

Comparison of Biomass and C Storage in Three Promising Fast Growing Tree Plantations under Agroforestry System in Sub-humid Tropics of Chhattisgarh, India

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Abstract The anthropogenic activities are alarmingly increasing the concentrations of CO₂ in the atmosphere leading to the climate change. Agriculture ecosystem especially tropical agriculture is most vulnerable to climate change posing a serious threat on food, nutritional security and livelihoods of poor farming communities. Agroforestry technologies indeed offer viable opportunity to mitigating the atmospheric accumulation of CO₂ and other Greenhouse gases, and potential for transforming to resilient farming systems and further help smallholder farmers of many tropical countries like India for adapting to climate change. However, the magnitude of C sequestration in many agroforestry systems is still unknown, which primarily depends on the choice of tree species and managerial practices. The present study corresponds to a part of the long term project on *Gmelina arborea*, *Populus deltoides* and *Ceiba pentandra* based agroforestry systems evaluated for C storage potentials in sub-humid tropics Chhattisgarh, India. At 5 years age, total biomass varied from 12.9 Mg ha⁻¹ to 25.1 Mg ha⁻¹ in *C. pentandra*, while 9.9 Mg ha⁻¹ to 21.4 Mg ha⁻¹ in *G. arborea*. The biomass was greater under narrow tree spacing. A significant growth and biomass variation was also exhibited by *P. deltoides* clones, where the total biomass ranged from 48.5 Mg ha⁻¹ to 62.2 Mg ha⁻¹. At 5 years age, total C storage in *G. arborea* stands ranged from 4.3 to 9.4 Mg ha⁻¹, *P. deltoides* from 22.5 to 30.1 Mg ha⁻¹ and *C. pentandra* from 4.5 to 10.1 Mg ha⁻¹. Soil organic C significantly enhanced under agroforestry system. Soil organic C in *G. arborea* stands increased from 6.8% to 11.9%, *P. deltoides* from 12.7% to 20.6%, and *C. pentandra* from 5.5% to 14.5% under different treatments. *P. deltoides* showed the greater potential for C sequestration than *G. arborea* and *C. pentandra* under agroforestry system. Clones 65/27 and D121 of *P. deltoides* were found outstanding and suggested to adopt under agroforestry. Soybean and wheat yields were decreased under agroforestry systems, which advocate introducing appropriate tree management practices to improve the complementarity to exploit synergies between tree and crop components. The paper discusses the

management implications and strategies for sustainable tree-crop production and improving C sequestration under agroforestry systems for mitigating the climate change.

Keywords Adaptation, Biomass, Carbon Sequestration, Climate Change, Greenhouse Gases, Mitigation, Tree-crop Interaction, Yield Losses

1. Introduction

Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC) emphasized to develop a strong rationale for mitigation and adaptation to climate change especially in developing countries of tropics to face the challenge of climate change (IPCC, 2014). There is growing concern among scientific community to evolve resilient agro-ecosystem to climate change as the livelihoods and economy of majority of population in tropics are dependent on climate sensitive agriculture sector (Verchot *et al.*, 2007; Murthy *et al.*, 2013; Nair and Nair, 2014). The small and marginal farmers are more vulnerable and facing the brunt of climate change in India. As more than 90% of the population in rural areas belongs to this community and agriculture is the mainstay of their livelihood and economy (Nath and Behera, 2011).

Impact of climate change on agriculture is striking in many parts of India including the state of Chhattisgarh, which is located in the eastern part of the country popularly known as rice-bowl of eastern India (Murthy *et al.*, 2013). Anthropogenic activities like deforestation, industrialization and rapid land use transformation are destructing the environment and contributing for the change in regional climate (Puri and Nair, 2004). According to a report of Sastri (2010), the rainfall decreased by 5-35% and number of rainy days decreased from 75 to 50 days in different regions of Chhattisgarh. The maximum temperature reached to peak beyond 46 °C during summer (May). In some pockets, the

climate changed from moist sub-humid type to semi-arid and other pockets from moist sub-humid to dry sub-humid. The negative impacts of climate change on agriculture are clearly evident in the region (Sastri, 2010). The large farmers have initiated mitigation and adaptation activities by changing the land management and agronomic practices as part of their climate smart agriculture. However, small and marginal farmers could not able to shift from traditional agriculture due to lack of knowledge and poor socio-economic conditions. Under these circumstances, the agroforestry systems which could help agro-ecosystem to adapt to greater climate variability as well as mitigate greenhouse gases through C sequestration and by buffering crops from the effects of temperature and precipitation variation (Verhot *et al.*, 2007; Chauhan *et al.*, 2012; Nair and Nair, 2014). Numerous reports are available on C sequestration potential of agroforestry systems (Albrecht and Kandji, 2003; Chauhan *et al.*, 2011; Nair and Nair, 2014). Fast growing tree plantations are considered highly efficient carbon sinks because of their adaptability and relatively high rates of productivity (Kumar and Nair, 2012).

However, the potentials of many multipurpose trees on C sequestration and crop productivity are yet to be exploited under agroforestry systems in Chhattisgarh, India. *Gmelina arborea*, *Populus deltoides* and *Ceiba pentandra* are three promising fast growing multipurpose species grown by farming communities (Puri and Nair, 2004). *G. arborea* is an indigenous tree practiced by the farmers for its timber and pulp wood, whereas the *P. deltoides* for match sticks and packaging boxes. The wood of *C. pentandra* on the other hand is an excellent source of match splint and packing cases, besides the silk cotton from pods mainly used for stuffing pillows, mattresses, life-belts etc. All three species have good economic value and readily sold in local markets. Despite the diverse value and economic benefits, only a limited scientific work was done (Puri *et al.*, 2002; Swamy *et al.*, 2003) and studies are lacking on comparative evaluation of species under agroforestry system. Therefore, a long term study was initiated with a goal to compare the biomass, tree-crop interaction, nutrient cycling and C sequestration potentials under *G. arborea*, *P. deltoides* and *C. pentandra* based agroforestry system in sub-humid tropics of Chhattisgarh, India. The present study is a part of this project related to the comparison of biomass and C storage as an indicator of C sequestration potential. The results of five year studies provide useful insights and opportunity to exploit the potentials of species under agroforestry system for C sequestration on degraded agricultural sites.

