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Carbon sequestration in agroforestry systems

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Viewpoint

Carbon sequestration in agroforestry systems

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Abstract

Management of trees in agroecosystems such as agroforestry, ethnoforests, and trees outside forests can mitigate green house gas (GHG) emissions under the Kyoto Protocol. Agroforestry systems are a better climate change mitigation option than oceanic, and other terrestrial options because of the secondary environmental benefits such as helping to attain food security and secure land tenure in developing countries, increasing farm income, restoring and maintaining above-ground and below-ground biodiversity, corridors between protected forests, as CH_4 sinks, maintaining watershed hydrology, and soil conservation. Agroforestry also mitigates the demand for wood and reduces pressure on natural forests. Promoting woodcarving industry facilitates long-term locking-up of carbon in carved wood and new sequestration through intensified tree growing. By making use of local knowledge, equity, livelihood security, trade and industry, can be supported. There is need to support development of suitable policies, assisted by robust country-wide scientific studies aimed at better understanding the potential of agroforestry and ethnoforestry for climate change mitigation and human well-being.

Keywords: Agroecosystems; Climate change mitigation; Carbon sink; Ethnoforestry; Equity of knowledge; Secondary environmental benefits

1. Introduction

Deforestation, averaging over 13 million ha per year during 1980–1995 (FAO, 1997), was responsible for 20 (Killmann, 2001) to 25% of global, anthropogenic green house gas (GHG) emissions during the 1990s, with the majority of deforestation occurring in tropical regions. Management of trees in agroecosystems such as agroforestry, ethnoforests, trees outside forests, and other anthropogenically-managed forests could be immediately implemented to mitigate GHG emissions.

Land management actions that enhance the uptake of CO_2 or reduce its emissions have the potential to remove a significant amount of CO_2 from the atmosphere over the next three decades (Noble

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and Scholes, 2001), and even beyond if the trees are harvested, accompanied by regeneration of the area, and sequestered carbon is locked through non-destructive (non-CO_2 emitting) use of such wood. This is important because after 30–50 years many species of trees attain the rotation age. Current annual increment in such cases is either almost nil or no longer enough to provide sufficient mitigation benefits.

2. The Kyoto Protocol, CDM and LULUCF

Carbon sequestration by growing trees is a comparatively cost-effective option for reducing the net emissions, that has additional social, economic and ecological benefits. Efforts on carbon sequestration can also buy time to develop appropriate technologies without hampering the progress during this period.

Now that LULUCF has been accepted as a credit-earning climate change mitigation option for the first 5-year commitment period of the Kyoto Protocol (2008–2012, UNFCCC, 2001a,b), it may be useful for nations to invest in actions that not only have potential to sequester carbon but also provide additional products and services to poor people in developing countries, help reduce the rate of deforestation, and contribute to sustainability. Agroforestry and management of trees outside forests are mechanisms that could be immediately implemented.

This is particularly important as the CDM will allow afforestation and reforestation projects but exclude all other project types, including those addressing tropical deforestation. This may provide some crediting opportunities for agroforestry projects—depending upon how the rules are written. It has been suggested that Annex I countries may potentially claim a net carbon offset as high as 0.2 Gt C per year by carrying out afforestation, reforestation and deforestation activities. However, to come up with an effective long-term climate mitigation regime, it may be necessary to craft mechanism for the enhancement of sinks coupled with the emission reduction. Activities related to sink enhancement should not be too large to eliminate the benefits of direct emissions reductions, nor too small to contribute significantly to mitigation (Yamagata and Alexandrov, 2001). However, if other benefits, such as those suggested here, are associated with carbon sink activities sink enhancement may prove to be more useful than currently understood.

3. The potential of agroforestry for carbon sequestration

Agroforestry systems include all forms of trees-growing in agroecosystems. Trees in agroforestry systems are an important resource providing products and services to society. For example, India is estimated to have between 14,224 million (Ravindranath and Hall, 1995) and 24,602 million (Prasad et al., 2000) trees outside forests, spread over an equivalent area of 17 million ha (GOI, 1999) supplying 49% of the 201 million tonnes of fuelwood and 48% of the 64 million m^3 of timber consumed annually by the country (Rai and Chakrabarti, 2001). This resource also serves as a source of income and well-being to those who practice tree-growing.

