Biomass productivity and carbon stocks of farm forestry and agroforestry systems of leucaena and eucalyptus in Andhra Pradesh, India

J. V. N. S. Prasad*, K. Srinivas, Ch. Srinivasa Rao, Ch. Ramesh, K. Venkatravamma and B. Venkateswarlu

Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad 500 059, India

Increasing concentration of greenhouse gases in the atmosphere and the adverse effects associated with climate change have necessitated the need for identification of systems with high carbon sink as a mitigation strategy. Tree-based systems with short rotation species either as farm forestry or agroforestry systems have the potential to sequester carbon in a short period. Leucaena and eucalyptus-based systems, mostly planted at closer spacing, are widely distributed in several districts of Andhra Pradesh, India. The objective of this communication is to analyse the carbon storage of two land-use systems (farm forestry and agroforestry) with two short rotation tree species, viz. leucaena and eucalyptus, and to evaluate their carbon sequestration potential in degraded lands. Trees in farm forestry systems were close planted at 1 × 1 m and 3 × 2 m, whereas those in agroforestry systems were planted at wider spacing of 3 × 0.75 m and 7 × 1.5 m in paired rows, in leucaena and eucalyptus respectively. The carbon stock of leucaena farm forestry system was 62 Mg/ha, whereas in eucalyptus farm forestry system, it was 34 Mg/ha for a rotation of 4 years. Biomass and carbon accumulation were relatively higher in farm forestry systems and the rate of accumulation was highest during the third year. It is concluded that, leucaena and eucalyptus systems can play an important role as carbon sinks and contribute significantly to the removal of CO_2 from the atmosphere.

Keywords: Agroforestry, biomass, carbon sequestration, farm forestry, intercrops.

CARBON sequestration (CS) through sink enhancement by way of integration of trees into landscapes is one of the cost-effective mitigation strategies. Land-use, land-use change and forestry (LULUCF), an approach that became popular in the context of the Kyoto protocol, allows afforestation and reforestation (A&R) as greenhouse gas (GHG) offset activities[1]. Agroforestry is an ideal land-use option as it optimizes tradeoffs between increased food production, poverty alleviation and environmental conservation[2]. Agroforestry has been recognized as a CS activity under A&R of clean development mechanism (CDM) and attracted attention as a CS strategy from both industrialized and developing countries. Agricultural lands are believed to be a major potential sink and can absorb large quantities of carbon if trees are introduced and judiciously managed with crops[3].

World over, it has been estimated that the potential area suitable for agroforestry from land-use change could be up to 630 m ha which would result in storing 586 mt C/yr by 2040, mostly in developing countries[4]. The transformation of low productive crop lands into agroforestry can triple carbon stocks from 23 to 70 t/ha in a 25-year period[4]. Agroforestry is also an attractive option for climate change mitigation as it sequesters carbon in vegetation and soil, produces wood, serving as substitute for similar products that are unsustainably harvested from natural forests, and also contributes to farmers' income[5]. Short rotation tree crops, either as farm forestry or agroforestry systems, are considered an effective means to mitigate the greenhouse effect, due to their ability to accumulate substantial quantities of carbon in vegetation in a limited period. In addition, production from plantation forests may relieve pressure on timber extraction from natural forests, and thus contribute to forest conservation.

In India, increase in population and consequent increase in demand for various kinds of paper and the emphasis on paper as an environment-friendly packaging material has increased the demand for wood. During 2006, wood demand was about 82 million m^3, of which forests contributed 12 million m^3, whereas plantations[6], farm forestry and agroforestry contributed 53 million m^3. In India, trees outside forests produce 80% of the industrial roundwood and 75% of the fuelwood[7]. The National Forest Commission (2006) emphasized that forests alone cannot meet the growing requirements of wood and hence agroforestry in private and community lands has to be promoted to bridge the shortfall[6]. Apart from paper and pulpwood industry, wood is increasingly being used as a substitute for coal in biomass-based power generation units due to commitments to reduce GHG emissions, desire to secure and diversify the supply of energy, and uncertainties related to oil price in many parts of the world[8]. Integrating trees into landscapes not only sequesters carbon, but also meets the requirements of various industries.

