and reforestation activities between 1995 and 2050 could average 1.1 to 1.6 Pg C y^{-1}, 70% of which would be in the tropics (*IPCC*, 2000). The area estimates are more of "guesstimates" than C-stock estimates. To add to such guesstimates, we are tempted to suggest the following:

- Agroforestry land-use systems are extensively practiced in a number of regions around the tropics (*Nair*, 1989; *Zhaohua* et al., 1991; *Clarke* and *Thaman*, 1993; *Tejwani*, 1994; *Boffa*, 1999; *Viswanath* et al., 2000; *Kumar*, 2006).

- Agroforestry systems are quite prevalent in the temperate regions as well (*Garrett* et al., 2000; *Reisner* et al., 2007; *Rigueiro-Rodríguez* et al., 2008).

- Considering 1 and 2 above, we propose that 20% of the arable and permanent cropped area and 15% of the pasture lands in the world is under silvopastoral combination. Globally, the cropped area of the world is 1,534 million ha and that of pasture is 3442 million ha (*FAO*, 2007). Therefore, the area under agroforestry farming practices is deduced as ([1534 × 0.20] + [3442 × 0.15])= 823 million ha.

- We propose that 5% of the world's forests are managed as agroforests; given that the total area under forest is 4000 million ha (*FAO*, 2007), the area under agroforestry in forestlands is 200 million ha.

- Thus, the total area under agroforestry in the world can be estimated as 1023 million ha.

This projection is, of course, tentative. It does not include areas that could potentially be brought under agroforestry, such as the vast areas of degraded forestland. For example, *IPCC* (2000) estimated that 630 million ha of unproductive croplands and grasslands could be converted to agroforestry worldwide, with the potential to sequester 391,000 Mg C y^{-1} by 2010 and 586,000 Mg C y^{-1} by 2040. Another estimate suggests that approx. 1.9 billion ha of land is degraded due to erosion, salinity, fertility depletion, and advancing deserts (*Brown*, 2004), and the potential of agroforestry to reduce the hazards of erosion and desertification as well as to rehabilitate such degraded land and to conserve soil and water has been well recognized (*Lal*, 2004; *Nair*, 2007).

3.3.3 Other methodological issues

The tree species and the way they are combined in different agroforestry systems also influence both the quantity and quality of the biomass returned to the soil. Although polycultures accrue more soil C, soil C stocks can also increase under monocultures of trees, depending on the species (*Russell* et al., 2004). Consistent with this, in a recent study comparing four neotropical tree plantations established on a degraded pasture of the Caribbean lowlands of Costa Rica, *Jimenez* et al. (2007) noted that the highest SOC pool occurred under *Hieronyma alchorneoides* followed by *Vochysia guatemalensis* (132 and 119 Mg C ha, respectively).

A major concern is the considerable variability in soil-profile depths sampled (ranging from 0 to 10 and from 0 to 200 cm) in the reported studies (Tab. 2), which makes comparisons impossible. Most studies showing improvements of SOC in agroforestry systems have concentrated on changes in the topsoil layer, 0–20 cm, where the largest C pools are detected (*Makumba* et al., 2007; *Oelbermann* and *Voroney*, 2007). Information on stocks of organic C in the deeper soil layers where most of the tree roots occur and that supply substantial amounts of C through root exudates and fine-root turnover is, however, lacking.

Roots are an important part of the C balance, because they transfer large amounts of C into the soil. More than half of the C assimilated by the plant is eventually transported belowground *via* root growth and turnover, root exudates (of organic substances), and litter deposition. Depending on rooting depth, a considerable amount of C is stored below the plow layer and is, therefore, better protected from disturbance, which leads to longer residence times in the soil. With some trees having rooting depths of >60 m, root C inputs can be substantial, although the amount declines sharply with soil depth (*Akinnifesi* et al., 2004). Most of the biomass of the roots of annual crops/grasses consists of fine roots (∅ < 2 mm) whereas biomass of tree roots, which is a large proportion of the belowground productivity, consists of coarse roots (∅ > 2 mm) (*Albrecht* et al., 2004; *Akinnifesi* et al., 2004). Fine roots of both trees and crops have a relatively fast turnover (days to weeks) (*van Noordwijk* et al., 1998), but the lignified coarse roots decompose much more slowly and may thus contribute substantially to belowground C stocks (*Vanlauwe* et al., 1996).