Agroforestry systems include trees in farms, community forestry and a variety of local forest management and ethnoforestry practices where sometimes trees may be retained for up to 300 years (Pandey, 1996, 1998). Duration of the retention of a carbon sink is an important consideration for the design of strategies to manage carbon storage (Fung, 2000). Agroforestry encompasses a wide variety of practices, including trees on farm boundaries, trees grown in close association with village rainwater collection ponds, crop-fallow rotations, and a variety of agroforests, silvopastoral systems, and trees in urban settlements (Huxley, 1999; Pandey, 2001). Agroforestry is practiced globally but it is widespread in the tropics. Approximately 1.2 billion people (20% of the world's population) depend directly on agroforestry products and services in developing countries (Leakey and Sanchez, 1997). The practitioners are often the poor people living in rural areas. We need to find innovative mechanisms that have the potential to help the poor locally and contribute to climate change mitigation globally.

Agroforestry practices have the potential to store carbon and remove atmospheric carbon dioxide through enhanced growth of trees and shrubs. It has been demonstrated to be a promising mechanism of carbon sequestration in India (Singh et al., 2000), Mexico (De Jong et al., 1997), the former Soviet Union (Kolchugina and Vinson, 1996), Canada (Stinson and Freedman, 2001) and sub-Saharan Africa (Unruh et al., 1993) among others. It also has strong implications for sustainable development because of the interconnection with food production, rural poverty, and environmental degradation. Agroforestry may provide a viable combination of carbon storage with minimal effects on the food production. Policies that promote agroforestry will help to increase carbon sequestration in agroecosystems, thereby providing climate change mitigation benefits (Watson et al., 2000).

Assessments of national and global terrestrial CO_2 sinks indicate beneficial attributes of agroforestry systems such as direct near-term C storage (decades to centuries) in trees and soils, and, the potential to offset immediate GHG emissions associated with deforestation and subsequent shifting agriculture.

For example, agricultural activities occurring on approximately half of the land in the contiguous US provide much of the opportunity to store carbon through afforestation on farms and ranches (NAC, 2000). Carbon sequestration in Indian agroforests varies from 19.56 t C ha^{-1} per year in north Indian state of UP (Singh et al., 2000) to a carbon pool of 23.46–47.36 t C ha^{-1} in tree-bearing arid agroecosystems of Rajasthan. The Cacao agroforests in humid parts of west and central Africa hold up to 62% of carbon stocks found in primary forests (Duguma et al., 2001).

Similarly, in Mexico an estimated 4.5×10^6 ha are available for farm forestry, and up to 6.1×10^6 ha could be saved from deforestation by making shifting agriculture more productive and sustainable. Various farm forestry systems are viable, including live fences, coffee with shade trees, plantations, tree enrichment of fallows, and taungya, with a carbon sequestration potential varying from 17.6 to 176.3 Mg C ha^{-1} (Mg $= 10^6$ g, De Jong et al., 1997).

Average sequestration potential in agroforestry has been estimated to be 25 t C ha^{-1} over 96 million ha of land in India, and 6–15 t C ha^{-1} over 75.9 million ha in China (Sathaye and Ravindranath, 1998). Estimates for global potential for mitigation action through improved management have been projected to be between 400 Mha in agroforestry and 1300 Mha in croplands (Watson et al., 2000) to a gross 1895 million ha in Asia, Africa and Latin America (Houghton et al., 1993).

Carbon sequestration rates have been found encouraging in secondary forest fallows (5–9 t C ha^{-1} per year); complex agroforests (2–4 t C ha^{-1} per year); simple agroforests with one dominant species such as oil palm, rubber, or Albizia falcataria (7–9 t C ha^{-1} per year). The lower carbon sequestration rate of some agroforestry systems in relation to natural secondary succession is partly because the families use some products. Thus, tree-bearing agricultural land-use systems sequester carbon at the higher rates than those containing only annual crops, pastures, or grasslands (Table 1). The transformation of low productivity croplands to sequential agroforestry is estimated to triple system carbon stocks in 20 years (Sanchez, 2000).

