

# Soil Carbon Sequestration under Agroforestry Systems

K. SRINIVAS

*Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad – 500 059*

## Soil C sequestration

Carbon sequestration is essentially the process of transforming carbon in the air (carbon dioxide or CO<sub>2</sub>) into stored soil carbon. Carbon dioxide is taken up by plants through the process of photosynthesis and incorporated into living plant matter. As the plants die, the carbon-based leaves, stems and roots decay in the soil and become soil organic matter. This is the basic process called carbon sequestration. Although most carbon enters ecosystems via leaves, and carbon accumulation is most obvious when it occurs in aboveground biomass, more than half of the assimilated carbon is eventually transported below ground via root growth and turnover, exudation of organic substances from roots, and incorporation of fallen dead leaves and wood (litter) into soil. Soils contain the major proportion of the total ecosystem carbon stock in all ecosystems.

As with total ecosystem carbon stocks, soils tend toward "equilibrium" carbon levels. With a change in carbon input and/or decomposition rates, soil carbon stocks change. This change is most rapid for the active fraction, including structural carbon (i.e., cellulose and hemicellulose) and metabolic carbon components (i.e., proteins, lipids, starches, nucleic acids); the slow fraction (i.e., microbial walls and metabolic components protected by soil clays and aggregates); and the passive soil carbon (i.e., clay-protected humics).

Carbon inputs to soil are determined by the amount and distribution of primary production, the life cycle of the vegetation, and exogenous organic matter additions (e.g., composts, manure). Thus, practices that increase net primary production (NPP) and/or return a greater portion of plant materials to the soil have the potential to increase soil carbon stocks. Organic matter decomposition is influenced by numerous physical, chemical, and biological factors that control the activity of microorganisms and soil fauna (Swift *et al.*, 1979). These factors include the abiotic environment (temperature, water, aeration, pH, mineral nutrients), plant residue quality (i.e., C:N ratio and lignin content), soil texture and mineralogy, and soil disturbance (tillage, traffic, logging, grazing, etc.). The root system, depth distribution, and chemical characteristics of the root biomass also play significant roles in SOC dynamics (Gale and Cambardella, 2000). Practices that reduce the decomposition rate by altering these physical, chemical, or biological controls also lead to carbon storage.

## Factors leading to aggradation of soil carbon

Net accumulation of soil carbon occurs through practices that increase the amount of plant-fixed carbon that is returned to soils in the form of residues (i.e., leaves, stems, and branches) and especially roots (Balesdent and Balabane, 1996) and/or reduce the specific rate of decomposition. Strategies to increase productivity-including plant selection and breeding, plant protection, irrigation, and reducing the frequency of bare fallowing-contribute to higher

carbon inputs. In addition, reducing the removal or burning of biomass (in crop, forest, and grazing lands) increases the portion of total productivity that is returned to soil.

Specific rates of decomposition (i.e., CO<sub>2</sub> emissions per unit soil carbon per unit time) can be reduced by creating a less favorable environment for decomposer organisms. The pores and surfaces of the soil are the habitat for decomposer organisms. Soil structure (i.e., the arrangement and stability of primary particles, aggregates, and pores within the soil) controls that habitat and therefore has a large effect on decomposition. Soil structure affects aeration and moisture dynamics and is itself affected by tillage, other disturbances, rooting habit, soil texture, clay mineralogy, and base cation status (Lal, 2000). Maintaining surface mulches, reducing incorporation of residues, and enhancing plant/forest canopy coverage can reduce soil surface temperatures. Increasing the opportunities for water extraction and atmospheric CO<sub>2</sub> fixation throughout a greater portion of the year (e.g., through crop selection and greater cropping frequency) can cause soil to dry more thoroughly, thereby reducing microbial activity and leading to increased soil organic carbon storage. Anaerobic conditions in suitably adapted ecosystems (i.e., native wetlands, flooded rice) retard decomposition rates and CO<sub>2</sub> emissions but increase emissions of CH<sub>4</sub>. Reducing soil disturbance associated with tillage, logging, and roading tends to reduce specific rates of soil organic matter decomposition (Lal and Kimble, 2000; Paustian *et al.*, 2000).

