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The Role of Forest and Soil Carbon Sequestrations on Climate Change Mitigation

Binyam Alemu
College of Agriculture, Department of Soil and Water Resources Management, Wollo University, Ethiopia
P.O.Box 1145, Dessie, Ethiopia
Corresponding Author: binyamalemu@yahoo.com

Abstract
The emission of CO_2 concentration from industries, burning of fossil fuels and deforestation causes GHGs. Hence, forests in terms of agroforestry, plantation, reforestation has been suggested as one of the most appropriate land management systems for mitigating atmospheric CO_2 through photosynthesis process. Forest ecosystems also contribute to store more than 80% of all terrestrial aboveground C and more than 70% of all SOC. Forests operate both as vehicles for capturing additional carbon and as carbon reservoirs in different carbon pools (above ground, root and litter). The other form of carbon pool is soil carbon sequestration also increases SOC stocks through judicious land use and recommended management practices. Forest soils are one of the major carbon sinks on earth, because of their higher organic matter content. Furthermore, soil carbon sequestration is a bridge across three global issues climate change, desertification, and biodiversity. Therefore, developed countries can implement their emission reductions at lower costs and developing countries receive more capital for environmentally sound investments that contribute to sustainable development. This offers an economic opportunity for subsistence farmers in developing countries, the major practitioners of agroforestry, afforestation and reforestation for selling of carbon sequestered to industrialized countries and it will be an environmental benefit to the global community at large as well.
Keywords: forest carbon sequestration, soil organic carbon, climate chang

1. Introduction

The increasing concentration of CO_2 and other GHGs in the atmosphere is now widely recognized as the leading cause of global warming. Carbon (C) is accumulating in the atmosphere at a rate of 3.5 Pg (Pg = 10^{15} g or billion tons) per annum, the largest proportion of which resulting from the burning of fossil fuels and the conversion of tropical forests to agricultural production (Paustian *et al*., 2000). 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).

At the current rate of CO_2 emissions, its concentration in the atmosphere will be doubled by the end of 21st century. Realizing the threat of global warming, United Nations established the IPCC and created the Kyoto Protocol by United Nations Framework Convention on Climate Change (UNFCCC) as the first international agreement on mitigating GHGs. The goal of this protocol is to reduce the GHGs of committed countries by at least 5% compared to the 1990 level by the period 2008-2012 (van Kooten, 2000). In order to reduce the GHGs in the atmosphere, two key activities are relevant (IPCC, 2007) first of all reduce the anthropogenic emissions of CO_2 and the second option proposes storing atmospheric C in the biosphere, and in that context, land-use systems such as agroforestry, reforestation and afforestation have considerable importance (Montagnini and Nair, 2004). Regarding the observed increase in the atmospheric concentration of CO_2 and the global climate question, forests offer two main options. First, the volume of atmospheric CO_2 may be reduced by increasing forest biomass. This may be achieved through an expansion of forests either by planting currently unforested land, or by allowing the existing forests to accumulate higher biomass. The second main approach is to utilize forest directly as a source of raw materials for energy production, usually referred to as bio-energy, which is considered a carbon neutral energy source. Use of bio-energy represents a positive contribution towards the CO_2 concentration problem if it replaces fossil fuels (van Kooten, 2000).

Forests play a prominent role in the global C cycle (Dixon *et al*., 1994; Smith *et al*., 1993). One possible strategy to reduce GHGs with great potential is to use forest to sequester CO_2. Forests are relevant to climate change issues due to its function as a reservoir of carbon. In addition, global forest ecosystems account for approximately 90% of the annual C flux between the atmosphere and terrestrial ecosystems (Dixon *et al*., 1994). Slowing worldwide soil degradation, especially impeding desertification, could conserve 0.5 to 1.5 Pg terrestrial C annually, a significant amount relative to the 3 Pg C which accumulates in the atmosphere each year (Cole *et al*., 1993). The IPCC special report on Land Use, Land-Use Change and Forestry shows that net increase in global C stocks are estimated to be 0.026 Pg (billion tons) C per year for improved agroforestry management and 0.39 Pg C per year for agroforestry-related land-use changes in 2010 (IPCC, 2007). Trees can contribute substantially to soil C sequestration (Nair *et al*., 2009).

Production of larger quantities of aboveground and belowground biomass compared to shrubs or herbs makes trees more efficient in promoting soil C sequestration (Brady and Weil, 2002). More biomass results in increased production of aboveground litter and belowground root activity. Research indicates that by adding trees in grassland or pasture systems the SOC content can be increased considerably (Reyes-Reyes *et al*., 2002; Yelenik *et al*., 2004). According to Montagnini and Nair (2004) the tree components of agroforestry systems are potential sinks of atmospheric C due to their fast growth and productivity, high and long term biomass stock, and extensive root system. Considering the beneficial effects of individual trees on the SOC, it can also be argued that the increase in tree density should ensure the increased production of aboveground and belowground biomass, which could contribute to SOC accumulation through litter and root decomposition. Therefore, the objective of this review is to assess the role of forest and soil carbon stock in climate change mitigation since both the forest and soil have a contribution to reduce the concentration of emission of carbon dioxide to the atmosphere and can reduce the green house gases effects.