2. Material and Methods

2.1. Study Site

The study was conducted at Forestry Research Farm of Indira Gandhi Agricultural University, Raipur (latitude 21° 12'N and longitude 81° 36' E), Chhattisgarh, India. The

climate of the region is sub-humid tropical with an annual precipitation of 1200-1400 mm, of which 80% is received during July to October. Mean monthly maximum and minimum temperatures range from 27 °C and 13 °C in December to 42 °C and 28 °C in May, respectively. The topography is almost plain with < 1% slope. The soil type is *Vertisol*, relatively fertile with black deep clayey soil characterized by fine texture, sticky in nature and angular blocky structure with good water holding capacity. It is fairly rich in organic carbon (0.43 ± 0.04 %), available potassium (358.6 ± 28.5 kg ha⁻¹) and medium in available nitrogen (253 ± 11.5 kg ha⁻¹) and low in available phosphorous (10.8 ± 0.95 kg ha⁻¹) with a pH of 7.5 ± 0.2 (Puri *et al.*, 2002). The site was an abandoned agricultural land, which was fallow and not cultivated for the last five years.

2.2. Site Preparation and Establishment of Agroforestry Experiments

Three agroforestry experiments of *G. arborea*, *C. pentandra* and *P. deltoides* were simultaneously established on abandoned agricultural land in study site. Each experiment was conducted on 1.2 ha of land leaving 15 m buffer to serve as control (treeless plots) for growing sole crop without any trees. The care has also taken to raise the guard rows of trees on boundaries to avoid the inter-specific competition. The methods adopted for establishing plantations and growing crops under trees in the form of agroforestry system are as follows.

2.2.1. Establishment of *G. arborea* and *C. pentandra* Stands

The land was ploughed and levelled for the establishment of *G. arborea* and *C. pentandra* based agroforestry systems. Nursery raised three-month-old uniform size (height 0.78 ± 0.15 m; collar diameter 0.65 ± 0.1 cm) healthy seedlings of *G. arborea* and *C. pentandra* were transplanted in 45 cm³ pits at three spacing (4 x 4 m, 4 x 6 m and 4 x 8 m) following three replications. A sum total of 432 trees were maintained for each species comprising 192 trees in 4 x 4 m, 144 trees in 4 x 6 m and 96 trees in 4 x 8 m spacing. Sixteen (16) trees falling in the central rows were marked for taking observations on trees and inter crops. A basal dose of 100 kg ha⁻¹ N, 40 kg ha⁻¹ P and 80 kg ha⁻¹ K was applied at the time of planting. After first year, nitrogen @ 120 kg ha⁻¹, phosphorous @ 40 kg ha⁻¹ and potassium @ 80 kg ha⁻¹ were applied every year for two years. N was applied in two equal splits (July and March) while P and K as a single dose in July. The plots were irrigated weekly in summer (March-June) and at monthly interval in winter (October to February), while no irrigation was provided in rainy season (July-September). The total water given ranged from 600 to 800 mm per annum. Pruning of lower branches was carried every year up to 1/3rd of crown height of trees at the beginning of winter (November). The crops were grown under different tree spacing of 5 yr-old stands of *G. arborea* and *C. pentandra*.

2.2.2. Establishment of *P. deltoides* Clones

In another experiment, clonal trial of Poplar was established as an agroforestry system. For this experiment, initially 106 clones of *Populus deltoides* (Poplar) were collected from different parts of north India and were evaluated in nursery and field conditions for three years. Among 106 clones, 19 clones were found promising and among them five best clones *viz.* 65/27, G3, G48, D121 and S7C1 were selected for establishing agroforestry system. These clones were chosen on the basis of their growth rate, crown characteristics and adaptability in juvenile stages. The 1-year-old entire-transplants (ETP) were planted at 4 x 5 m spacing as monoclonal blocks in a randomized block design. Each clone was replicated three times with a total number of 36 trees maintained for a clone per replication (plot) and thus in all forming 540 trees in the trial (5 clones x 3 replications x 36 trees per replication). Sixteen trees (16) located centrally rows were marked for recording observations on trees and intercrops. Each tree was fertilised with 50 g of single super phosphate (SSP) and 25 g of muriate of potash. Nitrogen in the form of diammonium phosphate (DAP) was given at 100 g plant⁻¹ in two split doses (last week of June and September). The fertilization was done initially during the first two years. Plantation was irrigated at weekly in summer (March-June) and fortnightly in winter seasons (October-February). No irrigations were provided during rainy season (July-September). A sum total of 1404 trees were planted for three species which include 432 trees each for *G. arborea* and *C. pentandra* and 540 for five clones of *P. deltoides*.

2.3. Intercropping of Soybean and Wheat

Soybean and wheat are the most common crops grown in rainy and winter seasons in study area of Chhattisgarh. Therefore, soybean (*Glycine max* var. JS 80-21) was intercropped during rainy season (June-November), while wheat (*Triticum aestivum* var. GW-273) in winter (November-March) under the stands of *G. arborea*, *C. pentandra* and *P. deltoides* as agroforestry system. The crop treatments were also arranged in a randomized block design and replicated three times. The crop treatments were consistent with tree spacing and clonal treatments. Monospecific crop plots (treeless controls) were established block-wise in the contiguous area for comparative purposes. Crops were grown following local recommendations in respect of agronomical practices and fertiliser applications. The methods followed for measurement of tree growth, biomass, C storage and yield attributes of crops are described below.

2.4. Tree Growth and Leaf Area Index (LAI)

Growth parameters like diameter at breast height (DBH), total height and clean bole were measured in 5 year old stands. Stand density was also recorded by counting the live and dead trees. Diameter at breast height was measured at 1.37 m on trunk and total tree height by calibrated pole. LAI of trees and amount of PAR (Photosynthetically active

radiation) intercepted by tree canopies were measured using a Plant Canopy Analyser (LAI 2000, LI-COR, Lincoln, NE). A single measurement of LAI was accomplished by taking the LAI 2000 unit outside the experimental plot (in the open) to record an "above canopy reading" of sky brightness and then sampling 10 random locations in the central region of each tree (beneath canopy readings). Care was taken to ensure that the unit was facing the same direction both outside and inside the stand. A sunlit canopy was avoided by taking measurements just after the sunrise and just before sunset when the solar elevation is low. A view restrictor 90⁰ was used in all measurements to prevent direct sunlight from reaching the sensor and at the same time to occlude the measuring person from the area of view.

2.5. Stand Biomass

Biomass estimation of stands was made by harvesting five trees proportionally distributed over the range of stem diameters (3.5– 25 cm) for each species and clones, was selected for destructive sampling. The trees were carefully cut at 15 cm from ground level. Each tree was further subdivided into components *viz.*, stems, branches and foliage. Fresh weight of these components was determined in the field. The component parts were later sub-sampled for moisture determination and chemical analysis. For quantifying coarse root (> 5 mm) biomass, roots of 25 trees were excavated by the skeleton method (dry excavation) up to 1 m³ soil volume and the fresh weight of roots were measured. All the sub-samples were oven dried at 70⁰ C to a constant weight. The total oven-dry weight of each component was calculated by applying oven-dry: fresh weight ratios. Total tree biomass was computed by summing the biomass of stem, branch, foliage and root components. The mean values of the five trees were used for estimating stand biomass. The stand biomass per hectare was calculated from the mean of dry weight totals of plots and expanded to a hectare basis.