### **Agroforestry**

Agroforestry is a management system that integrates trees on farms and in the agricultural landscape. It leads to a more diversified and sustainable production system than many treeless alternatives and provides increased social, economic, and environmental benefits for land users at all levels (Sanchez, 1995; Leakey, 1996; Fay *et al.*, 1998). Agroforestry is practiced from the Arctic to the south temperate regions, but it is most extensive in the tropics. Approximately 1.2 billion people (20 percent of the world's population) depend directly on agroforestry products and services in rural and urban areas of developing countries (Leakey and Sanchez, 1997). Agroforestry encompass a wide variety of practices, including crop-fallow rotations, complex agroforests, simple agroforests, silvopastoral systems, and urban agroforestry (Steppler and Nair, 1987; Fujisaka *et al.*, 1996; Huxley, 1999). Agroforestry practices in the temperate regions include planting trees at wide spacing in combination with pastures or crops; this practice results in increasing carbon density in UNFCCC's Annex I countries (36 industrialized countries and countries in transition) (Buck *et al.*, 1999)

Agroforestry systems can be superior to other land uses at the global, regional, watershed, and farm scales because they optimize tradeoffs between increased food production, poverty alleviation, and environmental conservation. They can also be inferior to other land uses, particularly when the technology is inappropriate or the accompanying policies are not enabling (Sanchez, 1995). Analysis of tradeoffs between private farmer benefits and global environmental benefits provide a solid basis for partitioning benefits arising from global environmental conventions and protocols.

Incorporation of trees on farms affects carbon stocks differently than cropland or forest management. For example, trees on farms provide tighter coupling of key processes such as nutrient cycling and weed control than in croplands; trees in agroforestry are

harvested more frequently than under forest management. One accounting option for agroforestry is the time-averaged carbon sequestration rate, which takes into account periodic woody biomass harvests based on the "average storage method" of Schroeder (1992). The potential land area suitable for agroforestry in Africa, Asia, and the Americas is 585-1215 Mha (Dixon, 1996). This estimate is a compilation of several estimates. The current area in agroforestry is on the order of 400 Mha, of which 300 Mha are "arable land" and 100 Mha are "forest lands" in the FAO database. For example, the 14 Mha of agroforestry in China are classified as agricultural land (Xu, 1999). It is estimated that an additional 630 Mha of current croplands and grasslands could be converted into agroforestry, primarily in the tropics.

Two kinds of agroforestry activities are considered here: land conversion and improved land use. Land conversion includes transformation of degraded cropland and grasslands, including those from slash-and-burn agriculture, into new agroforests. The potential area of new agroforests from land-use change could be on the order of 400 Mha during the next 25 years. Improved use of current agroforestry systems with interventions that result in increased carbon is analogous to "improved cropland"-but with trees on the farm. Both kinds of activities increase carbon stocks, and many also prevent carbon losses in adjacent forests and woodlands by avoiding further deforestation or land degradation. Two practices involving land-use change are discussed here: one from slash-and-burn agriculture and another that involves converting degraded cropland in Africa.

#### **From forests to slash-and-burn to agroforests after deforestation**

This major land conversion practice takes place mainly at the margins of humid tropical forests. Transformation of the original forest into various types of agroforests results in a smaller decrease in carbon stocks than transformation of forests into cropland, pastures, or degraded grasslands. Much of the uncertainty in the values of CO<sub>2</sub> fluxes from the tropics is the result of inadequate estimates of the biomass that is cleared, the fate of the carbon lost, the type of biomass and time course of subsequent land-use systems, and the regrowth rates of vegetation (Houghton, 1997). A project that used standardized methods to compare several such systems in Brazil, Cameroon, Indonesia, and Peru provided data on the foregoing parameters and the carbon sequestration potential of many land-use systems at the margins of the humid tropics (Sanchez, 2000). The time course of the land-use changes is described below.

#### **Rates**

Carbon sequestration rates are highly negative on forest clearance: -92 t C ha<sup>-1</sup> yr<sup>-1</sup> during the first 2 years after slash-and-burn - a period that is normally under annual cropping or pasture establishment (Neill *et al.*, 1997). Table 1 shows that carbon sequestration rates become positive with secondary forest fallows (5-9 t C ha<sup>-1</sup> yr<sup>-1</sup>); complex agroforests (2-4 t C ha<sup>-1</sup> yr<sup>-1</sup>); and simple agroforests with one dominant species such as oil palm, rubber, or *Albizia falcataria* (7-9 t C ha<sup>-1</sup> yr<sup>-1</sup>). The lower carbon sequestration rate of some agroforestry systems in relation to natural secondary succession is partly because agroforestry products are removed from the system for family use or for sale. This finding underscores the important tradeoffs between a global public good (carbon) and a private good (economic gain) (Tomich *et al.*, 1998). Croplands, pastures, and degraded grasslands lost carbon at a slow rate or show modest positive rates (-0.4 to +3 t C ha<sup>-1</sup> yr<sup>-1</sup>). Land-use systems that include trees, therefore,

produce higher carbon sequestration rates than those that are limited to annual crops, pastures, or grasslands.