2. Forest carbon stock

Carbon sequestration can be defined as the removal of CO_2 from atmosphere (source) into green plants (sink) where it can be stored indefinitely (Watson *et al*., 2000). These sinks can be above ground biomass (trees) or living biomass below the ground in soil (roots and micro organisms) or in the deeper sub-surface environments (Nair *et al*., 2009). Forests can be regarded as major sinks of mitigating atmospheric carbon dioxide (Sheikh *et al*., 2009). As a leading tree based system especially in the tropics, agroforestry, afforestation and reforestation has been suggested as one of the most appropriate land management systems for mitigating atmospheric CO_2 (Dixon, 1995; Albrecht and Kandji, 2003; Montagnini and Nair, 2004). Globally forestry has taken central stage as one of the options to mitigate climate change. It is estimated that the total global technical potential for afforestation and reforestation activities for the period 1995-2050 is between 1.1-1.6 Gt C per year of which 70% will be in the tropics (IPCC, 2000).

The average carbon stock (the above-ground vegetation plus litter) of the 4 selectively logged forests in Brazil was 150 t C ha^{-1} and 6 selectively logged forests sampled in Cameroon was averaged about 228 t C ha^{-1}. Forests sampled in Indonesia averaged 306 t C ha^{-1} for the two primary rainforest sites and 93 t C ha^{-1} for the logged-over forests (Palm *et al*., 1999). In 1990 the Austrian forests (3.9 Mha) represented a C-stock of 320 $\pm$ 42 Mt C (biomass). In the period 1961 to 1996 the Austrian forest biomass was each year an annual net C sink of between 1,014 kt C and 3,689 kt C (mean 2,527; uncertainty $\pm$ 748 kt C). It was estimated that the Austrian forest soils were also a net C sink (of about 10 % of the net C sink of the forest biomass) in this period (Weiss and Schlamadinger, 2000). Forests are land use systems with high tree population and play a major role in C sequestration. Forest ecosystems store more than 80% of all terrestrial aboveground C and more than 70% of all SOC (Six *et al*., 2002).

The results from the study in Thailand showed the range of aboveground biomass in tropical rain forest, dry evergreen forest and mixed deciduous forest as 275.46, 140.48, and 96.28 ton/ha, with calculated carbon sequestration as 137.73, 70.29, and 48.14 ton C/ha (Terakunpisut *et al*., 2007). Forest carbon stock in Indian of Kolli hills was estimated 2.74 Tg of total carbon stock of above ground biomass (Ramachandran *et al*., 2007). Vegetation carbon stock was estimated in China's forests within total area of 167.26 x 10^6 ha during 1901-2001 were from 11.5-17.4 pg C (Wang *et al*., 2007). Trees have the potential of producing larger quantities of aboveground and belowground biomass compared to shrubs or herbs. More biomass results in increased production of aboveground litter and belowground root activity and these make trees an important factor for SOC sequestration (Lemma *et al*., 2007). In India, Kumaun Central Himalaya the Oak forest site of the present investigation, the carbon stock in forest biomass ranged from 242.56-290.62 t ha^{-1} and in Pine forest site, the carbon stock varied from 81.31-115.40 t ha^{-1} (Jina *et al*., 2008). Evergreen temperate forest dominated by *Eucalyptus regnans* in the moist temperate region of the Central Highlands of Victoria, southeastern Australia has the highest known biomass carbon density in the world. Estimated that *Eucalyptus regnans* forest in the O'Shannassy Catchment of the Central Highlands (53 sites within a 13,000 ha catchment) contains an average of 1,053 t C ha^{-1} in living aboveground biomass and 1,867 t C ha^{-1} in living plus dead total biomass in stands with cohorts of trees >100 years old sampled at 13 sites (Keith *et al*., 2009). Arid and semiarid nature reserves store considerable amounts of C in aboveground biomass. Total carbon storage in the central region of Argentina ranged from 8 to 95 Mg ha^{-1}. Total carbon storage in mature woodlands ranged from 48 to 95 Mg ha^{-1}, in open and mixed woodlands from 21 to 36 Mg ha^{-1}, and in shrub lands from 8 to 19 Mg ha^{-1} (Iglesias *et al*., 2011).

Forest ecosystems can be also sources and sinks of carbon (Watson *et al*., 2000). Deforestation and burning of forests releases CO_2 to the atmosphere. Indeed, land-use change and forestry (LUCF) is responsible for about 25% of all greenhouse emissions. However, forest ecosystems could also help reduce greenhouse gas concentrations by absorbing carbon from the atmosphere through the process of photosynthesis. Of all the world's forests, tropical forests have the greatest potential to sequester carbon primarily through reforestation, agroforestry and conservation of existing forests (Brown *et al*., 1996). Forests contribute to climate change mitigation by preserving and expanding carbon stocks in the forests (including above and below-ground biomass, deadwood, litter, and soil), by producing renewable materials in order to substitute fossil fuel and materials for which production cost much fossil energy, and by storing carbon in harvested wood products (Watson *et al*., 2000).