In general, agroforestry can sequester carbon at time-averaged rates of 0.2–3.1 t C ha^{-1} per year (Watson et al., 2000). In temperate areas, the potential carbon storage with agroforestry ranges from 15 to 198 t C ha^{-1} (Dixon et al., 1994), with a modal value of 34 t C ha^{-1} (Watson et al., 2000; Dixon et al.,

Table 1
Carbon uptake rates of agroforestry systems

Land-use practice	Carbon uptake rates (t C ha^{-1} per year)			Duration (year)	Carbon stocks (time-averaged, t C ha^{-1})			Differences in modal carbon stocks (time-averaged, t C ha^{-1})	
	Low	Modal	High		Low	Modal	High	Forest	Pasture/grasslands
Crops/bush fallow	2	3	4	4	32	34	36	−196	+5
Tall secondary forest fallow	5	7	9	23	95	112	142	−118	+83
Complex agroforest	2	3	4	25–40	65	85	118	−145	+56
Simple agroforest	5	7	9	15	65	74	92	−156	+61

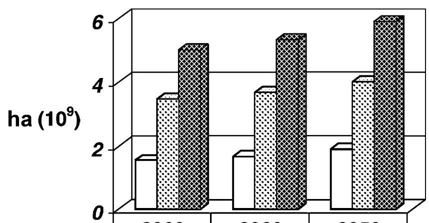
Source: modified after (Watson et al., 2000) and references cited therein.

1993). Estimates indicate that agroforestry can sequester 7 Gt C between 1995 and 2050 globally at a total cost of US\$ 30 × 10^9 (Sathaye and Ravindranath, 1998), but these estimates on potential are conservative in view of the area, observed rates and gaps in our understanding. Better estimates will require country-specific assessments.

However, a global synthesis can be projected based on the recent forecasts on agricultural expansion (Tilman et al., 2001). By the year 2050 land use is projected to reach 529 × 10^6 ha as irrigated agriculture, 1.89 × 10^9 as croplands and 4.01 × 10^9 as pastures. If the past trend continue, global croplands may increase by a net of 3.5 × 10^8 ha and pastures by 5.4 × 10^8 ha by the year 2050. By then, the combined total represents an 18% larger average global agricultural land base than at present (Fig. 1).

We can guide our efforts simultaneously for saving the biodiversity and generating ecosystem services such as carbon sequestration. In addition to agroforestry practices in the aforementioned lands, Tilman et al. (2001) have suggested that 1.4 × 10^8 ha projected removal of land from agriculture in developed nations could be restored to conserve biodiversity, yield water, and provide carbon sequestration benefits. Harnessing the potential of agroforestry systems for carbon sequestration is particularly important under such circumstances.

Agroforestry offers a cost-effective mitigation option available in developing countries, such as India and China, which have large potential to sequester carbon and provide products and services to the



	2000	2020	2050
Croplands	1.54	1.66	1.89
Pasturelands	3.47	3.67	4.01
Total	5.01	5.33	5.9

Fig. 1. Potential availability of area for tree-growing in croplands and pasturelands in the year 2000, 2020 and 2050 (data source: Tilman et al., 2001).

people. The estimated cost of mitigation via agroforestry ranges from US\$ 1.6 $(t\,C)^{-1}$ in India to US\$ 16.3 $(t\,C)^{-1}$ in China. It must be noted that these estimates do not include the opportunity costs of the land, costs of continuous management of a complex system, rising wage rates in the tropics, etc. Taking into consideration all these factors the private cost of carbon sequestration may be as high US\$ 100 $(t\,C)^{-1}$. However, compared to energy alternative (renewable energy, energy saving and efficiency, and fuel switch) tree-growing is still a cost-effective option because of the secondary social and environmental benefits. Costs vary within the forestry sector for different region—costliest in developed countries and least costly in developing countries.

