



## Review Article

# Carbon Sequestration Potentials of Agroforestry Systems under Climate Change Scenario – Brief Review with Special Emphasis on North-Eastern Hill Regions

R. SAHA<sup>1\*</sup> AND PRAMOD JHA<sup>2</sup>

<sup>1</sup>*Division of Soil Physics, Indian Institute of Soil Science, Nabibagh, Bhopal-462 038*

<sup>2</sup>*Division of Soil Chemistry, Indian Institute of Soil Science, Nabibagh, Bhopal-462 038*

## ABSTRACT

Conservation of biodiversity and mitigation of the fallout of climate change are two major environmental challenges today. In the context of climate change and the global carbon cycle, the relationship between plant biodiversity and soil organic carbon (SOC) sequestration has become a subject of considerable scientific interest. The Earth's terrestrial vegetation plays a pivotal role in the global carbon cycle. Not only are tremendous amounts of carbon stored in the terrestrial vegetation, but large amounts are also actively exchanged between vegetation and the atmosphere. In agroforestry systems C sequestration is a dynamic process and can be divided into phases. At establishment, many systems are likely to be sources of green house gases (loss of C and N from vegetation and soil). Then follows a quick accumulation phase and at maturation period, wherein tons of C are stored in the boles, stems, roots of trees and in the soil. At the end of the rotation period, when the trees are harvested and the land returned to cropping (sequential systems), part of the C is released back to the atmosphere. The C sequestration potential of agroforestry systems is estimated to be between 12 and 228 Mg ha<sup>-1</sup> with a median value of 95 Mg ha<sup>-1</sup>. Therefore, based on the earth's area that is suitable for the practice, 1.1–2.2 Pg C could be stored in the terrestrial ecosystems over the next 50 years. Realistically, C storage in plant biomass is only feasible in the perennial agroforestry systems (perennial-crop combinations, agroforests, windbreaks), which allow full tree growth and wherein the woody component represents an important part of the total biomass.

**Keywords:** Agroforestry, C sequestration, Climate change, NEH Region

## Introduction

Biodiversity decline and climate change are two major environmental issues of the world today. Increase in atmospheric concentrations of greenhouse gasses (GHG), of which the most common is carbon dioxide (CO<sub>2</sub>), is considered to be the primary cause of global warming and the Intergovernmental Panel on Climate change

(IPCC) estimates (IPCC 2007) that the current greenhouse gases (GHGs) concentrations are 30% more than the pre-industrial level. C is accumulating in the atmosphere at a rate of 3.5 Pg (Pg = 1015 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). Scientific evidence suggests that increased atmospheric CO<sub>2</sub> could have some positive effects such as improved plant

\*Corresponding author,  
Email: saharitesh74@rediffmail.com

productivity. However, negative changes in the global climate (rising temperatures, higher frequency of droughts and floods) are often the most consequential processes possibly associated with an increased concentration of CO<sub>2</sub> in the atmosphere.

Current terrestrial (plant and soil) C is estimated at  $2000 \pm 500$  Pg, which represents 25% of global C stocks (DOE, 1999). The sink option for CO<sub>2</sub> mitigation is based on the assumption that this figure can be significantly increased if various biomes are judiciously managed and/or manipulated. In this connection, agricultural lands have the potential to remove and store between 42 and 90 Pg of C from the atmosphere over the next 50–100 years.

Conversion of natural to agricultural ecosystems increases maximum soil temperature and decreases soil moisture storage in the root zone, especially in drained agricultural soils (Lal, 1996). Thus, land use has a strong impact on the accumulation of SOC (Pulleman *et al.*, 2000). The dynamic relationship between plant biodiversity and SOC depicts that any land use practices that increase vegetative cover, or reduce its removal, could have an influence on the global carbon budget by increasing or decreasing the terrestrial carbon sink. Promoting agroforestry (AFS) is one option many perceive as a major opportunity to deal with the problems related to land-use and CO<sub>2</sub>-induced climate change. AFS is defined as any land-use system that involves the deliberate retention, introduction or mixture of trees or other woody perennials with agricultural crops, pastures and/or livestock to exploit the ecological and economic interactions of the different components (Nair, 1993 and Young, 1997). Historical evidence showed that AFS has been widely practised through the ages as a means of achieving agricultural sustainability and slowing the negative effects of agriculture such as soil degradation and desertification. Loss of nutrients by leaching, erosion and runoff can be minimized by tree derived mulch, litter or foliage (Sanchez, 1987) and an annual crop or cover of legumes or other vegetation during the initial period of tree establishment can provide an effective soil cover to arrest soil erosion (Sanchez 1995).