Forests operate both as vehicles for capturing additional carbon and as carbon reservoirs. A young forest, when growing rapidly, can sequester relatively large volumes of additional carbon roughly proportional to the forest's growth in biomass. An old-growth forest acts as a reservoir, holding large volumes of carbon even if it is not experiencing net growth. Thus, a young forest holds less carbon, but it is sequestering additional carbon over time. An old forest may not be capturing any new carbon but can continue to hold large volumes of carbon as biomass over long periods of time. Managed forests offer the opportunity for influencing forest growth rates and providing for full stocking, both of which allow for more carbon sequestration. Forest management for carbon sequestration would have associated with it a relative increase in stock of carbon held captive in the forest ecosystem over what would have occurred in the absence of such focused management. Increases in the stock of carbon could be accomplished as the result of an increase in the forest biomass and as a result of an increase in forest soil carbon directly. Finally, if the stock of long-lived wood products increases, the carbon held captive in wood products stock would increase (Sedjo, 2001).

Concerning the role of tropical forests in mitigating climate change, Totten (1999) estimated that some 482 Mha would be suitable for carbon forestry in the tropics, with cumulative carbon conservation and sequestration potential ranging from 21.6 to 46.5 Gt C during the period 1995-2045. The five most significant tropical countries in this respect are Brazil, Indonesia, the Republic of Congo, India and Malaysia. What makes the carbon potential in these countries so significant is the fact that, despite deforestation, they still have large areas of natural forests left. For a number of other tropical countries, the carbon potential is mainly based on the availability of degraded lands for reforestation. Smith *et al*. (2000) conclude that the most important justification for including forests in the CDM might be the potential for forest conservation and sustainable use. Carbon trading should be seen as one more tool to promote forest conservation and sustainable use but not as a long-term solution to climate change. Consequently, the role of tropical forests in the mitigation of climate change would be to allow buying time until options that are more permanent become available. The carbon stocks estimates by IPCC (2000) for different ecosystems are listed in (Table 1) below.

Table 2: Global carbon stocks in vegetation and soil carbon pools to the depth of 1 m (IPCC, 2000)

Biome	Area (10^9 ha)	Global carbon stocks (Gt C)		
		Vegetation	Soil	Total
Tropical forests	1.76	212	216	428
Temperate forests	1.04	59	100	159
Boreal forests	1.37	88	471	559
Tropical savannas	2.25	66	264	330
Temperate grasslands	1.25	9	295	304
Deserts and semi-deserts	4.55	8	191	199
Tundra	0.95	6	121	127
Wetlands	0.35	15	225	240
Crop lands	1.60	3	128	131

The recent IPCC report estimated that the global forestry sector represents over 50% of global greenhouse mitigation potential (IPCC, 2007). Consequently, forestry became the focus of global climate change policy and is given a key position in international climate treaties. While sustainable management, planting and rehabilitation of forests can conserve or increase forest carbon stock; deforestation, degradation and poor forest management were the reverse i.e. decreasing forest carbon stock.

2.1. Litter carbon stock

Carbon is stored in trees (stem, branches, leaves and root), understory, forest litter and forest soils. The mechanism of species driven C sequestration in soil is influenced by two major activities, aboveground litter decomposition and belowground root activity (Lemma *et al*., 2007). Litter decomposition is one of the major sources of SOC and the quality of litter is very important in this regard (Mafongoya *et al*., 1998; Issac and Nair, 2006; Lemma *et al*., 2007). In systems with high plant diversity, it is likely that they would have litters with different degrees of chemical resistance, creating the possibility of longer residence of C through slower decomposition of litters from some species. Lignin in litter is highly resistant to decomposition and therefore, litter with high lignin content would have slower decomposition rate (Mafongoya *et al*., 1998). In contrast, litter with low lignin, phenols, and high N content would have faster rate of decomposition.

Litter carbon stock in China's forests was estimated 2.4 to 3.5 Pg C during 1901-2001 (Wang *et al*., 2007). Carbon stocks in surface litter in Texas increased linearly over time following woody plant encroachment, ranging from approximately 100 g C m^{-2} in woody plant stands <30 years old to >400 g C m^{-2} in stands >60 years old (Boutton *et al*., 2009).

2.2. Root carbon stock

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 below-ground 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 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).

Roots make a significant contribution to SOC (Strand *et al*., 2008). About 50% of the C fixed in photosynthesis is transported belowground and partitioned among root growth, rhizosphere respiration, and assimilation to soil organic matter (Lynch and Whipps, 1990; Nguyen, 2003). Roots help in accumulation of SOC by their decomposition and supply C to soil through the process known as rhizodeposition (Rees *et al*., 2005; Weintraub *et al*., 2007). Increased production and turnover rates of roots lead to increased SOC accumulation following root decomposition (Matamala *et al*., 2003).