In Andhra Pradesh, eucalyptus and leucaena systems are widespread, and Prakasam district alone has an area of one lakh acres producing 7 lakh tonnes of wood valued at Rs 560 million annually from private holdings of farmers[9]. The wood is suitable for a wide range of uses, from the traditional small-scale use by farmers to the more recent utilization by large-scale industries for pulp and energy generation[10]. Eucalyptus clones and leucaena are generally grown at a close spacing of 3 × 2 m and 1 × 1 m respectively, mostly under farm forestry systems. In farm forestry systems, intercrops are not generally taken up

*For correspondence. (e-mail: jasti2008@gmail.com)

and inter-cultivation is rarely done in eucalyptus and not practised in leucaena. A few farmers take up intercrops during the first year and from the second year onwards, intercropping is not possible due to shading from the trees. As the trees are harvested only after 4 years, the adoption of these systems is mostly confined to large farmers and farmers who have alternate sources of income, as small farmers need annual returns for sustenance. Growing food crops along with the trees in wider rows as agroforestry not only helps to realize grain yield from arable crops till the trees are harvested, but also ensures wood and food security requirements simultaneously. Though the forestry systems are known to accumulate substantial amounts of carbon, information related to the agroforestry systems is lacking.

In India, the potential of short rotation forestry in sequestering carbon has been reported for poplar[11,12], eucalyptus, sal, teak[13], leucaena, albizzia and acacia[14] species. The annual rate of accumulation of carbon in these tree species ranged from 1 Mg C/ha/yr in sal to 11.8 Mg C/ha/yr in poplar in the Indo Gangetic regions under irrigated conditions. The potential of agroforestry systems in terms of carbon storage in different ecoregions of the world was reviewed by Dixon *et al.*[3,15]. Nair *et al.*[1] summarized that the potential varied from 0.3 to 15.2 Mg C/ha/yr, the highest being in the humid tropics receiving high rainfall. Although the significance of agroforestry in carbon sequestration and CO_2 mitigation is being widely recognized, there is paucity of quantitative data on specific systems. Some short rotation crops are known to produce high biomass and accumulate carbon, but information on leucaena and eucalyptus, particularly in farm forestry and agroforestry systems, is scanty. On-farm experiments were conducted in collaboration with the paper company ITC-PSPD, Bhadrachalam to develop agroforestry systems of these two tree species. The data from these experiments was used to quantify wood production and carbon stocks in these two systems.

Experiments were conducted in three farmers' fields in three villages located close to Bhadrachalam town (82°52′05″E and 17°41′19″N) within 50 km distance of each other in Khammam district of Andhra Pradesh, South India, in degraded lands which are not being used for intensive arable cropping. The experimental sites lie in the alluvial belt of the Godavari river and have a relatively flat topography. The soils are neutral to slightly alkaline (pH 7.0–8.3) and non-saline electrical conductivity (EC) 0.14–0.19 dS/m), low in organic carbon (0.31–0.58%) and low in available forms of all the three major nutrients (63–100 kg N/ha, 9.6–12.5 kg P/ha and 75–110 kg K/ha) in the top 15 cm soil layer. The area receives an average annual precipitation of 1,120 mm, distributed in about 60 rainy days. About 85–90% of the total rainfall is received during June to October. *Eucalyptus tereticornis* clones were selected due to their high biomass production potential and uniform growth. *Leucaena leucocephala* variety K-636 was used because of its desirable characteristics such as low seed production and erect growth with fewer branches.

The experiments were conducted at three locations and at each location both the tree systems were taken up. In case of leucaena, the farm forestry system consisted of close planting at 1×1 m spacing (10,000 trees/ha), whereas agroforestry systems were planted at a spacing of 3×0.75 m (4,444 trees/ha). In case of eucalyptus, the farm forestry system was planted at 3×2 m spacing, whereas the agroforestry system was planted at 7×1.5 m spacing in paired rows. The distance between two paired rows of eucalyptus was 7 m and two tree rows in a pair were spaced at 1 m and within rows, trees were spaced at 1.5 m. In eucalyptus, both the planting geometries give the same tree density (1666 trees/ha). Trees were planted in August 2001. Cowpea crop was grown as intercrop during the *rabi* season in the initial years, and during the last year Guinea grass (*Panicum maximum*) was grown, following the recommended package of practices. In farm forestry, as crop growth in the second year was poor, intercrops were not grown from the third year onwards. The gross plot size varied between 324 and 1,144 sq. m and the net plot size varied from 60 to 540 sq. m depending on the land available in each farmer's field. Tree height and diameter at breast height (DBH) were measured on selected trees in each plot at monthly intervals. Leucaena was applied 23 kg N ha^{-1} during the first year and Rhizobium inoculation was done after transplanting. From second year onwards, 23 kg P ha^{-1} and 44 kg K ha^{-1} were applied. Eucalyptus was applied 26 kg P ha^{-1} during the first year and subsequently 46 kg N ha^{-1}, 23 kg P ha^{-1} and 44 kg K ha^{-1} were applied from the second year onwards. Fertilizers were mixed and the mixture was applied in 30 cm deep holes made at a distance of 0.5 m away from the stem on either side of the row, equally to all the trees in a plot. Trees were harvested 51 months after planting in November 2005. At harvest, tree height and DBH were recorded for all the trees and biomass was portioned into foliage, branches, bark and stem for a few trees in the net plot of each treatment.