The dynamics of growth, decay, and turnover of roots is one of the least understood aspects of belowground interactions in agroforestry (*Schroth* et al., 2007). Unlike in the case of annuals where all roots die at the final harvest of the aboveground part, the standing root system (the difference between cumulative growth and cumulative decay at a given time) changes little in the case of perennials, yet substantial growth and decay occur simultaneously. This turnover through dead and sloughed-off roots represents a substantial input to soil C pool. Typical methods for root studies include spatially distributed soil cores or pits for fine and medium roots and partial to complete excavation and/or allometry for coarse roots. Often the distinction between live and dead roots is not made and sampling depths are not standardized, yet the depth selected in a given study is assumed to capture practically all roots (*Brown*, 2002). The amounts of fine roots, litterfall, pruning residues, and crops are also variable, making it unreliable to use the general ratios that are used for stem-biomass estimation. Although we have seen some progress in the quantification of these issues at the plant and ecosystem levels, most of the methods used to measure such dynamics are problematic, especially in the case of perennials (*van Noordwijk* et al., 2004). Two other issues add to the difficulties in making reliable estimations of CSP in agroforestry: first, most of the reported studies are on SOC dynamics (that have the deficiencies discussed above) rather than on C sequestration, and second, most of the reported studies deal with only the top layers of soil (mostly up to 20 cm soil depth and seldom beyond 40 cm).

4 Agroforestry system management for carbon sequestration

4.1 Tree-species selection and silvicultural management

Growth-rate differences among tree species and the "native *vs.* exotic"–species controversy are among widely debated but not yet resolved biological issues related to C sequestration by trees in agroforestry systems. Most of such discussions originate from reports on C sequestration in tropical tree plantations, and in all these reports, C sequestration is considered synonymous to C stock—which in itself is not fully correct. Although such plantations occupy only limited areas (5% of tropical forests; *FAO*, 2007), they may become more important not only because plantations are expected to increase in area over the next few decades (*FAO*, 2007), but because many of the species promoted for tropical plantations will also be grown under agroforestry combinations. It is still unclear, however, whether native species, because of their supposedly better adaptability to local conditions, would be superior to exotic ones for use in such plantations (*Kumar* et al., 1998a).

The idea that planting forests/trees could be a cheap way to absorb emissions of CO_2 is being challenged as well. Based on experiments conducted in loblolly pine (*Pinus taeda*) forests in North Carolina, USA, *Oren* et al. (2001) reported that after an initial growth spurt, trees grew more slowly and did not absorb as much excess C from the atmosphere as expected. In two experiments with *Pinus taeda* trees exposed to elevated atmospheric CO_2, CO_2-induced biomass C 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 3 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. The authors concluded that assessment of future C sequestration should consider the limitations imposed by soil fertility as well as interactions with N deposition. In another study, *Schlesinger* and *Lichter* (2001) examined decomposing leaves and roots on the floor of the experimental pine-forest plots and found the total amount of litter increased in a CO_2-enriched atmosphere, but so did the rate at which it was broken down, resulting in the release of C back to the atmosphere rather than being incorporated into the soil. Although the findings do not mean that planting trees is not important, they suggest that planting trees may not serve as an adequate substitute for reducing heat-trapping GHG emissions.

Another aspect of uncertainty is the differences in wood quality of species in relation to their C-accumulation rates. In a study of 32 neotropical species in the Amazon, *Elias* and *Potvin* (2003) found that the pioneer species (*e.g., Ochroma pyramidale*) presented some of the highest and nonpioneers exhibited some of the lowest C values. However, the wood of slower-growing species is usually of higher specific gravity than that of faster-growing species, such that the slow-growing species may accumulate more C in the long-term (*Baker* et al., 2004; *Balvanera* et al., 2005; *Bunker* et al., 2005; *Redondo-Brenes* and *Montagini*, 2006). The more valuable, high-specific-gravity wood also constitutes a longer-term sink for fixed C (*e.g.*, construction timber, furniture, wood crafts) than low-specific-gravity wood used for short-lived purposes such as packaging cases and poles. Therefore, mixtures of fast-growing species and slower-growing species that produce harvestable wood at different rotation times—similar to species admixture in agroforestry systems—have been recommended for plantations in Costa Rica (*Montagnini* et al., 2005).

Mixed plantings of N_2-fixing tropical species and commercial timber trees have been reported to produce more aboveground biomass or volume production compared to their monoculture stands (*Kumar* et al., 1998b; *Bauhus* et al., 2004; *Forrester* et al., 2006). Species mixtures also offer greater resistance to insect infestation or disease outbreak (*Keenan* et al., 1995; *Ball* et al., 1995). A recent review, based on a meta-analysis of more than 50 field experiments which contrasted pure stand *vs.* mixed stand of the same tree species, demonstrated a significant increase in insect-pest damage in single-species stands (*Jactel* et al., 2005).