### Stocks

Results summarized in Table 1 provide a time course of changes in total carbon stocks (aboveground plus below-ground) in a 20-year traditional slash-and-burn sequence (Sanchez, 2000). The area changes from original forest, usually logged ( $230 \text{ t C ha}^{-1}$ ), to burned cropland ( $46 \text{ t C ha}^{-1}$ ), to bush fallow ( $34 \text{ t C ha}^{-1}$ ), and to tall secondary forest fallow ( $112 \text{ t C ha}^{-1}$ ). After burning and cropping for an average of 2 years, about 80 percent of the carbon stock is lost. These slash-and-burn systems do not include tillage. Crops are planted by digging holes in the ground with a stick or machete and dibbling seeds, pastures by broadcasting seeds on the surface, and trees by transplanting seedlings in holes. There is essentially no soil disturbance: The surface is covered with partially burned logs, branches, tree stumps, and leaf litter. Most of the carbon stock lost is by biomass burning; some is lost by increasing decomposition of soil carbon because of higher soil temperatures during fires and afterward as a result of increased incident solar radiation.

**Table 1:** Carbon uptake rates and time-averaged system carbon stocks and differences in carbon stocks from land transformation at margins of humid tropics. Summary of 116 sites with different land uses before and after slash-and-burn located in Pedro Peixoto (Acre) and Theobroma (Rondônia), Brazil; Ebolowa, M'Balmayo, and Yaounde, Cameroon; Jambi and Lampung, Sumatra, Indonesia; and Yurimaguas and Pucallpa, Peru.

Land-Use Practice	Carbon Uptake Rates ( $\text{t C ha}^{-1} \text{ yr}^{-1}$ )			Duration (yr)	Carbon Stocks (time-averaged) ( $\text{t C ha}^{-1}$ )			Differences in Modal Carbon Stocks (time-averaged) ( $\text{t C ha}^{-1}$ )	
	Low	Modal	High		Low	Modal	High	Forest	Pasture/Grasslands
Primary and logged forest	n/a <sup>b</sup>	n/a <sup>b</sup>	n/a <sup>b</sup>	?	192	230	276	-	-201
Cropping after slash-and-burn	-76	-92	-112	2	39	46	52	-184	+17
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
Pasture, <i>Imperata</i> grassland	-0.2	-0.2	-0.6	4-12	27	29	31	-201	-

Sanchez (2000)

n/a - not available; likely close to zero

Crop-short bush fallow rotations, pastures, and *Imperata cylindrica* grasslands that ensue have carbon stocks of about 30 t C ha<sup>-1</sup>, most in the soil. Therefore, about 88 percent of the carbon stock of the original forest is lost and emitted to the atmosphere in the transformation from forest to croplands or pastures within 4-12 years (Table 1). Improved short-term fallow systems or improved pastures do not significantly increase carbon stocks in relation to the current degrading practices.

Below-ground organic carbon stocks averaged 40 t C ha<sup>-1</sup> at 0-20 cm depth in undisturbed forests (Palm *et al.*, 2000). The following land uses resulted in different proportions of below-ground carbon relative to undisturbed forests:

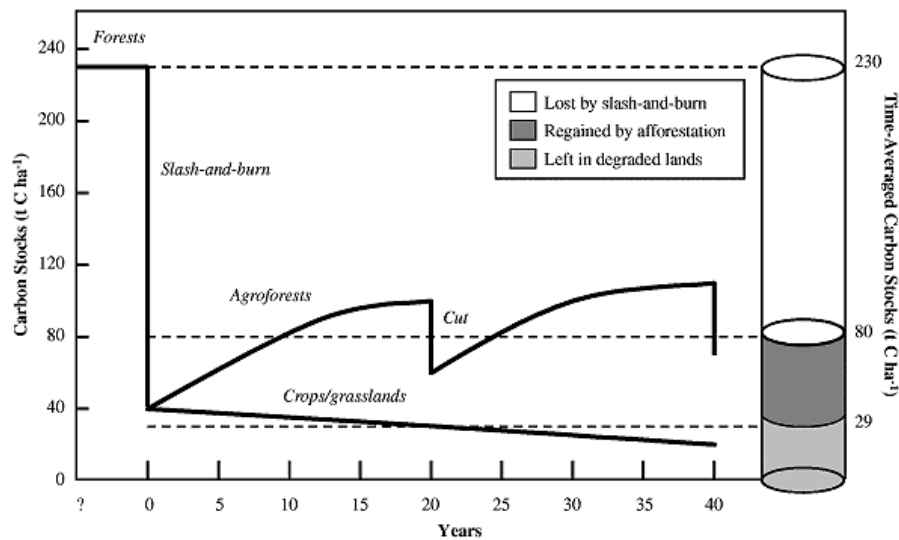
- Agroforestry systems: 80-100 percent
- Crop/long-term fallow sequence: 90-100 percent
- Pastures: 80 percent
- Crop/short-term fallow: 65 percent
- Degraded *Imperata* grasslands: 50 percent or less.

Except for the crop/short-term fallow and degraded *Imperata* grasslands, the other alternative land uses lost less than 20 percent of topsoil carbon. This finding suggests that the potential for carbon sequestration in the humid tropics is mainly above ground.