2.6. C Analysis in Plant and Soil Samples

The randomly collected plant samples of foliage, bole, branches and roots of three species were analysed for total C. It was estimated following dry combustion method using Shimadzu TOC – 5000 A with solid sample analysis module. C quantities in tree components were obtained from the product of total biomass of each component and the average C concentrations in that component. Total C storage was achieved by summing the C quantities in stem, branch, foliage and root components. The carbon quantities were further extrapolated to hectare basis by multiplying with the standing biomass per hectare.

The changes in C in soils were assessed in agroforestry system after 5 years. Soil samples were randomly collected under three stands (three randomly chosen points in each plot) at 0-20 cm and 20-40 cm depths. Soil was analysed for total organic C following dry combustion method using Shimadzu

TOC – 5000 A with solid sample module. The amount of soil organic C was determined by multiplying soil weight per given soil volume with mean C concentration values. The total C storage in stands (trees) was computed by summing the C stored in foliage, stem, branch and roots. The total C storage in the system was estimated by adding the C accumulated in vegetation and soil compartments in a five year period.

2.7. Statistical Analysis

Data on growth, biomass, C storage in tree and soil under three stands were analysed following analysis of variance procedures (Steel and Torrie, 1980). The crop yields were also analysed using similar procedure. Significant differences between treatment means for growth, biomass, C storage and crop yields were tested at $p \leq 0.05$ using least significant difference (LSD) test.

3. Results

3.1. Growth of *G. arborea* and *C. pentandra* Stands

The stand characteristics of *G. arborea* and *C. pentandra* are presented in Table 1. Tree stocking varied according to the degree of mortality suffered by each stand. The percent of mortality in stands increased with an increase in tree spacing. The stocking density was higher in *C. pentandra*, which ranged from 91% to 95%, while it was comparatively low and varied from 82% to 91% in *G. arborea*. A significant variation was found in growth traits of *C.*

pentandra due to different tree spacing (Table 1), whereas no such marked differences were observed in *G. arborea*. Dbh (diameter at breast height) and total tree height were relatively higher in *C. pentandra* compared to *G. arborea*. It was observed that Dbh was almost double in stands of *C. pentandra* in comparison to *G. arborea*. The stands in narrow tree spacing (4 x 4 m) recorded slightly better growth than those in the wide spacing (4 x 8 m). LAI (leaf area index) was almost similar in both stands and it gradually decreased with an increase in tree spacing, whereas photosynthetically active radiation (PAR) showed reverse trend. PAR levels were increased by 10% in *C. pentandra* stands at wide tree spacing (Table 1)

3.2. Biomass and C Storage in *G. arborea* and *C. pentandra* Stands

Biomass showed significant variations in tree components of *G. arborea* and *C. pentandra* stands due to different spacing (Table 2). The higher biomass was found in stands with more stocking density. Among different components, stem contributed a maximum to total tree biomass followed by roots and branches. About 62% to 65% to total biomass was augmented by stem component alone in *G. arborea*, while 56% to 62% in *C. pentandra* stands. Foliage contributed from 4.1% to 4.7% in *G. arborea* and 7.3% to 7.7% in *C. pentandra* stands. Total biomass was relatively higher in stands of *C. pentandra* than *G. arborea*. It varied from 12.9 Mg ha⁻¹ to 25.1 Mg ha⁻¹ in *C. pentandra* and 9.9 Mg ha⁻¹ to 21.4 Mg ha⁻¹ in *G. arborea* (Table 2).

Table 1. Stand characteristics of *G. arborea* and *C. pentandra* in Agroforestry system

Spacing (m)	Stand density (trees ha ⁻¹)		DBH (cm)		Tree height (m)		LAI		PAR (μmol s ⁻¹ m ⁻²)	
	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2
S ₁	564	596	10.1	19.7	6.58	9.29	3.45	3.36	1128.1	1023.25
S ₂	364	394	10.43	17.3	6.86	8.96	3.09	2.94	1184.6	1121.57
S ₃	258	284	10.29	17.1	7.25	8.76	2.81	2.67	1239.6	1187.44
LSD (P ≤ 0.05)	67.8	71.2	NS	0.91	NS	0.46	NS	0.31	NS	88.3

Note: AFS1- *G. arborea* based Agroforestry system; AFS2- *C. pentandra* based Agroforestry system, S₁ = 4 x 4 m, S₂ = 4 x 6 m, S₃ = 4 x 8 m, DBH = Diameter at breast height, LAI = Leaf area index, PAR = Photosynthetically active radiation, NS = Non significant

Table 2. Biomass (Mg ha⁻¹) distribution in tree components of *G. arborea* and *C. pentandra* stands in agroforestry system

Spacing (m)	Foliage (Mg ha ⁻¹)		Stem (Mg ha ⁻¹)		Branches (Mg ha ⁻¹)		Roots (Mg ha ⁻¹)		Total biomass (Mg ha ⁻¹)	
	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2
S ₁	0.88	1.82	13.9	13.92	2.19	3.12	4.4	6.4	21.4	25.1
S ₂	0.65	1.26	9.11	10.03	1.57	2.04	3.12	3.12	14.5	16.45
S ₃	0.47	0.98	6.1	8.02	1.12	1.44	2.25	2.44	9.9	12.88
LSD (P ≤ 0.05)	0.15	0.24	1.57	0.86	0.5	0.31	0.52	0.31	2.7	1.68

Note: AFS1- *G. arborea* based Agroforestry system; AFS2- *C. pentandra* based Agroforestry system, S₁ = 4 x 4 m, S₂ = 4 x 6 m, S₃ = 4 x 8 m, DBH = Diameter at breast height, LAI = Leaf area index, PAR = Photosynthetically active radiation; NS = Non significant