4. Agroforestry as a better GHG mitigation option than oceanic, and other terrestrial options

If the oceans were fertilized by adding large quantities of iron, the consequential increase in phytoplankton bloom could remove large amounts of CO_2 from the atmosphere (Frost, 1996). However, efforts in that direction, either through iron fertilization programmes (Chisholm et al., 2001), or through CO_2 injection into the deep sea may not be viable. It may affect the sea biota in ways currently not known to science. Analysis on how such deep-sea disposal of CO_2 may affect organisms living in these environments caution that even small perturbations in CO_2 or pH may have significant consequences for deep-sea ecosystems and for global biogeochemical cycles (Seibel and Walsh, 2001). Iron fertilization would be extremely difficult to validate and would significantly alter oceanic food webs and biogeochemical cycles (Chisholm et al., 2001). Pending the detailed studies in this aspect, agroforestry emerges as an important mitigation option.

Carbon sequestration benefits can be maximized further by linking the bioenergy options with CDM (Hall et al., 1991; Schlamadinger et al., 2001). Activities that reduce dependence on fossil fuels through product substitution shall be an important component of the Kyoto Protocol. LULUCF activities can yield more biomass and thereby reduce dependence on fossil fuels. Biomass from agroforestry systems can be used as a renewable substitute to fossil fuels and help in generating energy. Such activities can also supply wood to manufacture products that can substitute for other products that have energy-intensive production processes.

It has been suggested that much of the missing sink of carbon has gone in the organic matter of forests that is not often reported in forest inventories (Wofsy, 2001). For example, more than 75% of the carbon sequestered in the United States is found in organic matter that is not inventoried (Pacala et al., 2001). Agroforestry systems could be the missing sinks.

Some of this disappeared carbon may also have gone into tree-bearing farmlands—globally. Support for this inference may be seen in recent findings (Fang et al., 2001) that Asia seems to emerge as "another place to look for forest carbon sinks" (Wofsy, 2001).

5. The secondary social and environmental benefits

The secondary benefits of agroforestry include helping to attain food security and secure land tenure in developing countries, increasing farm income, restoring and maintaining above-ground and below-ground biodiversity (including corridors between protected forests), serving as CH_4 sinks, maintaining watershed hydrology, and decreasing soil erosion. Agroforestry systems, thus, can be better than alternative land-use options at the global, regional, watershed, and farm scales because they optimize farm production, poverty alleviation, and environmental conservation (Watson et al., 2000).

Agroforestry can also mitigate the demand of wood globally thereby reducing pressure on unmanaged old-growth or mature secondary forests. Intensive harvest of mature forests and/or conversion of mature forests to younger forest stands typically leads to significant carbon losses.

Agroforestry systems have less biodiversity compared to forests, but they can also act as an effective buffer to deforestation and conversion of forestlands to other land uses, which threaten forests (Noble and Dirzo, 1997). Trees in agroecosystems also support threatened cavity nesting birds, and offer forage and habitat to many species of birds (Pandey, 1991; Pandey and Mohan, 1993). Agroforestry also leads to a more diversified and sustainable production system than many treeless farming alternatives and provides increased social, economic, and environmental benefits for land users at all levels (Pandey, 1993; Watson et al., 2000).

If sustainable agriculture in developing countries can be made more beneficial to farmers it can contribute to future food security and poverty reduction as well. For instance, a feasibility study (De Jong et al., 1995) found that net income benefits due to converting fields from maize cultivation to farm forestry in Mexico ranged from US$ 500 to 1000 ha^{-1} depending upon the value assigned to the sequestered carbon. In this area, estimated amount of carbon sequestered ranged from 46.7 to 236.7 t C ha^{-1}.