#### **Difference in stocks between agroforestry and common practices**

Ten-year-old pastures in Brazil and 13-year-old *Imperata* grasslands in Indonesia (common practices after tropical deforestation) contained 201 t C ha<sup>-1</sup> less than the original forest that was cleared (Palm *et al.*, 2000). In contrast, agroforests that are established immediately after slash-and-burn by planting trees along with food crops contained 150 t C ha<sup>-1</sup> less than the original forest (Table 1). Agroforestry systems can regain 35 percent of the original carbon stock of the forest; croplands and pastures can regain 12 percent. Through the establishment of tree-based systems in degraded pastures, croplands, and grasslands, the time-averaged carbon stock in the vegetation increases by 50 t C ha<sup>-1</sup> in 20-25 years, whereas that in the soil increases by 7 t C ha<sup>-1</sup> (Palm *et al.*, 2000). Agroforestry practices therefore permit the sequestration of an additional 57 t C ha<sup>-1</sup>-three times as much as croplands or grasslands can sequester (Figure 1). This finding indicates the key contribution of agroforestry to increasing carbon stocks at the margins of the humid tropics.

The area that could be converted to this practice is 10.5 Mha annually if enabling government policies were in place (Fay *et al.*, 1998; Tomich *et al.*, 1998). The area calculation is based on two assumptions: 20 percent of the 15 Mha that is annually deforested (3 Mha) is put into agroforestry every year, and 3 percent of the 250 Mha of degraded lands at the forest margins (Sanchez *et al.*, 1994) is converted into agroforests every year (7.5 Mha). The difference in time-averaged carbon density from this land-use change is 35-90 t C ha<sup>-1</sup>, with a modal value of 57 t C ha<sup>-1</sup>. We further assume that the annual deforestation rate will stay constant for the next 10 years. If this happens, the global contribution of this practice to carbon sequestration would be on the order of 0.105-0.525 Gt C yr<sup>-1</sup>, with a modal value of 0.315 Gt C yr<sup>-1</sup>.



**Figure 1:** Time course of system carbon stocks (biomass and soil, solid lines) and time-averaged carbon stocks (dotted lines) in agroforestry systems vs. crops followed by grasslands at margins of humid tropical forest.

#### From low-productivity croplands to sequential agroforestry in Africa

The second major agroforestry practice is the transformation of unproductive cropland into agroforestry-based crop/tree fallow rotations. Although various expressions of this practice are found throughout the tropics (Buresh and Cooper, 1999), it is illustrated in this Special Report with the recent movement to replenish soil fertility in subhumid areas of tropical Africa. Soil carbon stocks have dramatically decreased in smallholder farms of sub-Saharan Africa because of nutrient depletion, which is increasingly recognized as the fundamental biophysical cause for declining food security in this region (Sanchez *et al.*, 1997a,b). Given the acute poverty and limited access to mineral fertilizers, an ecologically robust approach is being used by tens of thousands of farmers in eastern and southern Africa. This approach consists of bringing natural resources to farmer fields where crops can utilize them: nitrogen from the air by biological nitrogen fixation, phosphorus from indigenous phosphate rock deposits, and nutrient-rich shrub biomass from roadsides and farm hedges (Rao *et al* 1998; Kwesiga *et al.*, 1999; Sanchez, 1999). Replenishment of nitrogen and phosphorus has important effects on changes in carbon stocks.

#### Rates

Conventional cropping on clayey, oxidic Alfisols in Kabete, Kenya, shows a 28 percent decrease in topsoil carbon, from 36 to 26 t C ha<sup>-1</sup> during an 18-year period (Kapkiyai *et al.*, 1998). Another long-term trial in Muguga, Kenya, with similar soils shows a total loss of 91 t C ha<sup>-1</sup> to a depth of 120 cm with 8 years of continuous cultivation without inputs. About half of this loss (48 t C ha<sup>-1</sup>) took place in the top 15 cm (Woomer *et al*, 1997). The loss of topsoil organic carbon associated with soil nutrient depletion has been estimated at an average rate of -0.22 t C ha<sup>-1</sup> yr<sup>-1</sup> (Sanchez *et al.*, 1997b). When soil fertility is replenished, maize grain yields increase from 0.5 to 2 t C ha<sup>-1</sup> and carbon sequestration rates become positive, averaging 1.5 t C ha<sup>-1</sup> (Table 2). When more trees are planted on field boundaries and as

orchards, carbon sequestration rates increase further to 3.5 t C ha<sup>-1</sup>. Overall carbon sequestration rates may range from 1.2 to 5.1 t C ha<sup>-1</sup> yr<sup>-1</sup>, with a modal value of 3.1 t C ha<sup>-1</sup> yr<sup>-1</sup>.