Carbon concentrations varied among tree components of *C. pentandra* and *G. arborea* stands (Fig. 1 and Fig. 2). It was higher in woody components (stem, branches and roots) as compared to non woody components like foliage and twigs. Relatively C concentrations were higher in components of *G. arborea* compared to the *C. pentandra*. C stocks in *G. arborea* and *C. pentandra* showed significant differences (Table 3). In 5 year-old stands, the total C storage varied from 4.5 Mg ha⁻¹ to 10.1 Mg ha⁻¹ in *C. pentandra*, while 4.3 Mg ha⁻¹ to 9.3 Mg ha⁻¹ in *G. arborea* (Table 2). The contribution by different components for C storage was in the order: stems > roots > branches > foliage. Slightly a higher C storage was found in stands of *C. pentandra* than *G. arborea*. The C storage varied according to stocking density, which was higher in narrow tree spacing (4 x 4 m) and decreased with an increase in spacing. C sequestration in *C. pentandra* stands ranged from 0.9 to 2 Mg ha⁻¹yr⁻¹, whereas in *G. arborea* stands from 0.86 to 1.87 Mg ha⁻¹yr⁻¹ (Table 3)

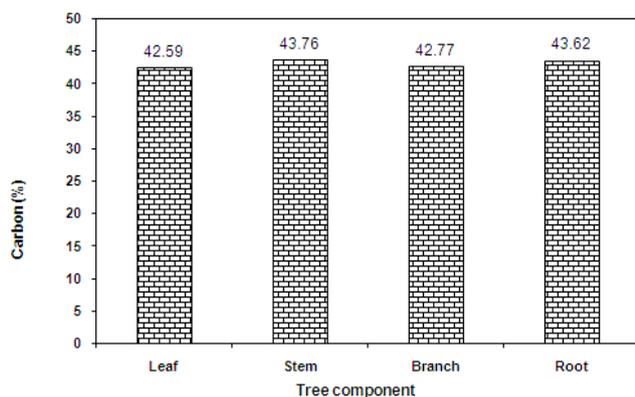


Figure 1. Carbon concentration in different components of *Gmelina arborea*

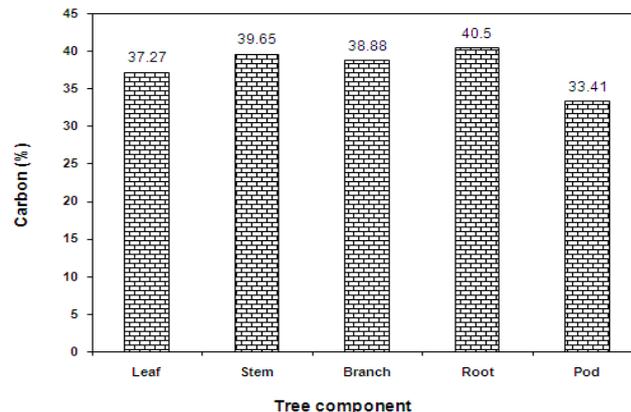


Figure 2. Carbon concentration in different components of *Ceiba pentandra*.

3.3. Yields of Soybean and Wheat Under *G. arborea* and *C. pentandra* Based Agroforestry System

The yields of soybean and wheat exhibited significant variation under stands of *C. pentandra* and *G. arborea* in agroforestry system (Table 4). Yield of crops decreased under agroforestry compared to sole crop system, and also it was more under narrow tree spacing (4 x 4 m). Reduction of yield was comparatively lower in wheat than in soybean. Relatively more yield losses were noticed in *C. pentandra* in comparison to *G. arborea* based agroforestry system. The yield of soybean decreased from 8.1% to 34.5% and wheat from 8.8% to 13.6% under different spacing of *G. arborea*. Similarly, soybean yield decreased from 26.1% to 43% and wheat from 5.3% to 17.8% under different spacing of *C. pentandra* (Table 4)

Table 3. Carbon stocks (Mg ha⁻¹) in tree components of *G. arborea* and *C. pentandra* stands

Spacing (m)	Foliage, fruits and pods (Mg ha ⁻¹)		Stem (Mg ha ⁻¹)		Branches (Mg ha ⁻¹)		Roots (Mg ha ⁻¹)		Total C stock (Mg ha ⁻¹)	
	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2
S ₁	0.37	0.7	6.08	5.5	0.94	1.3	1.92	2.6	9.31	10.1
S ₂	0.28	0.5	3.99	4.0	0.67	0.9	1.36	1.3	6.30	6.6
S ₃	0.20	0.4	2.67	2.6	0.48	0.6	0.98	1.0	4.33	4.5
LSD (P < 0.05)	0.11	0.21	1.21	0.3	0.28	0.4	0.46	0.6	2.21	1.4

Note: AFS1- *G. arborea* based Agroforestry system; AFS2- *C. pentandra* based Agroforestry system, S₁ = 4 x 4 m, S₂ = 4 x 6 m, S₃ = 4 x 8 m

Table 4. Productivity of soybean and wheat crops under *G. arborea* and *C. pentandra* agroforestry system

Spacing (m)	Grain yield of soybean (Mg ha ⁻¹)		Grain yield of wheat (Mg ha ⁻¹)		Yield reduction of soybean (%)		Yield reduction of wheat (%)	
	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2
S ₁	0.89	0.81	2.66	2.49	34.5	43.0	13.6	17.8
S ₂	1.11	0.96	2.76	2.66	25.0	26.1	10.4	12.2
S ₃	1.36	1.21	2.81	2.87	8.1	8.5	8.8	5.3
Sole crop	1.48	1.42	3.08	3.03				
LSD (P < 0.05)	0.28	0.27	0.28	0.29				

Note: AFS1- *G. arborea* based Agroforestry system; AFS2- *C. pentandra* based Agroforestry system, S₁ = 4 x 4 m, S₂ = 4 x 6 m, S₃ = 4 x 8 m

3.4. Soil Organic C under *G. arborea* and *C. pentandra* Stands in Agroforestry System

The C stocks in soil exhibited a significant variation under the stands of *C. pentandra* and *G. arborea* due to differences in bulk densities (1.48-1.56 Mg m⁻³) and C concentrations (0.58-0.69%)(Table 5). The C stocks decreased with an increase in tree spacing and soil depth. After 5 years, mean soil C stocks varied from 24.1 to 26.3 Mg ha⁻¹ and from 24.9 to 27 Mg ha⁻¹, respectively under stands of *G. arborea* and *C. pentandra*. The C stocks in soil increased by 6.8-11.9% under *G. arborea* stands and 5.5-14.5% under *C. pentandra*. C accretion in soil was slightly higher in *C. pentandra* compared to *G. arborea* stands. C sequestration in soil ranged from 1.3 to 3.4 Mg C ha⁻¹yr⁻¹ in *C. pentandra*, while it varied from 1.6 to 2.8 Mg C ha⁻¹yr⁻¹ in *G. arborea* stands (Table 5).

3.5. Growth, Biomass and C Storage in Poplar Clones Under Agroforestry

Poplar clones exhibited significant variation in growth, Leaf Area Index (LAI) and photosynthetically active radiation (PAR) after five years of establishment (Table 6).