The C storage in roots was estimated 3.0-4.2 Pg C in China's forests during 1901-2001(Wang *et al*., 2007). Carbon stocks in roots (0-30 cm) were significantly greater in all wooded landscape elements (1000-1500 g C m^{-2}) compared with remnant grasslands (< 400 g C m^{-2}) in Texas (Boutton *et al*., 2009).

2.3. Carbon sequestration by tree plantations

Forests store carbon by photosynthesis and carbon sequestered in forest biomass, 3.667 t of CO_2 is removed from the atmosphere. In general, plantation forests are a cost-effective means of sequestering C (Sedjo *et al*., 1995; Adams *et al*., 1999). Hence, countries that have a large forest sector are interested in C credits related to reforestation, and those with large tracts of agricultural land are interested in afforestation as a means for achieving some of their agreed upon CO_2 emissions reduction. The ability of these plantations to sequester carbon has received renewed interest, since carbon sequestration projects in developing nations could receive investments from companies and governments wishing to offset their emissions of greenhouse gases through the Kyoto Protocol's Clean Development Mechanism (Fearnside, 1999).

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 *eucalyptus* (Koskela *et al*., 2000). Various estimates are available on C sequestration rates of common plantation species of varying rotation ages (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).

Within boreal, temperate and tropical latitudes C storage in plantations forests estimated up to 25Mg/ha (Smith *et al*., 1993). The more intensive plantation systems had much higher C accumulations rates, almost reaching 10 t C ha^{-1} in oil pulpwood plantations in Indonesia (Palm *et al*., 1999). In central Panama the carbon stock of the *Anacardium excelsum* plantation is estimated to have increased from 0.53 Mg/ha in 1995 to 21.4 Mg/ha in 2000, for an average annual sequestration rate of 4.18 Mg/ha per year (Losi *et al*., 2003). Carbon density of tree plantations in Philippine forest ecosystems, the mean estimate being 59 tC ha^{-1} (Lasco and Pulhin, 2003).

2.4. Agroforestry carbon sequestration

Agroforestry is an attractive option for carbon mitigation as (i) it sequesters carbon in vegetation and soil depending on the pre-conversion vegetation and soil carbon (ii) the wood products produced serve as substitute for similar products unsustainably harvested from natural forests and (iii) it increases income to farmers (Makundi and Sathaye, 2004). 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). Realistically, C storage in plant biomass is only feasible in the perennial agroforestry systems (perennial-crop combinations, agroforests, wind-breaks), which allow full tree growth and where the woody component represents an important part of the total biomass. One comparative advantage of these systems is that sequestration does not have to end at wood harvest. C storage can continue way beyond if boles, stems or branches are processed in any form of long-lasting products (Albrecht and Kandji, 2003). 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).

In addition, the amount of biomass and 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 monoculture systems, agroforestry seems to have a unique advantage in terms of C sequestration (Montagnini and Nair, 2004). 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 (Nair *et al*., 2009). They even also suggested that agroforestry system that could realistically be implemented to mitigate the atmospheric CO_2 through terrestrial C sequestration. Estimation of C stocks all over the world indicated that, with the proper implementation of agroforestry at the global scale 1.1 to 2.2 Pg C can be removed from the atmosphere within 50 years (Albrecht and Kandji, 2003).

Agroforestry systems may also indirectly affect C sequestration by decreasing the pressure from the natural forests. It has been estimated that in the tropics one hectare of sustainable agroforestry may offset 5-20 hectares of deforestation (Dixon, 1995). Agroforestry systems had both forest and grassland nutrient cycling patterns and would produce more total annual biomass. 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 stem wood 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, sub humid, humid, and temperate regions (Schroeder, 1994). At a global scale, it has been estimated that agroforestry systems could be implemented on 585 to 1275 x 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).

Agroforestry systems can, however, be either sinks or sources of C and other green-house 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 C storage in trees and soils. 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 tree-less lands, their C sequestration value is considerably increased. (Montagnini and Nair, 2004).

Agroforestry is widely promoted in Philippines to help stabilize upland farms in sloping areas. There is a great variety of agroforestry systems ranging from alley cropping to multistory systems. Consequently, there is also a wide range of carbon stocks found in these systems (1.7-113 tC ha^{-1}) with some agroforestry farms such as alley cropping having little biomass carbon (Lasco and Pulhin, 2003). Chocolate forest of southern Cameroon store 243 Mg ha^{-1} of carbon. Plants associated with cocoa, cocoa trees, litter and roots store respectively 170, 13, 4, and 18 Mg of carbon ha^{-1}. These constituted respectively 70, 5, 2 and 7% of the total carbon stock of the plantation. High value timber trees, edible [i.e. exotic plants, Non Wood Forest Products (NWFP), Musa species and oil palm] and medicinal plants carbon stock account respectively for 30, 15 and 7% of the total amount of carbon stored by plants associated with cocoa (Sonwa *et al*., 2009).