**Table 2:** Estimates of carbon uptake rates and time-averaged system carbon stocks and differences in carbon stocks from land transformation from low-productivity cropland to sequential agroforestry in subhumid tropical Africa (Sanchez, 2000)

Land-Use Practice	Carbon Uptake Rates (t C ha <sup>-1</sup> yr <sup>-1</sup> )			Duration (yr)	Carbon Stocks (time-averaged) (t C ha <sup>-1</sup> )			Differences in Modal Carbon Stocks (time- averaged) (t C ha <sup>-1</sup> )
	Low	Modal	High		Low	Modal	High	
Current nutrient-depleted small farms <sup>a</sup>		-0.22		?		23		-
Fertility-replenished farms with maize-tree fallow rotations <sup>b</sup>	1.0	1.5	2.4	25	20	35	49	+12
Fertility-replenished farms (as above) + more trees on farm <sup>c</sup>		3.5		25		70		+47

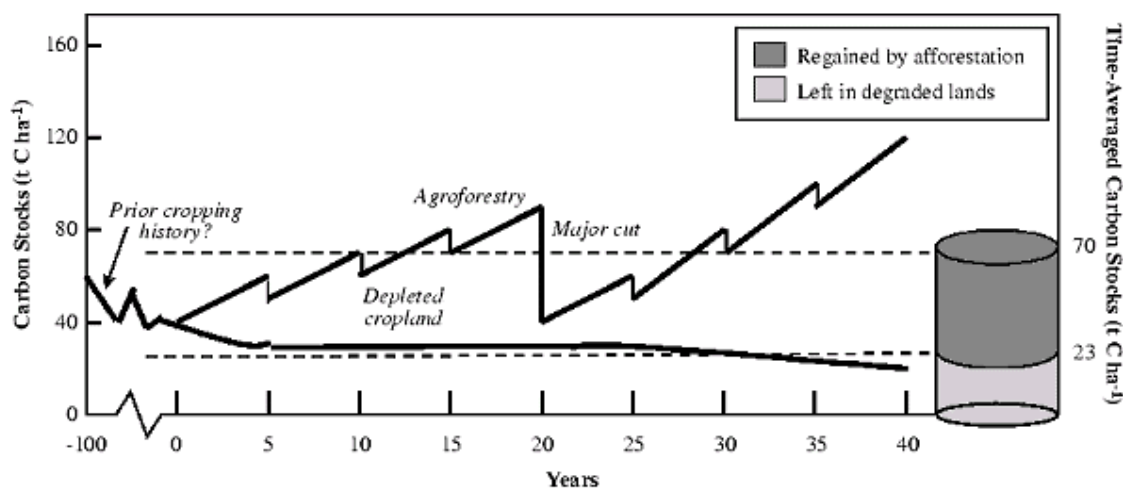
## Stocks

Nutrient-depleted fields have little biomass carbon stock; a time-averaged modal figure is on the order of 23 t C ha<sup>-1</sup>, virtually all below ground (Table 2). Soil fertility replenishment practices that are based on improved fallows, rock phosphate, and biomass transfers of *Tithonia diversifolia* for 25 years are estimated to result in time-averaged carbon stocks of 35 t C ha<sup>-1</sup>. Such stocks are virtually all in the soil; crop and fallow accumulation may account for only 1 t C ha<sup>-1</sup> above ground. The increase in soil carbon at equilibrium (8 t C ha<sup>-1</sup>) reflects 80 percent replenishment of the lost soil carbon. When trees are incorporated after fertility replenishment, total time-averaged stocks reach 70 t C ha<sup>-1</sup>, which includes 34 t C ha<sup>-1</sup> in aboveground biomass and 36 t C ha<sup>-1</sup> below ground (Table 2). It should be noted that all these figures are estimates rather than hard data as in the case of the humid tropical forest margins.

## Difference in stocks between agroforestry and common practices

The transformation of low-productivity croplands to sequential agroforestry in subhumid smallholder Africa can triple carbon stocks (from 23 to 70 t C ha<sup>-1</sup>) in a 25-year period (Figure 2). This transformation consists of a two-stage process: first fertility replenishment, then more trees on the farm. The first stage increases carbon stocks by 9 t C ha<sup>-1</sup> - all but 1 t C ha<sup>-1</sup> as soil carbon. The second step increases carbon stocks by an additional 28 t C ha<sup>-1</sup> - 5 t C ha<sup>-1</sup> as soil carbon and 23 t C ha<sup>-1</sup> as aboveground biomass. Assuming such increases can take place in 46 percent (37.5 Mha) of the smallholder farms of subhumid tropical Africa (Sanchez *et al.* 1997b), during the next 25 years-after which we assume equilibrium is reached-this

practice would provide a global contribution of 0.045-0.191 Gt C yr<sup>-1</sup>, with a modal value of 0.116 Gt C yr<sup>-1</sup>, in subhumid tropical Africa alone.



**Figure 2:** Project time course and system carbon stocks (biomass and soil) and time-averaged carbon stocks in sequential agroforestry systems based on soil fertility replenishment and intensification with high-value trees in subhumid tropical Africa.