In India, per capita forest area and biomass availability is low to the tune of about 0.08 hm<sup>2</sup> and 6.0 Mg as against 0.5 hm<sup>2</sup> and 82 Mg, respectively for developing world (NFAP, 2003). The biomass and growing stock of wood in natural forests of India is 93 Mg hm<sup>-2</sup> and 47 m<sup>3</sup> hm<sup>-2</sup> while the average figures of the developing world are 163 Mg hm<sup>-2</sup> and 113 m<sup>3</sup> hm<sup>-2</sup>, respectively. So, Indian forestry is in a phase of dismal scenario due to heavy pressure of burgeoning human population on land, growing demand of timber, fuelwood, fodder, grazing, encroachment, shifting cultivation, urbanization, industrialization, excessive mining activity and improper land management. In North-East India, shifting cultivation which is regarded as the 1<sup>st</sup> step in transition from food gathering or hunting to food production, believed to have originated in the Neolithic period around 7000 B.C., is still in practice (Singh *et al.*, 1981). Generally, soils of humid tropics are of low exchangeable base, low nutrient reserves, high aluminium toxicity, low phosphorus availability, low organic matter and mild to strong in soil acidity. The potential for AFS to increase nutrient stocks on infertile acid soils appears to be variable. The proposed abilities of AFS to maintain or improve soil chemical properties and organic matter and protect the soil surface from erosion are related to the processes of litter or fine root production, decomposition and transformation of soil organic matter.

### Agroforestry system approach

The agroforestry system (AFS) has today become an established approach to integrated land management, not only for renewable resource production, but also for ecological considerations. It represents the integration of agriculture and forestry to increase the productivity and sustainability of the farming system. AFS also known as multistrata tree gardens or analogue forests and homegardens are other variants of these complex systems, but involve higher plant diversity. Trees play an important role in soil C sequestration (Takimoto *et al.*, 2009); with an increase in the number of trees (high tree density) in a system, the overall biomass production per unit area of land will be higher, which in turn

may promote more C storage in soils. In fact, recent research has reported higher soil C stock (amount of carbon stored in soil) under deeper soil profiles in AFS compared to treeless agricultural or pasture land systems under similar ecological settings (Haile *et al.*, 2008; Nair *et al.*, 2009). Multipurpose trees (MPTs) form an integral component of different AFS interventions and models. MPTs, besides furnishing multiple outputs like fuel, fodder, timber, and other minor products, also help in the improvement of soil and other ecological conditions. The trees play various functions, including shading crops to reduce evapotranspiration, erosion control and nutrient re-cycling (Young, 1997). Some of the potential AFS are agri-horti-silviculture, multistoreyed AFS, home garden, agri-silviculture, horti-pastoral, Agri-horti-silvi-pastoral etc.

### Potential C storage in agroforestry systems

Agroecosystems play a central role in the global C cycle and contain approximately 12% of the world terrestrial C. The terrestrial (plant and soil) C is estimated at  $2000 \pm 500$  Pg, which represents 25% of global C stocks (DOE, 1999). The sink option for CO<sub>2</sub> mitigation is based on the assumption that this figure can be significantly increased if various biomes are judiciously managed or manipulated (Table 1). It is clear that forests have tremendous potential for C sequestration so as to reduce GHG concentrations in the atmosphere. In this connection, AFS will have a great impact on the flux and long-term storage of C in the terrestrial biosphere (Dixon, 1995) as the area of the world under AFS will hopefully increase substantially in the near future. The amount of C sequestered largely depends on

the AFS put in place, the structure and function of which are, to a great extent, determined by environmental and socio-economic factors. Other factors influencing carbon storage in AFS include nature and kind of species of tree and management of system.

A well managed AFS has greater amounts of C sequestration potential in and out of the soil. About 20–25% of the total living biomass of trees prevail in the roots and there is constant addition of organic matter to the soil through decaying dead leaves and roots, which leads to improvements in the C status of the soil (Balkrishnan and Toky, 1993). Better soil aggregation under natural forest, multistoreyed AFSs and silvi-hortipastoral systems maintaining intensive vegetative cover throughout the year could be ascribed to the presence and effect of the higher percentage of organic carbon.