For estimating tree biomass and volume yearwise, published equations were used. In the case of Leucaena, timber weight ($W = (339.913*D^2h) - 15.513$ kg/tree) and volume per tree ($V = (0.345714*D^2h) - 0.0157482$ m^3) were estimated by using the equations developed by Dhanda *et al.*[16]. In the case of Eucalyptus, timber volume ($V = (0.00003361*D^2h) + 0.00237$ m^3) was estimated using the equations developed by Ajit *et al.*[17] and weight was estimated by multiplying the volume with the density of the timber[18]. The estimated timber weight was compared with that of the measured values of 60 trees with varying DBH for each species. There was good agreement between the observed and the estimated values (Figure 1) and the r^2 values ranged from 0.97 to 0.99. Carbon content in the wood was estimated by combustion method and the below-ground biomass was estimated by using the Intergovernmental Panel on Climate Change (IPCC) factor of 0.25 of the above-ground biomass. Data on tree growth and biomass production of individual trees and stand productivity was analysed following the two-tailed *t*-test with equal variance at 1% and 5% levels of significance.

Growth data of leucaena trees revealed that mean height and DBH were higher with agroforestry system in comparison to the farm forestry system. Timber volume and timber weight of individual trees were significantly higher with trees in agroforestry system in leucaena in comparison to farm forestry system. In leucaena, the highest individual tree volume recorded at the time of harvest was in 3 × 0.75 m spacing (0.035 m^3/tree) which was about 66% higher in comparison to the narrow rows (Table 1). In eucalyptus, tree volume and weight of the individual tree were not significantly influenced by spacing and differences between agroforestry and farm forestry systems were not significant. Fresh biomass accumulation in individual trees varied between 5 and 15 kg/tree/year, being much higher in comparison to the other tree species such as Acacia[19], albizzia, *Azadirachta indica*, *Acacia nilotica* and *Acacia albida*[14] grown under rainfed conditions.

Estimated timber volume of farm forestry system in leucaena at the end of the first year of tree growth was 11.07 m^3/ha and increased to 149 m^3/ha at the time of harvest. Timber weight increased from 10.89 to 143 t/ha for the corresponding period. Farm forestry system recorded significantly higher timber volume and timber weight over agroforestry system in leucaena. In the case of eucalyptus, estimated timber weight in farm forestry system was 5.28 t/ha at the end of the first year and reached 92.40 t/ha at the time of harvest. Timber volume and timber biomass did not differ significantly due to the spacing of trees in eucalyptus.

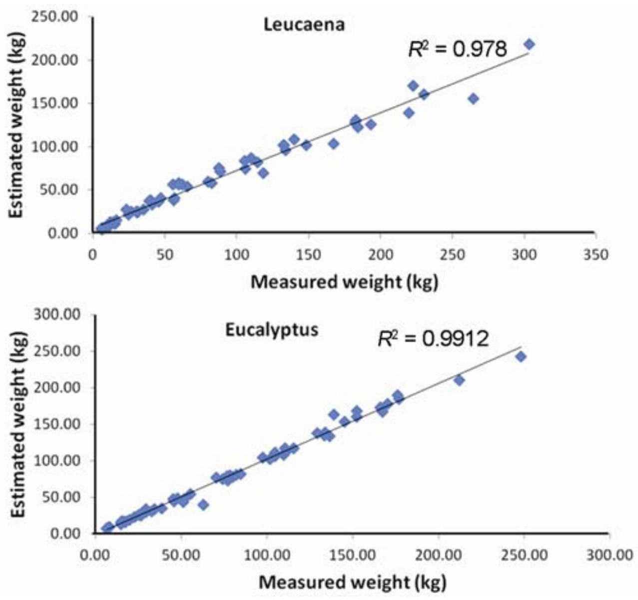

Figure 1. Relationship between estimated and measured timber weight (kg) in leucaena and eucalyptus (n = 60).