The stocking density of clones also varied according to the degree of mortality suffered by each clone. It ranged from 464 to 484. The mortality was lowest in clone 65/27 and highest in clone G 48. Clones 65/27, G48 and D121 achieved comparatively higher dbh, height and clean bole. LAI was also higher in these clones, whereas it was quite low in clones of S7C1 and G3. In contrary, photosynthetically active radiation (PAR) showed a reverse trend. It was higher under clones S7C1 and G3, while lower under clones 65/27, D121 and G48 (Table 6).

A significant clonal variation in biomass was found among different components (Table 7). In 5 year-old clones, the total biomass varied from 48.5 to 62.2 Mg ha⁻¹. Clone 65/27 achieved highest biomass among the five clones tested, whereas clone S7C1 attained lowest biomass. Biomass storage in the clones followed the order: 65/27 > D121 > G48 > G3 > S7C1. The contribution of different tree components to total biomass was in the order: stems > roots > branches > foliage. For the total biomass, stem contributed from 60.5% to 68.9%, branches 12.3% to 15%, roots 13.8% to 21% and foliage 3% to 7%. The root-shoot ratios ranged from 0.16 to 0.27. It was lowest in clone S7C1 and highest in clone G48 (Table 7).

Table 5. C socks in soil under *G. arborea* and *C. pentandra* agroforestry system

Spacing (m)	Soil depth (0-20 cm) (Mg ha ⁻¹)		Soil depth (20-40 cm) (Mg ha ⁻¹)		Mean C storage (Mg ha ⁻¹)		C accretion (Mg ha ⁻¹)	
	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2	AFS1	AFS2
S ₁	26.9	27.6	25.7	26.3	26.3	27.0	2.8	3.4
S ₂	25.8	26.5	24.8	25.1	25.3	25.8	1.8	2.2
S ₃	25.1	25.5	23.1	24.2	24.1	24.9	1.6	1.3
S ₀	24.3	24.1	22.7	23.1	23.5	23.6		
LSD (P< 0.05)	0.54	0.67	0.43	0.56				

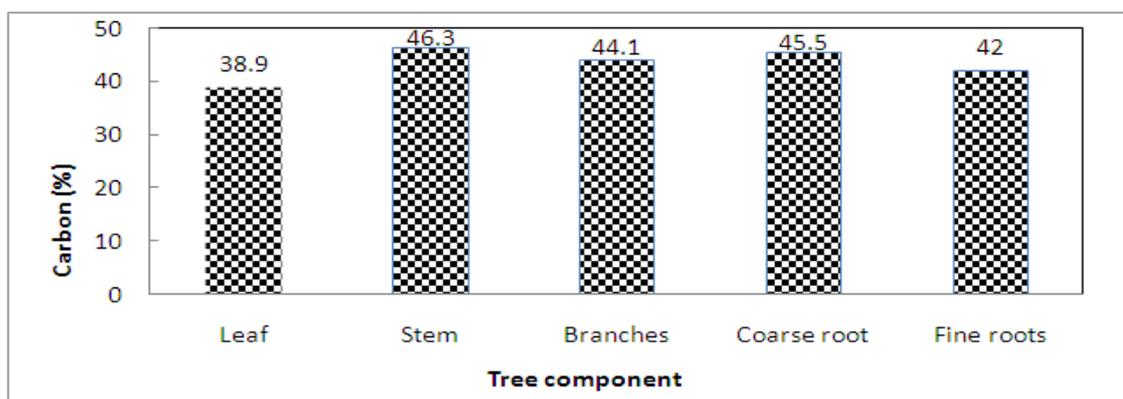
Note: AFS1- *G. arborea* based Agroforestry system; AFS2- *C. pentandra* based Agroforestry system, S₁ = 4 x 4 m, S₂ = 4 x 6 m, S₃ = 4 x 8 m

Table 6. Growth of *Populus deltoides* clones under Agroforestry

Clone	Stand Density (trees ha ⁻¹)	Dbh (cm)	Total height (m)	Clean bole (m)	LAI	PAR (μmol s ⁻¹ m ⁻²)
G3	464	19.3	13.6	4	3.8	1075.25
G48	467	19.7	14.5	4.9	4.1	1021.57
65/27	484	21.6	14.3	4.8	4.5	967.44
D121	471	20.1	13.0	3.6	4.2	984.57
S7C1	474	13.3	11.16	3.4	2.9	1137.44
LSD (P< 0.05)	11.2	3.57	1.85	0.1	0.5	40.8

Table 7. Standing biomass (Mg ha^{-1}) of *Populus deltoides* clones in agroforestry system

Clone	Leaves & twigs (Mg ha^{-1})	Stem (Mg ha^{-1})	Branches (Mg ha^{-1})	Coarse roots (Mg ha^{-1})	Fine roots (Mg ha^{-1})	Total Biomass (Mg ha^{-1})
G3	3.9	34.3	8.42	7.9	1.5	56.02
G48	3.6	34.9	7.10	10.9	1.2	57.70
65/27	3.7	38.7	8.64	11.2	0.9	62.24
D121	1.8	40.4	8.43	8.9	1.1	59.50
S7C1	2.3	33.4	6.14	5.9	0.8	48.50
LSD ($P \leq 0.05$)	0.46	4.2	13.2	1.35	0.14	8.22

**Figure 3.** Carbon concentration in different components of *P. deltoides***Table 8.** Carbon stocks in *P. deltoides* clones in agroforestry system

Clone	Foliage (Mg ha^{-1})	Stem (Mg ha^{-1})	Branch (Mg ha^{-1})	Coarse root (Mg ha^{-1})	Fine root (Mg ha^{-1})	Total (Mg ha^{-1})
G3	1.58	16.19	3.89	3.67	0.62	25.95
G48	1.48	16.79	3.30	5.14	0.51	27.22
65/27	1.54	18.77	4.04	5.35	0.38	30.09
D121	0.74	19.47	3.93	4.19	0.47	28.80
S7C1	0.92	15.73	2.79	2.73	0.33	22.51
LSD ($P < 0.05$)	0.21	1.7	0.76	1.3	0.12	2.72

Carbon concentrations varied within tree components of clones, however no appreciable variation was found among clones for a given component, therefore the average values were taken for accounting C stocks (Fig. 3). C stocks varied significantly in different components among clones (Table 8). The stems contributed maximum followed by roots and branches, while foliage contributed lowest to total C storage. The woody components (stems, roots and branches) almost contributed between 94-97% to total C storage, while foliage from 3% to 6%. Above ground components contributed from 79.2% to 86.4% and below ground components from 14% to 21% to total C stock. Root-shoot C ratios varied from 0.16 to 0.26. After 5 years, total C storage varied from 22.5 to 30.1 Mg ha^{-1} . Clone 65/27 achieved highest, whereas clone S7C1 minimum C storage. The C storage in the clones followed the

order: 65/27 > D121 > G48 > G3 > S7C1 (Table 8).