### Potential of agroforestry for carbon sequestration

With adequate management of trees in cultivated lands and pastures, a significant fraction of the atmospheric C could be captured and stored in plant biomass and in soils. However, increasing C stocks in a given period of time is just one step; the fate of those stocks is what ultimately determines sequestration. In agroforestry systems, C sequestration is a dynamic process and can be divided into phases for the sake of understanding. At establishment, many systems are likely to be sources of GHGs (loss of C and N from vegetation and soil). Then follow a quick accumulation phase and a maturation period when tons of C are stored in the boles, stems, roots of trees and in the soil. At

**Table 1.** Categorisation of biomes and their C sequestration potential (DOE, 1999)

| Biomes                     | Primary method to increase CS | Potential CS (Pg C Year <sup>-1</sup> ) |
|----------------------------|-------------------------------|-----------------------------------------|
| Agricultural lands         | Management                    | 0.85–0.90                               |
| Biomass croplands          | Manipulation                  | 0.50–0.80                               |
| Grasslands                 | Management                    | 0.50                                    |
| Rangelands                 | Management                    | 1.20                                    |
| Forests                    | Management                    | 1–3                                     |
| Deserts and degraded lands | Manipulation                  | 0.80–1.30                               |

the end of the rotation period, when the trees are harvested and the land returned to cropping (sequential systems), part of the C gets released back to the atmosphere (Dixon, 1995). Therefore, effective sequestration can only be considered if there is a positive net C balance from an initial stock after a few decades. Realistically, C storage in plant biomass is only feasible in the perennial AFS (perennial-crop combinations, agroforests, windbreaks), which allow growth of tree to their full potential and where the woody component represents an important part of the total biomass.

### ***Multipurpose trees***

The multipurpose tree species (MPTs) form an integral component of different AFS interventions in crop sustainability. The MPTs, besides furnishing multiple outputs such as fuel, fodder, timber and other miscellaneous products, help in the improvement of soil health and other ecological conditions. Screening of MPTs is an important prerequisite for determining the suitability of AFS models for various agroecological regions. Jha *et al.* (2010) suggested that inclusion of species like *P. Juliflora*, *L. Leucocephala*, *A. nilotica* and *A. indica* could be a better choice for restoring and rehabilitation of degraded ravine lands in the riparian zone. They reported that the SOC contents in forest systems with these MPTs to be twofold higher in comparison to the reference site. Mishra *et al.* (2004) also reported increase of SOC under 6-year-old plantations of *P. juliflora*, *D. sissoo* and *E. tereticornis*. The poplar based AFS improves aggregation of soil through amendment of huge amounts of organic matter in the form of defoliant leaf biomass. The extent of improvement may be affected by the age of the poplar trees and the soil type. Gupta *et al.* (2009) reported that the poplar trees could sequester higher soil organic carbon in 0–30 cm profile during the first year of their plantation ( $6.07 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ ) than in the subsequent years ( $1.95\text{--}2.63 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ ).

### ***Hedgerow intercropping***

Hedgerow intercropping (HI) refers to the AFS where crops are grown between rows of regularly coppiced woody species. Initially, it has

been developed to restore the fertility of degraded soils in the humid and sub-humid tropics. HI has later been adopted in other regions not only to ameliorate soils, but also to provide other bi-products (e.g. fodder) and services (e.g. erosion control). Scientific literature showed strong variations in C storage potential in HI ( $1\text{--}37 \text{ Mg C ha}^{-1}$ ) depending on climate, soil type and system management (Kang *et al.*, 1999). However, C storage is only temporary in HI systems since the biomass is continuously harvested for prunings (or fodder) and firewood. In many areas of the tropics, regular addition of prunings and root turnover through natural processes over the years have contributed to the build up of SOM and nutrient stocks in the soil (Rao *et al.*, 1998; Kumar *et al.*, 2001). In a 12-year HI trial on a Nigerian Alfisol, *G. sepium* and *L. leucocephala* increased surface soil organic carbon (SOC) by 15% ( $2.38 \text{ Mg C ha}^{-1}$ ) compared to sole crops (Kang *et al.*, 1999). Presence and build-up of sub-soil microflora and insects also helps in speedy decomposition of organic matter and its accumulation in the soil.