Food security and biodiversity conservation can be enhanced due to greater income through intensified agroforestry practices as well as enhancement in the yield of products and services from biodiversity-rich agroecosystems. For example, approximately 4 million ha of agroforests in Indonesia not only yield rubber valued at US$ 1.9 billion but may also contain 250–300 species of plants (Leakey, 1999; Mc Neely and Scherr, 2001).

Three types of traditional agroforestry systems in San Jose—the milpa (a slash-and-burn agriculture system), cacao (*Theobroma cacao*) cultivation under shade trees, and the homegarden—almost entirely meet a family's requirements for food and wood, and generate at least 62% of family income in Maya community of Belize (Levasseur and Olivier, 2000). A survey of 237 ha of pastures in Costa Rica, found 5583 trees of 190 species (mean density of 25 trees ha^{-1}). Primary forest trees accounted for 57% of all of the species and 33% of tree individuals. Over 90% of the species are known to provide food for forest birds and other animals. In addition, many of the species are important locally for humans as sources of timber (37%), firewood (36%) or fence posts (20%). Farmers mentioned 19 reasons for leaving trees in pastures including shade for cattle, timber, fruits for birds and fence posts, etc. (Harvey and Haber, 1999).

Agroforestry systems, in some cases, support as high as 50–80% of biodiversity of comparable natural systems (Noble and Dirzo, 1997), and also act as buffers to parks and protected areas. The landscape mosaics created by the interplay of rainwater harvesting and consequent growth of vegetation in agroforestry systems (Pandey, 2001) acts as corridor providing avenues for dispersal and gene flow in wildlife population (Hale et al., 2001).

A survey of the avifauna in Costa Rica (Daily et al., 2001) involving 8 forest fragments (0.3–25 ha) and 13 open habitat sites (1.0 ha each) in the agricultural landscape found that out of the 272 locally available bird species, 149 (55%) occurred in forest habitats only. Of the remaining 123 species, 60 (22% of the total) occurred both in forest and open habitats. Sixty-three species (23%) occurred in open habitats only including three non-native species (1%). Thus, a large proportion of the native bird fauna occurs in agricultural landscape. Countryside habitats may buy time for the conservation of some species, and may even sustain a moderate fraction of the native biota.

Agroforestry systems create landscape structure that is important for the biological pest control. For example, population of rape pollen beetle (*Meligethes aeneus*), an important pest on oilseed rape (*Brassica napus*), had increased mortality resulting from parasitism due to presence of old field margin strips along rape fields. Presence of adjacent, large, old fallow habitats had an even greater effect. In structurally complex landscapes, parasitism was higher and crop damage was lower than in simple landscapes with a high percentage of agricultural use (Thies and Tscharntke, 2000). Agroforestry systems produce a diverse landscape structure that supports populations of natural enemies of the agricultural pests. This helps in the biological pest control. CAST (1999) estimates that natural enemy populations that live in natural and semi-natural areas adjacent to farmlands control more than 90% of potential crop insect pests. The estimated cost of substitution of biological pest control service to pesticides may be worth US$ 54 billion per year.

In tropics, Dixon (1995) estimates that 1 ha of sustainable agroforestry can provide goods and services which potentially offset 5–20 ha of deforestation. Additionally, 1400 million ha of croplands and agroecosystems may be providing ecosystem services worth US$ 92 ha^{-1} per year as pollination, biological control, and food production amounting to total US$ 128×10^9 per year at the 1994 prices (Costanza et al., 1997). Agroecosystems are also an essential component of developmental intervention for rural livelihood in developing countries (Mathur and Pandey, 1994; Pandey, 1996; Ravindran and Thomas, 2000).

Wood-carving industry is emerging as an important source of income to local artisans worldwide. Promotion of species used in wood-carving industry has three advantages: it facilitates long-term locking-up of carbon in carved wood coupled with creation of new sequestration potential through intensified tree-growing; supports local knowledge on wood-carving and tree-growing, therefore, strengthens livelihood security, and helps trade and industry. For example, Rajasthan is fast emerging as major center of wood-carving export industry in India due to existence of the local knowledge and traditional skills and a continuous history of patronage to the artistic wood-craft by the erstwhile rulers since 8th century A.D. These processes are expected to enhance the ability of developing countries to participate in the growing global economy.