3.6. Yields of Soybean and Wheat under Poplar Clones in Agroforestry System

Yields of soybean and wheat crops were significantly reduced under Poplar clones in agroforestry compared to sole crop system (Table 9). Grain yield of soybean varied from 0.99 to 1.29 Mg ha^{-1} and wheat from 2.67 to 3.01 Mg ha^{-1} under different clones. Reduction of yield was quite lower (3.2-10.3%) in wheat than in soybean, which ranged from 9.2% to 30.3%. The yield losses of crops were greater under clone 65/27 and lesser under clone S7C1. The yield losses of crops under Poplar clones followed the order: 65/27 > D121 > G48 > G3 > S7C1. Unlike grain yield, stover

yields also decreased under clones. The Stover yield of soybean was found to be lowest under clone G3 and highest under clone G3. Similarly, straw yield of wheat was lowest under clone 65/27 and highest under clone G3 (Table 9).

3.7. Soil Organic C Under Poplar Clones

Poplar clones significantly affected the soil C stocks due to differences in bulk densities (1.48-1.58 Mg m⁻³) and C concentrations (0.61-0.73%) (Table 10). The C stocks decreased with an increase in soil depth. After 5 years, mean soil C stocks varied from 25.7 to 27.5 Mg ha⁻¹. C sequestration in soil ranged from 2.9 to 4.7 Mg ha⁻¹yr⁻¹ under different clones in comparison to sole crop system (control)(Table 10).

3.8. C Stocks Under Three Agroforestry Stands

Comparative account on C stocks in three agroforestry systems after 5 years of establishment revealed that Poplar based agroforestry system found to be more promising than *G. arborea* and *C. pentandra* systems (Table 11). Poplar based system accumulated almost 2.4 – 3.2 times higher C storage in tree components than *G. arborea*. Similarly, the soil C stocks also 1.4 to 2.3 times higher in Poplar compared to *G. arborea* based agroforestry system. The C stocks in tree components and soil are more or less similar in *G. arborea* and *C. pentandra* systems, however it was slightly higher in *C. pentandra* based system. The total C stocks (tree+soil) were almost 2 -2.7 times higher in Poplar based agroforestry system compared to *G. arborea* and *C. pentandra* based agroforestry systems (Table 11).

Table 9. Productivity of soybean and wheat crops under *P. deltoides* clones in agroforestry system

Clones	Grain yield of soybean (Mg ha ⁻¹)	Stover yield of soybean (Mg ha ⁻¹)	Grain yield of wheat (Mg ha ⁻¹)	Straw yield of wheat (Mg ha ⁻¹)	Grain yield reduction in soybean (%)	Grain yield reduction Inwheat (%)
G3	1.18	2.48	2.98	4.04	16.9	4.2
G48	1.21	3.62	2.87	3.36	14.8	5.5
65/27	0.99	3.36	2.67	2.97	30.3	10.3
D121	1.02	3.38	2.85	3.44	28.2	8.4
S7C1	1.29	3.28	3.01	3.53	9.2	3.2
Sole crop	1.42	3.80	3.11	4.24		
LSD (P<0.05)	0.13	0.54	NS	5.94		

Table 10. C stocks in soil under *P. deltoides* based agroforestry system

Clone	C stock in soil depth (Mg ha ⁻¹)		Mean C (Mg ha ⁻¹)	C accretion
	0-20 cm	20-40 cm		
G3	27.09	26.23	26.7	3.9
G48	26.91	25.01	26.0	3.2
65/27	28.54	26.91	27.5	4.7
D121	27.92	26.35	27.1	4.3
S7C1	26.27	25.17	25.7	2.9
Control	23.01	22.68	22.8	
LSD (P<0.05)	1.64	1.41	1.52	

Table 11. Comparative account on C storage (Mg/ha) in three Agroforestry systems

Agroforestry system	C stocks in trees (Mg ha ⁻¹)	C stocks in soil (Mg ha ⁻¹)	Total C storage (Mg ha ⁻¹)
<i>Gmelina arborea</i>	4.3 - 9.3	1.3-3.4	5.6-12.7
<i>Ceiba pentandra</i>	4.5 - 10.1	1.6-2.8	6.1–12.9
<i>Populus deltoides</i>	22.5 - 30.1	2.9-4.7	25.4–34.8

4. Discussion

4.1. Growth and Biomass in Stands of *G. arborea*, *C. pentandra* and Clones of *P. deltooides*

Developing mitigation and adaptation strategies to minimize the negative impacts of climate change on ecosystems have prompted a renewed interest in establishing promising tree based land use systems across India. Agroforestry technologies have tremendous potentials in supplying diverse products as well as sequestering significant amount of C in degraded agro-ecosystems. Plantation establishment is a critical phase, during which the trees require inputs but do not provide economic outputs. The survival of more than 85% was achieved in stands of *G. arborea*, *C. pentandra* and *P. deltooides* due to planting of quality stock and adopting appropriate management practices (weeding, pruning, irrigation and fertilization) at different stages of stand development. Growth of *G. arborea* stands is comparatively slower than *C. pentandra* and clones of *P. deltooides*, which is attributed to difference in the genetic potentials of the species. Both *P. deltooides* and *C. pentandra* are recognized as fast growing exotic species, while *G. arborea* is moderately fast growing indigenous species. The results of this study are in line with findings of Chauhan *et al.* (2009), where it was clearly demonstrated that the indigenous species of *Acacia nilotica* and *Toona ciliata* attained poor growth than fast growing exotic species of *P. deltooides* and *Eucalyptus teriticornis*. Differential growth trajectories in multipurpose trees do not seem to be extraordinary as many workers reported such variations in the past (Puri *et al.*, 2002; Chauhan *et al.*, 2009; Kumar and Nair, 2011).