### ***Pasture management***

On a global basis, grassland/grazing lands occupy 3460 Mha. Restoring degraded grazing lands and improving forage species is important to sequestering SOC and SIC. Furthermore, converting marginal croplands to pastures (by CRP and other set-aside provisions) can also sequester C. Similar to cropland, management options for improving pastures include judicious use of fertilizers, controlled grazing, sowing legumes and grasses or other species adapted to the environment, improvement of soil fauna and irrigation (Follett *et al.*, 2001). Conant *et al.* (2001) reported rates of SOC sequestration through pasture improvement ranging from  $0.11$  to  $3.04 \text{ Mg C ha}^{-1} \text{ year}^{-1}$  with a mean of  $0.54 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ .

### ***Traditional and improved fallow***

Traditional fallow refers to the abandoned agricultural phase in which secondary vegetation develops with normal density and it is mainly



**Table 2.** Growth, litter production, fine root biomass of promising MPTs in humid tropics and their contribution on SOC content (Saha *et al.*, 2010)

| MPTs                 | Annual litter production<br>(g m <sup>-2</sup> ) | Time required<br>for decomposition<br>(days) | Total fine<br>root biomass<br>(g m <sup>-2</sup> ) | Organic C<br>(g kg <sup>-1</sup> ) |
|----------------------|--------------------------------------------------|----------------------------------------------|----------------------------------------------------|------------------------------------|
| <i>P. kesiya</i>     | 621.5                                            | 718                                          | 496.75                                             | 35.4                               |
| <i>A. nepalensis</i> | 473.75                                           | 350                                          | 435.50                                             | 32.2                               |
| <i>P. roxburghii</i> | 341.75                                           | 385                                          | 415.50                                             | 23.1                               |
| <i>M. oblonga</i>    | 512.25                                           | 390                                          | 462.00                                             | 33.6                               |
| <i>G. arboria</i>    | 431.75                                           | 360                                          | 419.00                                             | 28.6                               |

composed of native trees. This phase lasts a variable period of 10 to more than 50 years, depending on land availability. The definition of improved fallows (IF) is restricted to the AFS in which one (pure) or a few (mixed) tree species are planted as a substitute to natural fallow, to achieve the benefits of the latter in a short time (Young, 1997). Rao *et al.* (1998) distinguished two categories of IF: (1) the short-duration fallows with fast growing leguminous trees or shrubs seeking to replenish soil fertility; and (2) the medium-to-long-duration fallows with plantation of diverse species and aimed at rehabilitating degraded and abandoned lands as well as exploiting tree products such as poles and firewood. Lasco and Suson (1999) calculated an average C storage of 16 Mg ha<sup>-1</sup> over the 6-year period under *L. leucocephala* during the fallow phase of the Naalad system. Several studies have shown increased SOM after a few seasons of tree plantation on degraded soils. Considering the changes in bulk density of soil induced by the improved fallow practice and the sampling depth, SOC accretions were estimated between 0.73 and 12.46 Mg ha<sup>-1</sup>.

### North-eastern hilly region scenario

Assessment of soil quality is an invaluable tool in determining the sustainability and environmental impact of agricultural ecosystems. Soil quality under different agro-ecosystems using soil organic carbon (SOC), soil total nitrogen (STN) and soil microbial C (SMBC) and Nitrogen (SMBN) suggests that the shifting cultivated areas had the lowest SMBC value of 192 mg kg<sup>-1</sup> while soil under *Michelia oblonga* plantation had the

significantly ( $P < 0.05$ ) highest value of 478 mg kg<sup>-1</sup>. The proportion of SMBC to total soil organic carbon (SOC) was in the range of 0.76 to 1.96% across all the systems. Multipurpose tree species like *P. kesiya*, *A. nepalensis*, *P. roxburghii*, *M. oblonga* and *G. arboria* with greater surface cover, constant leaf litter fall and extensive root systems increased soil organic carbon by 96.2% (Table 2), besides they helped with better aggregate stability by 24.0%, improved available soil moisture by 33.2%, and in turn reduced soil erosion by 39.5% (Saha *et al.*, 2010; Saha *et al.*, 2007). Similarly, a comparative study on the effect of various MPTs on soil organic carbon