Carbon sequestration in subhumid Africa may therefore be considerable with land conversion to agroforestry systems that involve soil fertility replenishment and intensification and diversification of farming with the use of high-value domesticated trees. Lesser amounts can be expected in semiarid tropical areas with similar practices. The widespread use of green manure cover crops in subhumid Latin America (Bunch, 1999) and subhumid West Africa (Buckles *et al.*, 1998) suggest considerable carbon sequestration potentials, but the rates have yet to be estimated.

### Improved agroforests

Improvements include the incorporation of shelter belts; superior germplasm of tree and crop species; trees planted at a higher density; better nutrient management; integrated pest management; and other agronomic, silvicultural, and silvopastoral techniques in Annex I and non-Annex I countries. Rising saline water tables occur in 15 of the 65 Mha (23 percent) of cultivated land in Australia. This slow process is mainly blamed on the gradual removal of trees from the agricultural landscape; because of their deep rooting habits, these trees formerly kept saline water tables well below the surface. Although deep drainage and other standard salinity management practices are recommended, the main vehicle of restoration is to repopulate trees on farms and in the landscape-particularly trees that are deep-rooted and salinity-tolerant. Woody species could provide more stable biomass pools than grasses in locations with variable climate.

Agroforestry improvement practices generally have a lower carbon uptake potential than land conversion to agroforestry practices because existing agroforestry systems have much higher carbon stocks than degraded croplands and grasslands that can be converted into



agroforestry. Improving agroforestry land use could sequester carbon at time-averaged rates of 0.02-1.0 t C ha<sup>-1</sup> yr<sup>-1</sup>, with a modal value of 0.50 t C ha<sup>-1</sup> yr<sup>-1</sup>, in Annex I countries. The estimate for non-Annex I countries (0.08-0.33 t C ha<sup>-1</sup> yr<sup>-1</sup>, with a modal value of 0.22 t C ha<sup>-1</sup> yr<sup>-1</sup>) is lower because of greater institutional constraints. The foregoing estimates are based on expert opinion that considers technical, social, and institutional constraints, as well as existing policy environments. Policy issues affecting tree species selection in agroforestry projects (e.g., benefits for local biomass energy use, commercial pulping, native vs. non-native species) and requisite institutional and regulatory frameworks affect the success of agroforestry programs. Policy improvements that support secure land tenure, improved road infrastructure, and increased access to credit and markets are likely to contribute as much or more to increasing the productivity of existing agroforests than technological improvements in non-Annex I countries (Sanchez, 1995, 1999). In temperate areas, the potential carbon storage with agroforestry ranges from 15 to 198 t C ha<sup>-1</sup> (Dixon *et al.*, 1994), with a modal value of 34 t C ha<sup>-1</sup> (Dixon *et al.*, 1993).

### **Overall contribution**

The potential contributions of agroforestry systems to carbon sequestration are summarized in Table 3 under the headings of improved management within a land use and land-use change. The latter is an order of magnitude higher than the former, given the lower initial levels of carbon stocks. Overall, agroforestry can sequester carbon at time-averaged rates of 0.2-3.1 t C ha<sup>-1</sup>. In temperate areas, the potential carbon storage with agroforestry ranges from 15 to 198 t C ha<sup>-1</sup> (Dixon *et al.*, 1994), with a modal value of 34 t C ha<sup>-1</sup> (Dixon *et al.*, 1993). The associated impacts of agroforestry include helping to attain food security and secure land tenure in developing countries, increasing farm income, restoring and maintaining aboveground and below-ground biodiversity (including corridors between protected forests), serving as CH<sub>4</sub> sinks, maintaining watershed hydrology, and decreasing soil erosion.

Table 3: Potential net carbon storage of additional activities under Article 3.4 of the Kyoto Protocol (IPCC, 2000)