High biomass production is an important consideration in all tropical tree planting programmes. This is particularly significant in view of the rising CO₂ levels and the growing need to sequester it. Total biomass was almost 2.5 ± 0.3 to 3.8 ± 0.3 times higher in clones of *P. deltooides* compared to stands of *G. arborea* and *C. pentandra*. The higher biomass was achieved in Poplar clones due to fast growth, while the slow growth leads to lower biomass in stands of *G. arborea*. Comparison of biomass with plantation of similar age indicates that present estimates of biomass are well within the range of biomass values found in Poplar plantations studied elsewhere (Fang *et al.*, 1999; Fang *et al.*, 2007; Raizada and Shrivastava, 1989). Fang *et al.* (1999) observed 53.5 to 60 Mg ha⁻¹ biomass in 6 yr-old clones of *P. deltooides* planted at density of 500 trees ha⁻¹. Labrecque and Teodorescu (2005) reported 66.4 to 72.2 Mg ha⁻¹ biomass in 4 year-old Poplar clones. In contrary, Lodhiyal and Lodhiyal (1997) reported higher biomass ranging from 60 to 108.9 Mg ha⁻¹ in 3-and 4-year-old plantations in Tarai region of U.P., India. The higher dbh and height accompanied with more planting density (666 trees ha⁻¹) resulted in higher biomass, whereas low stocking density (<540 trees ha⁻¹) and poor dbh growth was responsible for lower biomass production in our study. Moreover, Poplar grows profusely in moist and fertile

sites of Tarai region of north India, while dry sub-humid and low fertility conditions of the study area resulted in less growth. Although, the growth rate of *C. pentandra* stands was relatively higher as compared to *G. arborea*, however biomass range is more or less similar. This could be attributed to the higher specific gravity (0.44 ± 0.11) of wood of *G. arborea*, which was almost two times greater compared to *C. pentandra* (0.23 ± 0.06). Chauhan *et al.* (2009) also reported slow growth rates in indigenous species and opined that it could be compensated to some extent by their high specific gravity values in wood but the fast growing species are usually preferred by farmers under agroforestry for immediate economic returns, while slow growing species under afforestation and reforestation programmes. Biomass distribution revealed that more biomass was allocated to stems followed by roots, branches and foliage. This is consistent with earlier studies showing more of biomass allocation by woody components in plantations (Lodhiyal *et al.*, 1995; Puri *et al.*, 2002; Chauhan *et al.*, 2009).

4.2. C stocks in Stands of *G. arborea*, *C. pentandra* and Clones of *P. deltooides*

Results showed that C concentration varied within tree components of *P. deltooides*, *G. arborea* and *C. pentandra* stands. It was higher in stems followed by roots, branches whereas it was lowest in leaves. A similar trend in C concentration was observed by Singh and Singh (1991) for dry tropical forests of India. C concentration is generally assumed to be 50% of the dry biomass (IPCC, 2007), however it is usually less than that and varies among tree components and species (Nair and Nair, 2014). Chauhan *et al.* (2009) reported 43-47% of C concentrations in different components of multipurpose trees. Similarly Arrora *et al.* (2014) also found 39.7% to 51.1% C concentration in different components of *P. deltooides*. The C concentrations in the present study are slightly lower but comparable to the average value of 45.24% reported by Chhabra and Dadhwal (2004). A marked variation in C accumulation (22.5 to 30.1 Mg C ha⁻¹) was found among popular clones. The estimates of C stocks in our studies are quite lower than those reported by Arrora *et al.* (2014) and Rizvi *et al.* (2011), however the values fall within the range and comparable to those reported by Yadava (2010) and Chauhan *et al.* (2012). The C stocking largely governed by quality planting material (clones), site conditions, age, stand density and management practices adopted. Clones 65/27 and D121 achieved higher C accumulation due to better adoptability and efficient utilization of resources which might result in higher growth and biomass.

C accumulation was 2-3 times higher in *P. deltooides* clones than *G. arborea* and *C. pentandra* stands. The lesser biomass and C concentrations resulted lower C accretion in these species, however the C stocks are comparable with the estimates made elsewhere (Albrecht and Kandji, 2003; Nair *et al.*, 2010). The C storage in tree components followed the order stems > roots > branches > leaves. Similar trend in C

was also observed by earlier workers (Chauhan *et al.*, 2012; Arrora *et al.*, 2014).

4.3. Productivity of Crops under Stands of *G. arborea*, *C. pentandra* and Clones of *P. deltoides*

The results indicated that productivity of soybean and wheat crops decreased under agroforestry system. Yield losses were higher under narrow (4 x 4 m) compared to wide tree spacing (4 x 8 m) in *G. arborea* and *C. pentandra* stands. The strong competition between trees and crops for above-ground and below-ground resources in narrow tree spacing might result more yield losses. It has been well documented that higher tree stocking exert more competition and drastically reduced crop yields in agroforestry systems (Rao *et al.*, 1998; Puri and Nair, 2004). Yield losses of soybean and wheat were higher under Poplar clones compared to *G. arborea* and *C. pentandra* stands. This might be due to higher competition between Poplar clones and crops sharing of light, moisture and nutrient resources. Poplar clones attained higher leaf area index (LAI) than *G. arborea* stands, which resulted in 6-15% decrease in PAR levels under Poplar clones. Kocabas *et al.* (1993) reported that a 20% reduction in radiation throughout growing season would result 15% lower yield. The Poplars are fast growing species need huge quantities of nutrients, light and moisture for dry matter production. The tree canopies of Poplar intercept maximum solar radiation and also trees efficiently uptake nutrients due to their well-developed crown and root system compared to crops. It was well demonstrated by Puri *et al.* (1994) that most of the Poplar clones are shallow rooted and their bulk of fine and coarse roots are distributed 0-20 cm soil depth, where the crop root lies in the same zone. Therefore, both root and light competition exists in Poplar based agroforestry systems. The competition for light, moisture and nutrients due to lack of niche differentiation in resource sharing could be possible cause for yield reduction. The reduction of yields was more under clones 65/27 and D121 that could be attributed to a strong competition with crops for sharing resources. The results were in line with findings of Puri *et al.* (2002).

Among two crops, soybean grown in rainy season (June-October) showed highest yield reduction compared to the wheat in winter season (December- April). This is due to the fact that *G. arborea*, *C. pentandra* and *P. deltoides* are deciduous trees and shed their entire foliage during winter (November to February), which might transmit an higher amount of light (PAR) to wheat crop. On the other hand, the dense foliage in rainy season seems to restrict the transmission of adequate amount of light and resulted in shading, which might cause yield losses in soybean. Therefore, the study suggests introducing appropriate tree and soil management practices, which could able to recover yield losses in soybean under the agroforestry system. The significance of tree management practices in improving the crop yields in tropical agroforestry systems are well

documented (Rao *et al.*, 1998; Puri and Nair, 2004; Chauhan *et al.*, 2012).