**Table 3.** Changes in SOC (Mg hm<sup>-2</sup>) over the years under various MPTs in humid tropics (Datta and Singh, 2007)

| MPTs                     | Years |      |      |      |
|--------------------------|-------|------|------|------|
|                          | 4     | 8    | 12   | 16   |
| <i>A. auriculiformis</i> | 11.1  | 11.9 | 17.9 | 21.9 |
| <i>M. alba</i>           | 9.9   | 9.9  | 9.9  | 15.9 |
| <i>L. leucocephala</i>   | 11.5  | 11.5 | 12.8 | 16.7 |
| <i>D. sissoo</i>         | 13.1  | 12.5 | 13.1 | 13.9 |
| <i>G. maculate</i>       | 13.1  | 13.1 | 13.9 | 14.9 |
| <i>A. indica</i>         | 10.9  | 10.9 | 14.7 | 28.6 |
| <i>M. champaca</i>       | 13.9  | 13.7 | 13.9 | 16.9 |
| <i>E. hybrid</i>         | 9.9   | 9.9  | 14.9 | 16.1 |
| <i>T. grandis</i>        | 11.5  | 11.3 | 11.5 | 12.9 |
| <i>G. arborea</i>        | 12.2  | 12.2 | 12.8 | 21.8 |
| <i>S. saman</i>          | 10.6  | 11.3 | 11.3 | 13.9 |
| <i>A. procera</i>        | 13.5  | 13.1 | 13.5 | 14.7 |
| Open space<br>(Control)  | 11.9  | 11.9 | 11.1 | 9.1  |

pool (Table 3) showed a concomitant rise in SOC in soils under MPTs and a subsequent decline in soils of open space over 4-16 years. Maximum rise in SOC was noticed in soils of *A. indica* (28.6 Mg hm<sup>-2</sup>) followed by *A. Auriculiformis* (21.9 Mg hm<sup>-2</sup>), *G. arborea* (21.8 Mg hm<sup>-2</sup>), *M. Champaca* (16.7 Mg hm<sup>-2</sup>), etc. The minimum rise in SOC was noted in soils under *T. grandis*. Therefore, an increase of SOC was noted from 3.8 Mg hm<sup>-2</sup> in soils of open space to 19.5 Mg hm<sup>-2</sup> in that under MPTs over a period of 16 years. The comparatively high humin carbon present in soils under *A. auriculiformis*, *L. leucocephala* and *G. Arborea* indicated an enhanced storage of organic carbon pool in agroforestry systems (Datta and Singh, 2007). Swamy *et al.* (2003) estimated that a six year old *G. arborea* based agri-sivicultural systems in India sequestered 31.4 Mg hm<sup>-2</sup> carbon.

## Conclusions

The potential of SOC sequestration is finite in magnitude and duration. It is only a short-term strategy in mitigating anthropogenic enrichment of atmospheric CO<sub>2</sub>. The public concern about the issue of global climate change has emphasized the need for developing and implementing strategies of agroecosystem management that will reduce carbon dioxide concentration in the atmosphere as well as improve soil fertility. SOC storage and the dynamics of C stock change in agroforestry (AFS) are important for evaluating the impact of agroecosystem management on global climate change. The analysis of C stocks from various parts of the world showed that significant quantities of C (1.1–2.2 Pg) could be removed from the atmosphere over the next 50 years if agroforestry systems are implemented on a global scale.

## References

- Balkrishnan and Toky, O.P. 1993. Significance of nitrogen fixing woody legume trees in forestry. *Indian Forester* **119**: 126-134.
- Conant, R.T., Paustian, K. and Elliott, E.T. 2001. Grassland management and conversion into grassland: effects on soil carbon. *Applied Ecology* **11**: 343-355.
- Datta, M. and Singh, N.P. 2007. Growth characteristics of multipurpose tree species, crop productivity and soil properties in agroforestry systems under subtropical humid climate in India. *Journal of Forestry Research* **18**: 261-270.
- Dixon, R.K. 1995. Agroforestry systems: sources or sinks of greenhouse gases? *Agroforestry Systems* **31**: 99-116.
- Department of Energy (DOE) 1999. *Carbon Sequestration: State of the Science*. US DOE, Washington, DC.
- Follett, R.F., Kimble, J.M. and Lal, R. 2001. The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. CRC/Lewis, Boca Raton, FL. pp. 442.
- Gupta, N., Kukal, S.S., Bawa, S.S. and Dhaliwal, G.S. 2009. Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. *Agroforestry Systems* **76**: 27-35.
- Haile, S.G., Nair, P.K.R. and Nair, V.D. 2008. Carbon storage of different soil-size fractions in Florida silvopastoral systems. *Journal of Environmental Quality* **37**: 1789-1797.
- Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate change 2000: the scientific basis*. Oxford University Press, Oxford.
- Jha, Pramod, Mohapatra, K. P. and Dubey, S.K. 2010. Impact of land use on physico-chemical and hydrological properties of ustifluent soils in riparian zone of river Yamuna, India. *Agroforestry Systems* **80**: 437-445.
- Kang, B.T. 1997. Alley cropping—soil productivity and nutrient recycling. *Forest Ecology and Management* **91**: 75-82.
- Kang, B.T., Caveness, F.E., Tian, G. and Kolawole, G.O. 1999. Long-term alley cropping with four species on an Alfisol in southwest Nigeria—effect on crop performance, soil chemical properties and nematode population. *Nutrient Cycling in Agroecosystems* **54**: 145-155.
- Kumar, B.M., George, S.J. and Suresh, T.K. 2001. Fodder grass productivity and soil fertility changes under four grass + tree associations in Kerala, India. *Agroforestry Systems* **52**: 91-106.
- Lal, R. 1996. Deforestation and land use effects on soil degradation and rehabilitation in western Ni-