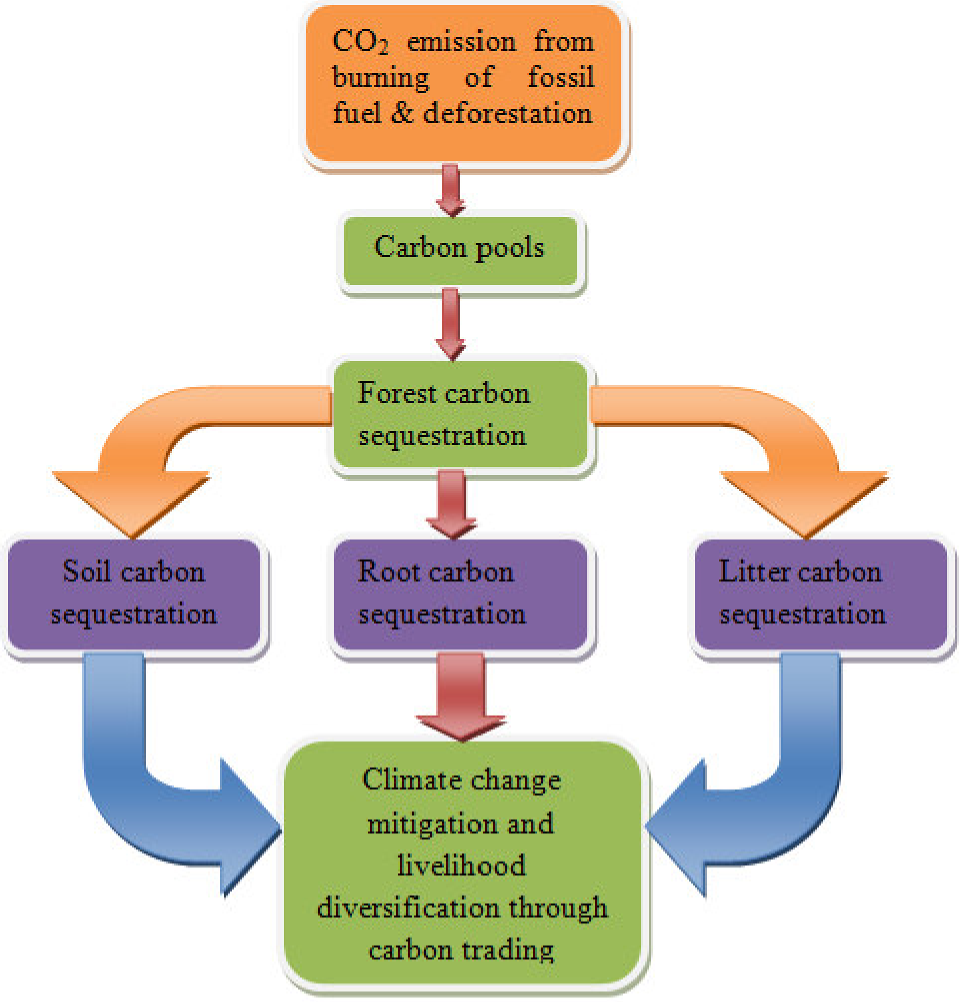

Figure 1: Conceptual frame work on the role of different carbon pools on climate change mitigation

The above frame work shows the emission of CO_2 from burning of fossil fuel and deforestation. Then, this green house gas effect reduces by different carbon pools such as forest, root, litter and soil carbon sequestration. Therefore, the overall outcome is to mitigate climate change and livelihood diversification through carbon trading.

3. Soil carbon stock

The term ''soil C sequestration'' implies removal of atmospheric CO_2 by plants and storage of fixed C as soil organic matter. The strategy is to increase SOC density in the soil, improve depth distribution of SOC and stabilize SOC within stable micro aggregates so that C is protected from microbial processes or as recalcitrant C with long turnover time. Soil C sequestration also increases SOC stocks through judicious land use and recommended management practices. The potential soil C sink capacity of managed ecosystems approximately equals the cumulative historic C loss estimated. The attainable soil C sink capacity is only 50 to 66% of the potential capacity. The strategy of soil C sequestration is cost-effective and environmentally friendly (Lal, 2004a).

Soils are the largest carbon reservoirs of the terrestrial carbon cycle 1500–1550 Gt of organic soil carbon and soil inorganic C approximate 750 Gt both to 1 m depth. About three times more carbon is contained in soils than in the world's vegetation 560 Gt and soils hold double the amount of carbon that is present in the atmosphere 720 Gt (Post *et al*., 2001; Lal, 2004a). Soils play a key role in the global carbon budget and greenhouse effect. Soils contain 3.5% of the earth's carbon reserves, compared with 1.7% in the atmosphere, 8.9% in fossil fuels, 1.0% in biota and 84.9% in the oceans (Lal, 2004a).