Activity (Practices)	Group	Area <sup>a</sup> (10 <sup>6</sup> ha)	Adoption/ Conversion (% of area)		Rate of Carbon Gain Area <sup>b</sup> (t C ha <sup>-1</sup> yr <sup>-1</sup> )	Potential (Mt C yr <sup>-1</sup> )	
			2010	2040		2010	2040
<i>a) Improved management within a land use</i>							
<b>Cropland</b> (reduced tillage, rotations and cover crops, fertility management, erosion control, and irrigation management)	AI	589	40	70	0.32	75	132
	NAI	700	20	50	0.36	50	126
<b>Rice paddies</b> Area <sup>c</sup> (irrigation, chemical and organic fertilizer, and plant residue mgmt.)	AI	4	80	100	0.10	<1	<1
	NAI	149	50	80	0.10	7	12
<b>Agroforestry</b> Area <sup>d</sup> (better management of trees on croplands)	AI	83	30	40	0.50	12	17
	NAI	317	20	40	0.22	14	28
<b>Grazing land</b> (herd, woody plant, and fire management)	AI	1297	10	20	0.53	69	137
	NAI	2104	10	20	0.80	168	337
<b>Forest land</b> (forest regeneration, fertilization, choice of species, reduced forest degradation)	AI	1898	10	50	0.53	101	503
	NAI	2153	10	30	0.31	69	200
<b>Urban land</b> (tree planting, waste management, wood product management)	AI	50	5	15	0.3	1	2
	NAI	50	5	15	0.3	1	2
<i>b) Land-use change</i>							
<b>Agroforestry</b> (conversion from unproductive cropland and grasslands)	AI	~0	~0	~0	~0	0	0
	NAI	630	20	30	3.1	391	586
<b>Restoring severely degraded land</b> Area <sup>e</sup> (to crop-, grass-, or forest land)	AI	12	5	15	0.25	<1	1
	NAI	265	5	10	0.25	3	7
<b>Grassland</b> (conversion of cropland to grassland)	AI	602	5	10	0.8	24	48
	NAI	855	2	5	0.8	14	34
<b>Wetland restoration</b> (conversion of drained land back to wetland)	AI	210	5	15	0.4	4	13
	NAI	20	1	10	0.4	0	1
<i>c) Off-site carbon storage</i>							
<b>Forest products</b>	AI	n/a <sup>e</sup>	n/a	n/a	n/a	210	210 <sup>e</sup>
	NAI	n/a	n/a	n/a	n/a	90	90
<i>Totals</i>							
	AI					497	1063
	NAI					805	1422
	<i>Global</i>					1302	2485

AI = Annex I countries; NAI = non-Annex I countries.

## REFERENCES

- Balesdent, J. and M. Balabane, 1996: Major contribution of roots to soil carbon storage inferred from maize cultivated soils. *Soil Biological Biochemistry*, 28(9), 1261-1263.
- Buck, L.E., J.P. Lassoie, and E.C.M. Fernandes (eds.), 1999: *Agroforestry in Sustainable Agricultural Systems*. CRC Press, Boca Raton, FL, USA, 416 pp.
- Buckles, D., A. Eteka, O. Osiname, M. Galiba, and G. Galiano, (eds.), 1998: *Cover Crops in West Africa: Contributing to Sustainable Agriculture*. International development Research Centre, Ottawa, Canada.
- Bunch R. 1999. *Greener Fields with Green Technology: Case Studies of Sustainable Low-input Agricultural Development in Central America*. COSECHA, Honduras
- Buresh, R.J. and P.J.M. Cooper (eds.), 1999: The science and practice of short-term improved fallows. *Agroforestry Systems*, 47, 1356.
- Dixon, R.K., J.K. Winjum, and P.E. Schroeder, 1993: Conservation and sequestration of carbon: the potential of forest and agroforest management practices. *Global Environmental Change*, 3(2), 159-173.
- Dixon, R.K., J.K. Winjum, K.J. Andrasko, J.J. Lee, and P.E. Schroeder, 1994: Integrated systems: assessing of promising agroforest and alternative land use practices to enhance carbon conservation and sequestration. *Climate Change*, 30, 1-23.
- Dixon, R.K., 1996: Agroforestry systems and greenhouse gases. *Agroforestry Today*, 8(1), 11-14.
- Fay, C., H. de Foresta, M. Sarait, and T.P. Tomich, 1998: A policy breakthrough for Indonesian farmers in the Krui damar agroforests. *Agroforestry Today*, 10(2), 25-26.
- Fujisaka, S., L. Hurtado, and R. Uribe, 1996: A working classification of slash-and-burn agricultural systems. *Agroforestry Systems*, 34(2), 151-169.
- Gale and Cambardella, 2000. W.J. Gale and C.A. Cambardella, Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. *Soil Science Society of America Journal* 64 (2000), pp. 190–195.
- Houghton, R.A., 1997: Terrestrial carbon storage: Global lessons from Amazonian research. *Ciencia e Cultura*, 49, 58-72.
- Huxley, P., 1999: *Tropical Agroforestry*. Blackwell Science Publishers, London, United Kingdom, 371 pp.
- IPCC 2000. Land Use, Land-Use Change, and Forestry. A Special Report of the Intergovernmental Panel on Climate Change
- Kapkiyai, J.J., N.K. Karanja, P. Woome, and J.N. Qureshi, 1998: Soil organic carbon fractions in a long-term experiment and the potential for their use as a diagnostic assay in highland farming systems of central Kenya. *African Crop Science Journal*, 6(1), 19-28.
- Kwesiga, F.R., S. Franzel, F. Place, D. Phiri, and C.P. Simwanza, 1999: *Sesbania sesban* improved fallows in Eastern Zambia: Their inception, development and farmer enthusiasm. *Agroforestry Systems*, 47, 49-66.
- Lal, R. and J.M. Kimble, 2000: Tropical ecosystems and the global carbon cycle. In: *Global Climate Change and Tropical Ecosystems* [Lal, R., J.M. Kimble, and B.A. Stewart (eds.)]. CRC-Lewis Publishers, Boca Raton, FL, USA, pp. 3-32.
- Lal, R., 2000: Soil aggregation and carbon sequestration. In: *Global Climate Change and Tropical Ecosystems* [Lal, R., J.M. Kimble, and B.A. Stewart (eds.)]. CRC-Lewis Publishers, Boca Raton, FL, USA, pp. 317-329.
- Leakey, R.R.B., 1996: Definition of agroforestry revisited. *Agroforestry Today*, 8(1), 5-7.