By acknowledging and making use of peoples' knowledge on tree-growing we shall also promote the principle of equity of knowledge (Pandey, 1998). Equity of knowledge between local and formal sciences results in empowerment, security and opportunity for local people. If the state and formal institutions incorporate people's knowledge into the resource management decisions, it reduces the social barriers to participation and enhances the capacity of the local people to make choices to solve the problem. Traditional societies have accumulated a wealth of local knowledge, transmitted from generation to generation. Experience has taught them how the water, trees, and other natural resources should be used and managed to last a long time.

Equity of knowledge can also enhance the security in its broadest sense. By capitalizing on the collective wisdom of formal and traditional sciences, we shall be able to help people address the problem of global warming as well as to manage the risks they face because of the destruction of the local resources. Collective wisdom can help in the planning and implementation of suitable programmes for managing the agroforests. This results in ecological, economic, and social security.

Equity of knowledge also provides opportunity for local people to participate in the management of local affairs with global implications. It also provides the opportunity for self-determination. The process of acquisition, transmission, integration, and field application of indigenous knowledge on tree-growing with formal science promises to enhance the productivity and efficiency of managing the natural resource.

6. Implications for policy and practice

This discussion suggests that in order to use agroforestry systems as an important climate change mitigation option, we will have to aim research, policy and practice towards achieving five distinct goals:

1. conservation of the existing agroforestry carbon pool (ACP) either by deferred harvest, or harvest followed by commensurate regeneration;
2. enhancing the size of the ACP by growing more trees in agroecosystems and bringing additional areas under farming systems that combine agriculture and tree-growing;
3. designing context-specific silvicultural and farming systems for multiple land-use management to optimize food production, carbon sequestration, biodiversity conservation, and other ecosystem services under socially and economically just circumstances;
4. a continuous cycle of regeneration–harvest–regeneration as well as locking the wood in non-emitting use to further enhance the value of ACP;
5. linking the market mechanisms to multiple products and services from agroforestry systems to support local economy and poverty reduction.

Negotiations will decide modalities for afforestation and reforestation projects under Article 12 of the Kyoto Protocol during the first commitment period taking into account the issues of non-permanence, additionality, leakage, uncertainties, and socio-economic and environmental impacts (UNFCCC, 2001a,b). Adoption of rules and modalities should make sure specifically to provide crediting for reforestation/afforestation projects that create agroforestry systems, and decide the modalities for the project implementation.

The project implementation modality and resource transfer mechanisms are yet to be clear. Implementation of agroforestry projects for carbon sequestration will necessitate monitoring and evaluation to meet the criteria of the Kyoto Protocol. The monitoring issues will include quantum of sequestered carbon, additionality, in terms of demonstrated GHG mitigation additional to the 'business-as-usual' scenario, externalities or unwanted side effects, and capacity to implement project's activities (Costa et al., 2000). The scientific methodology for calculating the carbon offsets and the methodology for data collection and statistical analysis will need standardization. The amount of carbon offsets quantified will require adjustment to take into account the uncertainty associated with the methodology and data used. All these issues will require putting in place the credible monitoring systems.

In the negotiations it will also be useful to address the difficulties related to leaky sinks (Andersson and Richards, 2001) related to agroforestry systems which is particularly challenging due to the problems related to self-interest, differing information, and multiplicity of project activities (Richards and Andersson, 2001). Experiences of demonstration projects (De Jong et al., 1997) can be useful in crafting such rules.

Asia, South America and Africa offer opportunity for carbon sequestration through agroforestry and local forest management practices. The obvious next step is clear policies and programmes globally to sustain existing agroforest carbon pool, extension and productivity enhancement of existing pool, establishment of new pool, and long-term locking-up of carbon in wood products. There is a need to support local forest management practices through development of suitable policies, assisted by robust country-wide scientific studies aimed at a better understanding about the potential of agroforests for climate change mitigation and human well-being.

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