Forest soils are one of the major carbon sinks on earth, because of their higher organic matter content. Soils can act as sinks or as a source for carbon in the atmosphere depending on the changes happening to soil organic matter. Equilibrium between the rate of decomposition and rate of supply of organic matter is disturbed when forests are cleared and land use is changed (Lal, 2004a). Soil organic matter can also increase or decrease depending on numerous factors, including climate, vegetation type, nutrient availability, disturbance, and land use and management practice. About 40% of the total SOC stock of the global soils resides in forest ecosystem (Six, and Jastrow, 2002; Baker, 2007).

The Soil Science Society of America recognizes that C is sequestered in soils in two ways: direct and indirect (SSSA, 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.

In 1990 the Austrian forests (3.9 Mha) represented a C-stock of 463 $\pm$ 185 Mt C of soil carbon pool (Weiss and Schlamadinger, 2000). China's forest coverage from 1900 to 2001 total storage of C stocks in SOC was range from 13.3-14.3 pg C (0-30 cm) (Wang *et al*., 2007). Forest soil carbon stock in Indian of Kolli hills was estimated 3.48 Tg (Ramachandran *et al*., 2007). In Texas increases in SOC stocks at 0 to 15 cm from 1000 g C m^{-2} in grasslands to >4000 g C m^{-2} in drainage woodlands. Over the past century, SOC accumulation rates (upper 30 cm of profile) have ranged from 11.5 g C m^{-2} yr^{-1} in upland clusters to 43.2 g C m^{-2} yr^{-1} in low-lying drainage woodlands, and most of this soil C accumulation (70-90%) was stored in the upper 15 cm of the profile (Boutton *et al*., 2009).

Sequestered SOC with a relatively long turnover time were important in decreasing the rate of accumulation of atmospheric CO_2 concentration. Converting degraded soils under agriculture and other land uses into forests and perennial land use can enhance the SOC pool. The magnitude and rate of SOC sequestration with afforestation depends on climate, soil type, species and nutrient management (Lal & Follett, 2009). Global warming is a "century-scale" problem and a "global commons" issue. Soil C sequestration is a related but separate issue with its own merits of increasing productivity, improving water quality, and restoring degraded soils and ecosystems, irrespective of the global warming debate. Offsetting fossil-fuel emissions by achievable SOC potential provides multiple biophysical and societal benefits. Furthermore, soil C sequestration is a bridge across three global issues climate change, desertification, and biodiversity (Lal, 2004a).

Soils of the tropics are severe depletion and degradation, the C sink capacity of soils of the tropics may be high, but the rate of sequestration can be low. The need for enhancing soil quality is also more urgent in soils of the tropics than in soils of high latitudes because of low crop yields. Yet, the challenge is greater because of weak institutions, limited infrastructure, and predominantly resource poor agriculture systems. Soil restorative farm policies must be implemented to mitigate soil degradation trends. Soil C sequestration is a natural, cost-effective, and environment-friendly process. Once sequestered, C remains in the soil as long as restorative land use. Soil sink capacity and permanence are related to clay content and mineralogy, structural stability, landscape position, moisture and temperature regimes, and ability to form and retain stable micro aggregates (Lal, 2004a).

3.1. Agroforestry and soil carbon

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: first, direct near-term C storage (decades to centuries) in trees and soils; and second, a potential to offset immediate greenhouse gas emissions associated with deforestation and subsequent shifting cultivation. 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 increasing the C stocks in a twenty-year period, to 70 Mg C ha^{-1} (Watson *et al*., 2000). 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^{-1} yr^{-1}, with potential for sequestering 26 Tg C yr^{-1} by 2010 and 45 Tg C yr^{-1} by 2040 (1Tg = 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 impact of any agroforestry system on soil C sequestration depends largely on the amount and quality of input provided by tree and non-tree 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; Jobbagy 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). Humification (conversion of biomass into humus), aggregation (formation of organic mineral complexes as secondary particles), trans-location 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.
The soil under cocoa agroforestry store 37 Mg ha^{-1} in the chocolate forest in southern Cameroon (Sonwa *et al*., 2009). In Indonesia the soil carbon stock was about 90 Mg/ha in permanent rubber agroforests and 50 Mg/ha in more intensively managed rotational rubber plantations (Bruun *et al*., 2009).