Intercrop yields were not influenced in eucalyptus during the first cropping season after tree planting (i.e. 2001, post-rainy season), but during the subsequent years, crop yields were significantly reduced (Table 2). In 2002, post-rainy season, cowpea intercropped in eucalyptus yielded 45% of the sole crops, whereas cowpea intercropped in leucaena recorded 36% of the sole crop yield. The extent of yield reduction was greater, nearer to the tree rows. Magnitude of crop yield losses in agroforestry systems is known to increase with age of trees due to increased size of trees and their ability to draw resources at the expense of crops particularly under rainfed conditions[20].

Dry biomass in various tree parts of eucalyptus ranged from 33% to 55% of fresh biomass, whereas in leucaena, it ranged from 32% to 58%. Carbon content of various tree parts of eucalyptus ranged between 41% and 47%, and in leucaena, it ranged from 45% to 51%. Carbon stock in leucaena was highest in farm forestry system (62 t/ha) and significantly higher than agroforestry system (Table 3). Among the various tree components, carbon stock was highest in bole (44 t/ha), whereas contribution of below-ground biomass was about 12 t/ha. In the case of eucalyptus, carbon stock ranged from 31 to 34 t/ha and was higher in farm forestry system, but the differences were not significant. In the present study, the average annual carbon sequestration rates achieved for leucaena and eucalyptus system were 15.51 and 8.61 Mg/ha/year, which are relatively higher than those of poplar (8 Mg/ha/year), eucalyptus (6 Mg/ha/year) and teak (2 Mg/ha/year)[13]. Accumulation of CO_2 was significantly higher with leucaena systems in closer spacings of farm forestry land-use (228 Mg/ha/4 years) compared to wider rows (212 Mg/ha/4 years) (data not presented). Similarly, narrow rows of eucalyptus accumulated about 126 Mg CO_2/ha/4 years. Some of the carbon accumulated in the branches, leaves and bark reaches to soil through litter fall and contributes significantly to soil carbon stocks in the long run.

The poplar-based system has carbon accumulation rate of about 11.9 Mg/ha/year under irrigated conditions of Indo-gangetic plains[11] and in acacia hybrid-based system, the recorded rates are 3.3 Mg/ha/year under high rainfall conditions[19]. Eucalyptus and leucaena systems had higher rates of carbon accumulation in comparison to poplar, teak, albizzia and acacia systems reported from various places in India. Carbon sequestration in leucaena system is the highest when compared to other tree systems in semi-arid conditions under rainfed situations. The present study was carried out in degraded lands which are not under intensive arable cropping. The study reveals the potential of short rotation forestry with these tree species

Table 1. Growth of leucaena and eucalyptus trees in farm forestry and agroforestry systems in Khammam district of Andhra Pradesh, India

Tree parameters	Tree species	Spacing (m)	Year 1	Year 2	Year 3	Year 4	At harvest
Timber volume (m^3/tree)	Leucaena	1 × 1 (FF)	0.0016	0.0055	0.011	0.015	0.021
		3 × 0.75 (AF)	0.0019 NS	0.0074*	0.018**	0.028**	0.035**
	Eucalyptus	3 × 2 (FF)	0.0029	0.016	0.038	0.044	0.050
		7 × 1.5 Paired rows (AF)	0.0026 NS	0.012 NS	0.031 NS	0.039 NS	0.049 NS
Timber weight (kg/tree)	Leucaena	1 × 1 (FF)	1.53	5.44	10.57	12.85	20.20
		3 × 0.75 (AF)	1.88 NS	7.27*	18.02**	27.53**	34.12**
	Eucalyptus	3 × 2 (FF)	3.60	20.00	47.00	54.93	63.00
		7 × 1.5 Paired rows (AF)	3.30 NS	15.40 NS	39.00 NS	49.13 NS	61.00 NS

FF, Farm forestry system; AF, Agroforestry system.