- geria. II: soil chemical properties. *Land Degradation and Development* **7**: 87-98.
- Lasco, R.D. and Suson, P.D. 1999. A *Leucaena leucocephala*-based indigenous fallow system in central Philippines: the Naalad system. *International Tree Crops Journal* **10**: 161-174.
- Mishra, A., Sharma, S.D., Pandey, R. and Mishra, L. 2004. Amelioration of a highly alkaline soil by trees in northern India. *Soil Use and Management* **20**: 325-332.
- Nair, P.K.R. 1993. An Introduction to Agroforestry. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 499.
- Nair, P.K.R., Kumar, B.M. and Nair, V.D. 2009. Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science* **172**: 10-23.
- National Forestry Action Plan (NFAP) 2003. Ministry of Environment and Forests, Govt. of India, New Delhi, India, 1-303.
- Paustian, K., Six, J., Elliott, E.T., Hunt, H.W. 2000. Management options for reducing CO<sub>2</sub> emissions from agricultural soils. *Biogeochemistry* **48**: 147-163.
- Pulleman, M.M., Bouma, J., van Essen, E.A. and Meijles, E.W. 2000. Soil organic matter content as a function of different land use history. *Soil Science Society of America Journal* **64**: 689-693.
- Rao, M.R., Nair, P.K.K. and Ong, C.K. 1998. Biophysical interactions in tropical agroforestry systems. *Agroforestry Systems* **38**: 3-50.
- Saha, R., Ghosh, P.K., Mishra, V.K., Majumdar, B. and Tomar, J.M.S. 2010. Can agroforestry be a resource conservation tool to maintain soil health in the fragile ecosystem of north-east India? *Outlook in Agriculture* **39**(3): 191-196.
- Saha, R., Tomar, J. M. S., and Ghosh, P. K. 2007. Evaluation and selection of multipurpose tree for improving soil hydrophysical behaviour under hilly eco-system of northeast India. *Agroforestry System* **69**: 239-247.
- Sanchez, A. 1995. Science in agroforestry. *Agroforestry System* **30**: 5-55.
- Sanchez, P.A. 1987. Soil productivity and sustainability in agroforestry systems. In: Steppler H.A. and Nair P.K.R.(eds), *Agroforestry: A decade of development*. Nairobi, Kenya: ICRAF, 1-345.
- Schlesinger, W.H. 2000. Carbon sequestration in soil: some cautions amidst optimism. *Agricultural Ecosystems and Environment* **82**: 121-127.
- Singh, A. and Singh M.D. 1981. *Soil erosion hazards in North-Eastern Hill Region, Research*, Bulletin No.10. Meghalaya: ICAR Research Complex for NEH Region, Meghalaya, India, 1-45.
- Swamy, S.L., Puri, S. and Singh, A.K. 2003. Growth, biomass, carbon storage and nutrient distribution in *Gmelina arborea* stands on red lateritic soils in Central India. *Bioresource Technology* **90**: 109-126.
- Takimoto, A., Nair, V.D. and Nair, P.K.R. 2009. Contribution of trees to soil carbon sequestration under agroforestry systems in the West African Sahel. *Agroforestry Systems* **76**: 11-25.
- Young, A. 1997. *Agroforestry for Soil Management*, 2nd ed. CAB International, Wallingford, UK, pp. 320.

---

Received: 26 June 2012; Accepted: 30 August 2012