3.2. Impact of soil degradation on climate change

Conversion of natural forests to agricultural ecosystems causes depletion of the SOC pool by as much as 60% in soils of temperate regions and 75% or more in cultivated soils of the tropics. The depletion is exacerbated when the output of C exceeds the input and when soil degradation is severe. Some soils have lost as much as 20 to 80 tons C/ha, mostly emitted into the atmosphere. Severe depletion of the SOC pool degrades soil quality, reduces biomass productivity, and adversely impacts water quality, and the depletion may be exacerbated by projected global warming (Lal, 2004b).
The SOC is preferentially removed by wind and water borne sediments through erosion processes. Some of the SOC enriched sediments are redistributed over the landscape, others are deposited in depression sites, and some are carried into the aquatic ecosystems. Although a part of the C translocated by erosion may be buried and redistributed (Smith *et al*., 2001), the rest is emitted into the atmosphere either as CO_2 by mineralization or as CH_4 by methanogenesis. Erosion induced deposition and burial may be 0.4 to 0.6 Gt C per year compared with perhaps 0.8 to 1.2 Gt C per year emitted into the atmosphere (Lal, 2003). Quantification of emission versus burial of C is a high priority. Yet, an effective soil erosion control is essential to sustainable use of agricultural soils and improving environment quality.
Global hotspots of soil degradation with the practice of complete residue removal for fodder and fuel are a norm in south Asia and Africa. Thus, depletion of SOC stock from the root zone has adversely affected the soil productivity and environmental quality of these regions (Lal, 2004b). Soil degradation decreases biomass productivity, reduces the quantity and quality of biomass returned to the soil, and as a consequence decreases the SOC pool. Among all soil degradative processes, accelerated soil erosion has the most severe impact on the SOC pool. Several experiments have shown on-site depletion of the SOC pool by accelerated erosion (De Jong and Kachanoski, 1988). However, on-site depletion does not necessarily imply emission of GHGs into the atmosphere. Some of the SOC redistributed over the landscape by erosion and carried into the aquatic ecosystems and depression sites may be mineralized and released as CO_2; while the other is buried and sequestered (Smith *et al*., 2001). Accelerated soil erosion affects the C pool and fluxes because of breakdown of soil aggregates, exposure of C to climatic elements, mineralization of organic matter in disrupted aggregates and redistributed soil, transport of sediments rich in SOC down slope into protected areas of the landscape, and sequestration of C with sediments in depositional sites and aquatic ecosystems. It is estimated that about 1.14 Pg of C are annually emitted into the atmosphere through erosion induced processes (Lal, 2001).
Anthropogenic process exacerbates the emission of CO_2 from soil caused by decomposition of SOM or soil respiration (Schlesinger, 2000). The emissions are accelerated by agricultural activities including tropical deforestation and biomass burning, plowing, drainage of wetlands and shifting cultivation (Tiessen *et al*., 2001). Conversion of natural forests to agricultural ecosystems increases maximum soil temperature and decreases soil moisture storage in the root zone, especially in drained agricultural soils. Thus, land use history has a strong impact on the SOC pool. Biomass burning is an important management tool, especially in agricultural ecosystems of the tropics. The process emits numerous gases immediately but also leaves charcoal as a residual material. Charcoal, produced by incomplete combustion, is a passive component, and may constitute up to 35% of the total SOC pool in fire prone ecosystems (Skjemstad *et al*., 2002). As the SOC pool declines due to cultivation and soil degradation, the more resistant charcoal fraction increases as a portion of the total C pool (Skjemstad *et al*., 2001). Knowledge of the impact of erosion processes on SOC dynamics, and understanding the fate of C translocated by erosion processes is crucial to assessing the role of erosion on emissions of GHGs into the atmosphere. Therefore, adoption of conservation effective farming systems and judicious management of soil erosion are crucial to maintaining and enhancing the SOC pool (Lal, 2004b).

4. Societal values and benefits of carbon stocks

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. The Clean Development Mechanism (CDM) was proposed for the particular purpose of enhancing cooperation between developed and developing countries in mitigating climate change, and to allow industrialized countries to accrue certified emission reductions in return for their financing activities that limit emissions in developing countries. Both developed and developing countries may derive benefits from the CDM; developed countries can implement their emission reductions at lower costs, and developing countries receive more capital for environmentally sound investments that contribute to sustainable development (Koskela *et al*., 2000). This offers an economic opportunity for subsistence farmers in developing countries, the major practitioners of agroforestry, afforestation and reforestation for selling the C sequestered 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).

Some tropical countries have been very active on this issue of carbon trading. In 1997, Costa Rica became the first country in the world to sell carbon stock of its forests by issuing "Certified Tradable Offsets", based on a forest carbon sequestration program with performance guarantees, carbon pools and a third party certification. Other stakeholders have also taken a pro-active role. In 1998, the state government of New South Wales, Australia, signed the country's first carbon offset programme, including carbon credits to be marketed worldwide. The World Bank is also launching the Prototype Carbon Fund with USD 110-120 million (operational until 2012) to finance country projects that help to mitigate climate change (Koskela *et al*., 2000).

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. According to a FAO report, in 2000 green house 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. 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 (Nair *et al*., 2009).