4.4. Soil Carbon Under Stands of *G. arborea*, *C. pentandra* and Clones of *P. deltoides*

One of the major issues of keeping the soil resource productive and in place could be accomplished by means of maintaining the levels of soil organic carbon. Agroforestry systems helped in improving the status of organic C in the soil. As the mean C content of soil increased by 6.8-11.9% under *G. arborea*, 5.5-14.5% under *C. pentandra* and 12.7-20.6% under Poplar stands. Scientifically acceptable evidence to support the positive influence of trees in enhancing soil organic C is overwhelming (Chavan *et al.*, 1995; Rao *et al.*, 1998; Soto-Pinto *et al.*, 2010; Gupta *et al.*, 2009; Chauhan *et al.*, 2012; Nair and Nair, 2014). The C accumulation in soils under *G. arborea* stands in our study was quite low compared to Chavan *et al.* (1995), where 47% of soil C recorded under 10 year old *G. arborea* stands grown as monoculture on lateritic soil. However, our estimates are comparable to Datta and Dhiman (2001), which showed an increase of 9% organic C and 3% available N in soil under 12 year stands of *G. arborea* based agroforestry system. In Poplar based agroforestry system, Chauhan *et al.* (2011) reported 35.6% increase in the soil organic C after 6 years of planting, which was quite higher but our estimates comparable to Gupta *et al.* (2009). They reported that soil organic C increased significantly with tree age in the 0-15 cm soil depth and it was 18.6% higher under 6 year old plantation than in the soils under 1 year old plantation. It is well established fact that soil factors (type, water content, pH, aeration, micro flora etc.), climatic conditions (temperature, rainfall) and litter fall (quantity) determine to a great extent the soil resources (Kaul *et al.*, 2010). In this context it is envisaged that the increased litter input and addition of root residues seems to have improved C storage under plantation.

The results of the study indicate marked differences in C content in soil, which gradually decreased with an increase in soil depth under *G. arborea*, *C. pentandra* and *P. deltoides* stands in agroforestry. A significant increase in C was observed in the topsoil even after short-duration of 5-year plantation. This is in consistent with the findings of earlier workers (Datta and Dhiman, 2001; Chauhan *et al.*, 2012; Arrora *et al.*, 2014). Poplar trees on an average add 3.5 Mg ha⁻¹ of litter fall every year (Arrora *et al.*, 2014). Power (2004) previously demonstrated that the most marked differences in soil organic C in the upper than deeper soil layers in plantations. However, the deeper layer seems to be more stable and respond for long term C sequestration. The higher amount of leaf litter and root residues in surface soil layer might attribute for higher C pool. Mean annual increment in soil C under agroforestry stands ranged from 0.6 to 0.94 Mg C ha⁻¹ yr⁻¹, which is comparable with 0.16 to 1.08 Mg C ha⁻¹ yr⁻¹ as reported by Kaur *et al.* (2002) and Nair and Nair (2014).

4.5. C Sequestration in *G. arborea*, *C. pentandra* and *P. deltoides* Based Agroforestry System

C sequestration by trees and soils together accounted for 4.5 to 6 Mg C ha⁻¹ yr⁻¹ under *P. deltoides*, which is slightly lower than values of 5.8 to 6.5 Mg C ha⁻¹ as reported by Arrora *et al.* (2014). The Poplar stands in fertile soils *Tarai* region of India usually attain profuse growth and development as compared sub-humid conditions of Chhattisgarh. The better growth and development resulted in higher biomass, which contributed for greater C sequestration in Poplar stands grown in *Tarai* region. Clonal variation found in the C sequestration of present study do not seems to be extraordinary, which was resulted as a consequence of differential growth and biomass production. A strong genotype x environment caused such variation. C sequestration in *G. arborea* and *C. pentandra* stands was quite lower (1.2-2.54 Mg C ha⁻¹ yr⁻¹) as compared to *P. deltoides*. This is presumably due to low biomass C and soil C accretion under these stands. However, the C sequestration rates in 5 year old stands of *G. arborea* and *C. pentandra* are within the range and comparable to the rates found in other tropical agroforestry system (Albrecht and Kandji, 2003; Nair and Nair, 2014).

5. Conclusions

The present study demonstrated that agroforestry system accumulated significant carbon as living biomass, as well as soil carbon, indicating the potential to offer the additional environmental service of C sequestration. As per the targets of Greening India Mission under the National Climate Change Action Plan targets, 1.5 million (M) ha of degraded agricultural lands and fallows to be brought under agroforestry; about 0.8 M ha under improved agroforestry practices on existing lands and 0.7 M ha of additional lands under agroforestry (Murthy *et al.*, 2013). The studies give a clear indication that *G. arborea*, *C. Pentandra* and *P. deltoides* could be potentially exploited under agroforestry in sub-humid tropics of Central India for mitigation of climate change due to their promising growth and higher C sequestration. Among three species, the *P. deltoides* was found outstanding compared to *C. pentandra* and *G. arborea* under agroforestry. Clones 65/27 and D121 were identified as most promising clones of Poplar which could able to sequester 5.8 ± 0.8 Mg C ha⁻¹ yr⁻¹. However, further there is need to evaluate these clones in a multi locational trials before advocating them under large scale plantations in agroforestry. In case of *G. arborea* and *C. Pentandra*, narrow tree spacing (4 x 4 m) is suggested for ensuring higher C sequestration. Shifting from traditional agriculture to *P. deltoides*, *C. pentandra* and *G. arborea* based agroforestry ensure the farmers gaining additional economic benefits of C sequestration by C trading under CDM projects. However, it depends on willingness of the farmers to adopt these potential tree based land use practice.

Crop yields significantly reduced under agroforestry system, which indicates there was competition between trees and crops for sharing and utilizing resources. Although, the yield losses of soybean and wheat were higher under Poplar clones 65/27 and D121, and also in narrow tree spacing of *G. arborea* and *C. Pentandra*, which could be minimized by introducing appropriate tree management practices (lopping, pruning, hoeing, root trenching) to reduce the competition and improve the complementarity to exploit synergies between tree and crop components. The high tree biomass produced in agroforestry could also compensate to a greater extent for yield losses in long run.

Growth rate differences among exotic and indigenous tree species is widely debated across the world but not yet resolved biological issues related to C sequestration by trees especially in tropical agroforestry systems. Although, the potential exotics like *P. deltoides* and *C. pentandra* are currently confined to a limited area (<5%) in India but it will certainly expand in the future to fulfil the growing demands of wood supplies and enhancing C pools under global treaties. Despite the fact that world over emphasis is given on adopting fast growing exotic species under agroforestry systems especially for C sequestration and other economic benefits, the ecological consequences and sustainability shall be carefully examined before introducing them in large scale plantations.

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