Other silvicultural aspects such as stand density and rotation length may also influence biomass production (and the perceived CSP) of species. Overall, high-density stands sequester larger amounts of C than lower-density stands. Although these findings *per se* do not imply that mixed species planting is not important, they suggest that choice of species and its management are critical to promoting C sequestration. This may, however, create conflicts with plantation-management objectives such as timber, highlighting the need for stand-density regulation approaches that are in sync with land-management objectives (*Kumar* et al., 1995). Design of planting schemes to make trade-offs between generating ecological services (*e.g.*, C sequestration) and goods (*e.g.*, timber) is indeed a major silvicultural challenge.

4.2 Carbon-sequestration programs and rural livelihood security

The CDM under the Kyoto Protocol allows industrialized countries with a GHG reduction commitment to invest in mitigation projects in developing countries as an alternative to what is generally more costly in their own countries. This offers an economic opportunity for subsistence farmers in developing countries, the major practitioners of agroforestry, for selling the C sequestered through agroforestry activities to industrialized countries; it will be an environmental benefit to the global community at large as well. Projects under the CDMs have the dual mandate of reducing GHG emissions and contributing to sustainable development. Carbon trading is also rapidly expanding, now that the World Bank and other institutions have established funds to facilitate the establishment of CDM projects (*World Bank*, 2004). Industrialized countries consider CDM as a potential source for low-cost emission credits, while developing countries hope it may attract new and additional investment for sustainable development. Potentially there are two ways in which farmers could benefit from entering into contracts to sequester C: (1) farmers would be compensated for the C they sequester, based on the quantity of C sequestered and the market price of C; (2) farmers would benefit from any gains in productivity associated with the adoption of C-sequestering practices.

The economic feasibility of C-sequestration contracts was assessed by *Antle* et al. (2007) using a simulation model designed to simulate the value of terrace and agroforestry investments in the highland tropics of Peruvian Andes. The analysis showed that participation in C contracts could increase adoption of terraces and agroforestry practices in N Peru, with the rate of adoption depending on the C-accumulation rate and key factors affecting terrace productivity. There was a relatively low economic potential for C sequestration in this agricultural system at C prices <\$50 per Mg C, but that potential increased substantially for C prices >\$50 per Mg C. Moreover, under favorable conditions for C sequestration and a C price of \$100 per Mg C, terrace and agroforestry adoption and C sequestration had the potential to raise per capita incomes by up to 15% on farms with steeply sloped fields and reduce poverty by as much as 9%. *Takimoto* et al. (2008a) conducted a cost-benefit analysis of C sequestration in two improved agroforestry systems (live fence and fodder bank) and the traditional parkland agroforestry systems in semiarid Mali that represents the vast W African Sahel region. They concluded that C-credit sale was likely to contribute to economic development of the subsistence farmers in the region. Considering the systems as 25-year projects, the traditional systems had high C stock in their biomass and soil, but little potential for sequestering additional C; on the other hand, the improved systems had low C stock, but high sequestration potential. For the standard size live-fence (291 m) and fodder-bank (0.25 ha) projects, the estimated net present values (NPV) were \$96.0 and \$158.8 without C-credit sale and \$109.9 and \$179.3 with C sale, respectively. From the C sale perspective, live fence seemed less risky and more profitable than fodder bank.

Thus, although agroforestry projects can theoretically contribute to income generation, poverty reduction, and environmental preservation, it is unclear whether CDM will play a vital role in relation to the development of agroforestry and forestry projects. The profitability of land-use-related CDM projects will depend on the price of C in the international market, additional income from the project like the sale of timber, and the cost related to C monitoring. Estimates of future C prices are highly uncertain. There are examples that demonstrate how sink-related CDM projects can promote sustainable development. For instance, in Mexico, a CDM project assisted farmers to switch from swidden agriculture to agroforestry, either by combining crops and timber trees or by enriching fallow lands (*Nelson* and *de Jong*, 2003). The bottom-line is that C-sequestration projects in the land-use sector must be able to offer C credits at a competitive price as compared to the other sectors of the economy.