Global-scale assessments suggest that a high price for carbon (e.g., US$ 75 t^{-1} of C) would lead to substantial amounts of carbon sequestered through forestation, whereas a lower price for carbon would lead to substantially less carbon sequestration. The IPCC synthesized data from several studies and estimated that by 2030 global afforestation could sequester between 1.6 and 4.0 Gt $year^{-1}$ of C at carbon prices ranging from US$ 25 to 100 t^{-1} of C. Altering forest management practices to increase carbon density within forest stands by maintaining partial forest cover, minimizing loss of dead organic matter, avoiding slash burning, planting immediately after harvest, fertilizing, or lengthening harvest rotation could sequester even more carbon: 2.0–5.8 Gt $year^{-1}$ of C given prices ranging from US$ 25 to 100 t^{-1} of C (Conant, 2011). Nearly 80% of estimated potential carbon sequestration benefits in developing countries are accrued at carbon prices below US$ 50 t^{-1} of C, whereas in developed countries more than 40% of the carbon benefits accrue at carbon prices between US$ 50 and 100 t^{-1} of C (IPCC, 2007). For the concept of SOC credits trading to become routine as a part of the solution to mitigate climate change, the ability to measure short term (3 to 5 year) changes in SOC pool exists, but the price of soil C must be based on both on-site and off-site societal benefits. Increase in SOC stock increases crop yield even in high input commercial agriculture, but especially in soils where it has been depleted (Lal, 2004a).

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 Northern 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%.

5. Ethiopian forest resources and carbon sequestration potential

At a national level, forest inventories, woody biomass assessments, agricultural surveys, land registry information and scientific research can prove useful data for acquisition of forest carbon accounting. In this context World Bank-funded Woody Biomass Inventory and Strategic Planning Project (WBISPP) data is relevant source of information for Ethiopian forest carbon accounting. Thus, the national carbon stock presented in the table below was estimated based on WBISPP data (Moges *et al*., 2010). Generally, National-level forest biomass carbon stocks estimates based on forest inventory according (Brown, 1997; Achard *et al*., 2004) Ethiopia have a potential of forest carbon stock about 168 Mt C. (Gibbs and Brown, 2007) also estimates the potential of Ethiopia forest carbon stock at national level 867 Mt C.

Table 3: Mean aboveground carbon density and total carbon stocks in major forest categories of Ethiopia (Moges *et al*., 2010)

Forest Category	Free-Bole Biomass (tons ha^{-1}) (A)	BEF (tons ha^{-1}) (B)	AGB C (tons ha^{-1}) (A*B*0.5)	Area (Million ha)	Total C Stock (Million Tons)
High forest	131.5	2.74	106.68	4.07	434.19
Woodland	21.0	6.9	42.75	29.55	1,263.13
Plantation	178.8	2.33	123.0	0.50	61.52
Lowland bamboo	26.0	6.19	47.5	1.07	50.80
Highland bamboo	83.0	3.44	84.23	0.03	2.53
Shrub land	14.9	8.20	36.04	26.40	951.54
Total C					2,763.70

*AGB = Aboveground biomass and BEF = Biomass expansion factor

In the above table there is high carbon stock in the woodlands than other forest categories; this is because there is higher area coverage i.e. 29.55 Mha in the woodlands of Ethiopia. The national carbon stocks shown here largely agree with 2.5 billion tons in 2005 reported by Sisay *et al.* (2009). Brown (1997) reported a carbon density of 101 tons ha^{-1} for high forests in Ethiopia, and agrees well with the estimate presented here. However, some case studies show even higher carbon density values of close 200 tons ha^{-1} than the estimates based on WBISPP for high forests in Bale Mountains (Tadesse, 2010). The discrepancy is due to the different methods and tools applied, regional variability in soil, topography, and forest type and the uncertainties associated with the methods used. Therefore, enhancing the natural processes that remove CO_2 from the atmosphere is thought to be one of the most useful methods of mitigating the atmospheric levels of CO_2.

6. Conclusion and Recommendation

6.1. Conclusion

The value of forests in sequestering carbon and reducing carbon dioxide emission to the atmosphere is being recognized increasingly the world wide. 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 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 addition, sequestration of atmospheric carbon dioxide is an effective strategy for mitigating and reducing global warming; soil is considered to be a major pool of carbon in the biosphere. Any accumulation of SOM on the land would contribute to a net sink for CO_2 that could offset emissions of CO_2 from fossil fuel combustion and contribute to the Kyoto protocol. Soil carbon sequestration, has positive impacts on environmental services, including improvement in soil quality, increase biomass productivity, purification of water and increase in biodiversity and also, soil carbon sequestration, both through increases in organic and inorganic components, offsets fossil fuel emissions and mitigates climate change due to atmospheric enrichment of CO_2.

As the concept of 'carbon credits' being paid by fossil fuel emitters to projects that sequester or reduce carbon outputs are very important in mitigation of climate change. 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. 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 and it will be an environmental benefit to the global community at large as well.

6.2. Recommendation

❖ Awareness creation of the importance and the role of global forest resources in climate change mitigation should be international commitment to take adequate action on protection of the remaining forest resources.

- Deforestation avoidance and rehabilitation of degraded land through afforestation and reforestation activities should have prior action for combating global warming.
- Governmental and NGOs organization should support financial and technical requirement in plantation forest activities to increase the forest coverage for the purpose of carbon sequestration and mitigate the climate change.
- Carbon sequestration through forest activity has considerable potential to generate low-cost sequestration alternatives, especially in certain developing countries. Therefore, care must be taken to recognize the true opportunity costs of alternative land uses and to identify that, in many cases, social values other than carbon sequestration are also involved, and trade-off is necessary.

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