Table 2. Intercrop yields in farm forestry and agroforestry systems in Khammam district of Andhra Pradesh, India

		Cowpea yield (kg/ha)				Guinea grass fodder yield (Mg/ha)
Tree species	Spacing (m)	Year 1	Year 2	Year 3	Year 4	At tree harvest
Leucaena	1 × 1 (FF)	–	–	–	–	–
	3 × 0.75 (AF)	1002	127	85	–	–
Eucalyptus	3 × 2 (FF)	879	296	121	134	0.88
	7 × 1.5 Paired rows (AF)	926 NS	485*	405*	229*	1.36*

Table 3. Carbon stock (Mg C/ha) in leucaena and eucalyptus plantations in farm forestry and agroforestry systems in Khammam district of Andhra Pradesh, India

	Leucaena				Eucalyptus			
Year	Bole	Branch + bark + leaves	Below ground	Total	Bole	Branch + bark + leaves	Below ground	Total
	Farm forestry (1 × 1 m)				Farm forestry (3 × 2 m)			
Year 1	3.31	0.47	0.94	4.71	1.34	0.18	0.38	1.91
Year 2	11.72	1.65	3.34	16.71	7.47	1.01	2.12	10.59
Year 3	22.77	3.21	6.49	32.49	17.54	2.37	4.98	24.90
Year 4	39.00	5.49	11.10	55.61	23.30	3.15	6.61	33.04
Harvest	43.52	6.13	12.41	62.05	24.26	3.28	6.89	34.43
	Agroforestry (3 × 0.75 m)				Agroforestry (7 × 1.5 paired rows)			
Year 1	2.23	0.31	0.64	3.18	1.19	0.16	0.34	1.69
Year 2	8.63	1.21	2.46	12.30	5.55	0.75	1.58	7.88
Year 3	21.39	3.00	6.10	30.49	14.06	1.90	3.99	19.96
Year 4	37.12	5.21	10.60	52.91	20.90	2.90	5.95	29.81
Harvest	40.49	5.68	11.54	57.71	21.99	2.98	6.24	31.21

for accumulating carbon, particularly in degraded lands, which can be used as potential sinks and can be put to profitable land-use, and can meet the economic and environmental goals under rainfed conditions.

In the present study, differences in carbon accumulation between farm forestry and agroforestry systems of eucalyptus were not significant. Planting in wider rows as in agroforestry system facilitates extended intercropping for the entire period of rotation besides the biomass production from the trees. In the case of leucaena agroforestry system, the wider rows of 3 m facilitate normal yields of intercrop during the first 2 years of tree growth contributing to farmers' income. The yields of intercrops were higher in agroforestry systems in comparison to farm forestry systems[21,22]. In view of the concerns of global climate change and the escalating prices of food grains, agroforestry is an important mitigation strategy which can accumulate carbon quickly without impacting food grain production. However, in severe degraded lands which are not suitable for arable intercropping, farm forestry systems with narrow spacing can be grown profitably and can meet both production and environmental goals. Under both the situations, eucalyptus and leucaena species were found to be promising.

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Compositional variation recorded in deep-sea ferromanganese deposits of the Central Indian Ocean

Mitali Chandnani[1], Dev Kumar Gupta[1], Yashrakshita[1], Rachana Singh[2], Pulkit Singh[1], Sweta Baidya[3] and Virupaxa Banakar[3,*]

[1]Department of Earth Sciences, Indian Institute of Technology, Roorkee 247 667, India
[2]Department of Geology, Banaras Hindu University, Varanasi 221 005, India
[3]Geological Oceanography Division, CSIR-National Institute of Oceanography, Dona Paula, Goa 403 004, India

Traditionally, the genesis of marine ferromanganese deposits (abyssal nodules and seamount crusts) has been discussed mostly based on their bulk composition. But, marine ferromanganese deposits are products of an intimate mixture of ultra-fine lithogenous silicates of continental origin (residue component) and colloidal Fe–Mn hydroxides precipitated within the seawater environment (hydrolysate component). The former component, although not dominant, has the ability to mask actual genetic relationships between various elements associated with hydrolysate component, in turn, affecting the understanding of the genesis of marine ferromanganese deposits. Against this background, we present here, the compositional variations recorded by the hydrolysate component of Fe–Mn hydroxide deposits and discuss the results in terms of their genesis.

Keywords: Chemical composition, Fe–Mn deposits, genesis, Indian Ocean.

OCEANIC ferromanganese deposits (Fe–Mn nodules and seamount Fe–Mn crusts) were discovered over a century

*For correspondence. (e-mail: banakar@nio.org)