Apart from the role of wood acting as C sink as discussed, it also substitutes the more energy-intensive construction materials (*e.g.*, concrete, steel) and fossil fuels (*Schlamadinger* and *Marland*, 1996; *Arroja* et al., 2006). In 1990, the worldwide sequestration of C in wood products was estimated as a meager 139 Tg C y^{-1} (*Winjum* et al., 1998), a small fraction of the estimated C sequestration in terrestrial ecosystems. Recently, however, agroforestry systems such as alley cropping have been refocused on as they have the potential to integrate the production of lignocellulosic crops (*Gruenewald* et al., 2007). They provide a promising land-use option for energy supply in rural areas and for diversification of agricultural production focusing rather on the provision of biomass for energy and industry than on food (*Volk* et al., 2004). Production and use of woody biomass for energy-transformation purposes entails numerous benefits, such as job creation and further positive implications for the added value at regional scales (*Hüttl* et al., 2000; *Volk* et al., 2004). *Gruenewald* et al. (2007) argue that a sustainable supply of fuelwood is possible even in the temperate zone under marginal ecological conditions in the tropics if tree species well adapted to specific climatic and edaphic conditions are chosen.

The success in the implementation of the agroforestry project for GHG mitigation will depend on the farmers' willingness to participate in the project. Several reasons have been recognized in support of introducing C-sequestration benefits into smallholder agroforestry practices in developing countries: (1) the sequestration service does not need to be physically transported, thus, it can benefit people in remote areas, most of whom are very poor. (2) There are no quality differences: a molecule of carbon is the same wherever it is located; so the problem often faced by smallholders in not being able to achieve the quality required by international markets in agricultural commodities does not apply here. Furthermore, even small amounts of additional income would make a great difference for these subsistence farmers who have very limited alternate employment opportunities to make such additional cash income (*Takimoto* et al., 2008a).

Appendix 1: Major agroforestry practices in the tropical and the temperate regions. (Source: *Nair* et al., 2008).

Agroforestry practice	Description
Tropical agroforestry	
Alley cropping (hedgerow intercropping)	fast-growing, preferably leguminous, woody species grown in crop fields; the woody species pruned periodically at low height (<1.0 m) to reduce shading of crops; the prunings applied as mulch into the alleys as a source of organic matter and nutrients, or used as animal fodder
Homegardens	intimate multistory combinations of a large number of various trees and crops in homesteads; livestock may or may not be present
Improved fallow	fast-growing, preferably leguminous, woody species planted and left to grow during fallow phases between cropping years for site improvement; woody species may yield economic products
Multipurpose trees (MPTs) on farms and rangelands	fruit trees and other MPTs scattered haphazardly or planted in some systematic arrangements in crop or animal production fields; trees provide fruits, fuelwood, fodder, timber, *etc.*
Silvopasture:	integrating trees in animal production systems:
Grazing systems	cattle grazing on pasture under widely spaced or scattered trees
Cut and carry system (protein banks)	stall-feeding of animals with high-quality fodder from trees grown in blocks on farms
Shaded perennial–crop systems	growing shade-tolerant species such as cacao and coffee under or in between overstory shade, timber, or other commercial tree crops.
Shelterbelts and windbreaks	use of trees to protect fields from wind damage, sea encroachment, floods, *etc.*
Taungya	growing agricultural crops during the early stages of establishment of forestry plantations
Temperate agroforestry	
Alley cropping	trees planted in single or grouped rows in herbaceous (agricultural or horticultural) crops in the wide alleys between the tree rows
Forest farming	utilizing forested areas for producing specialty crops that are sold for medicinal, ornamental, or culinary uses
Riparian buffer strips	strips of perennial vegetation (tree/shrub/grass) planted between croplands/pastures and streams, lakes, wetlands, ponds, *etc.*
Silvopasture	combining trees with forage (pasture or hay) and livestock production
Windbreaks	row trees around farms and fields, planted and managed as part of crop or livestock operation to protect crops, animals, and soil from wind hazards

5 Conclusions

Agroforestry systems that integrate tree production with crop and animal production systems are believed to have a higher potential to sequester C than pastures or field crops. This conjecture is based on the notion that tree incorporation in croplands and pastures would result in greater net aboveground as well as belowground C sequestration. Although some estimates of so-called "C-sequestration potential" of agroforestry systems are available, these are mostly estimates of C stocks and, overall, the data are not rigorous. Methodological difficulties in estimating C stock of biomass and the extent of soil C storage under varying conditions and the lack of reliable estimates of area under agroforestry systems are serious limitations in exploiting this low-cost environmental benefit of agroforestry.

Globally, C trading is rapidly expanding, and the CDM of the Kyoto Protocol offers an attractive economic opportunity for subsistence farmers in developing countries, the major practitioners of agroforestry, for selling the C sequestered through agroforestry activities to industrialized countries. It will be an environmental benefit to the global community at large as well. The political environment is also favorable for enhancing smallholder involvement in GHG-mitigation projects. The success in the implementation of such projects will depend on the farmers' willingness to participate in the project.

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