- Neill, C., J.M. Melillo, P.A. Steudler, C.C Cerri, J.F.L. Moraes, M.C. Piccolo, and M. Brito, 1997: Soil carbon and nitrogen stocks following forest clearing for pasture in the southwestern Brazilian Amazon. *Ecological Applications*, 7(4), 1216-1225.
- Palm C.A., Woomer P.L., Alegre J.C., Arevalo L., Castilla C., Cordeiro D.G. et al. 2000. Carbon sequestration and trace gas emissions in slash-and-burn and alternative land-uses in the humid tropics. ASB Climate Change Working Group Final Report, Phase II. Nairobi, Kenya.
- Palm, C.A., R.J.K. Myers, and S.M. Nandwa, 1997: Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: *Replenishing Soil Fertility in Africa* [Buresh, R.J., P.A. Sanchez, and F. Calhoun (eds.)]. SSSA Special Publication 51, Soil Science Society of America, Madison, WI, USA, pp. 193-218.
- Paustian, K., J. Six, E.T. Elliott, and H.W. Hunt, 2000: Management options for reducing CO<sub>2</sub> emissions from agricultural soils. *Biogeochemistry*, 48, 147-163.
- Rao, M.R., A. Niang, F. Kwesiga, B. Duguma, S. Franzel, B. Jama, and R. Buresh, 1998: Soil fertility replenishment in sub-saharan Africa. New techniques and the spread of their use on farms. *Agroforestry Today*, 10(2), 3-8.
- Sanchez, P.A., P.L. Woomer, and C.A. Palm, 1994: Agroforestry approaches for rehabilitating degraded lands after tropical deforestation. In: *JIRCAS International Symposium Series*, vol. 1. Tsukuba, Japan, pp. 108-119.
- Sanchez, P.A., K.D. Shepherd, M.I. Soule, F.M. Place, R.J. Buresh, A.-M.N. Izac, U. Mokwunye, F.R. Kwesiga, C.G. Ndiritu, and P.L. Woomer, 1997a: Soil fertility replenishment in Africa: an investment in natural resource capital. In: *Replenishing Soil Fertility in Africa* [Buresh, R.J., P.A. Sanchez, and F. Calhoun (eds.)]. SSSA Special Publication 51, Soil Science Society of America, Madison, WI, USA, pp. 1-46.
- Sanchez, P.A., R.J. Buresh, and R.R.B. Leakey, 1997b: Trees, soils and food security. *Philosophical Transactions of the Royal Society of London, Series B*, 353, 949-961.
- Sanchez, P.A., 1995: Science in agroforestry. *Agroforestry Systems*, 30, 5-55.
- Sanchez, P.A., 1999: Delivering on the promise of agroforestry. *Environment, Development and Sustainability*, 1: 275-284.
- Sanchez, P.A., 2000: Linking climate change research with food security and poverty reduction in the tropics. *Agriculture, Ecosystems and Environment*, 82, 371-383.
- Schroeder, P.E., 1992: Carbon storage potential of short rotation tropical tree plantations. *Forest Ecology and Management*, 50, 31-41.
- Steppler, H.A. and P.K.R. Nair (eds.), 1987: *Agroforestry-a Decade of Development*. International Centre for Agroforestry, Nairobi, Kenya, 335 pp.
- Swift, M.J., O.W. Heal, and J.M. Anderson, 1979: *Decomposition in Terrestrial Ecosystems*. Blackwell Science Publishers, Oxford, United Kingdom, 372 pp.
- Tomich, T.P., M. van Noordwijk, S. Vosti, and J. Witcover, 1998: Agricultural development with rainforest conservation: Methods for seeking best-bet alternatives to slash-and-burn, with applications to Brazil and Indonesia. *Agricultural Economics*, 19, 159-174.
- Woomer, P.L., C.A. Palm, J.N. Qureshi, and J. Kotto-Same, 1997: Carbon sequestration and organic resource management in African smallholder agriculture. In: *Management of Carbon Sequestration in Soil* [Lal, R., J.M. Kimble, R.A. Follett, and B.A. Stewart (eds.)]. CRC Press, Boca Raton, FL, USA, pp. 153-173.
- Xu, D., 1999: Forestry and land use change assessment for China. In: *Forestry and Land Use Change Assessment*. Asian Development Bank, Manila, Philippines, pp. 73-97.