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Growth, biomass, carbon stocks, and sequestration in an age series of *Populus deltoides* plantations in Tarai region of central Himalaya

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Abstract: Growth, biomass, carbon storage, and carbon sequestration potential along an age series in *Populus deltoides* plantations were assessed. The growth rate of diameter at breast height and height was higher in trees of 4 to 7 years and 2 to 5 years, respectively. The total aboveground biomass (AGB) increased with age and reached its maximum (180.2 Mg ha^{-1}) at 11 years of age. Mean carbon concentration in aboveground components varied from 39.7% to 51.7%. Allometric equations were developed to estimate biomass and biomass carbon in different tree components, which had adjusted R squares greater than 94%. Aboveground carbon stocks in *P. deltoides* increased from 0.5 Mg ha^{-1} at 1 year to 90.1 Mg ha^{-1} at 11 years. The carbon sequestration rate (i.e. carbon sequestrated in wood products and by the substitution of biomass for coal) in mature plantations (7–11 years) varied from 5.8 to 6.5 Mg C ha^{-1} per year. Soil carbon stocks increased with age (1–11 years) from 61.2 to 66.8 Mg ha^{-1} and decreased with soil depth. Soil carbon stock in different ages of plantations varied from 63.9 to 83.8 Mg ha^{-1} at 0–30 cm depth, 57.5 to 60.1 Mg ha^{-1} at 30–60 cm depth, and 55.5 to 59.7 Mg ha^{-1} at 60–90 cm depth. The amount of total carbon stock (AGB and soil) increased from 64.4 Mg ha^{-1} at 1 year to 173.9 Mg ha^{-1} at 11 years. This study recommends *P. deltoides* planting as a viable option for sustainable production and carbon mitigation.

Key words: Biomass, carbon sequestration, carbon stocks, growth, *Populus deltoides*

1. Introduction

Tree growth serves as an important means of capturing and storing atmospheric carbon in vegetation, soil, and biomass products. The United Nations Framework Convention on Climate Change has recognized the importance of plantation forestry as a greenhouse gas mitigation option, as well as the need to monitor, preserve, and enhance terrestrial carbon stocks (Updegraff et al., 2004). Due to fast growth and better silvicultural practices and management, plantation forestry has an edge over natural forests. Projections of the International Centre for Research in Agroforestry suggest that significant funds could potentially be available to finance sustainable rural development and adaptation to climate change, as the carbon market may exceed US $1 trillion by 2025 (ICRAF, 2009).

Poplar (*Populus deltoides* W.Bartram ex Marshall), a short-rotation plantation crop, has received wide acceptance during the last 3 decades in India. Due to its fast growing habit, its compatibility with agriculture crops, and high industrial requirements, the species is widely grown in Indo-Gangetic region of the country. An area of 312,000 ha is planted with *P. deltoides* in the country, out of which 60% is block plantation and 40% is bund plantation (ICFRE, 2012). The tree is harvested at a short rotation of 7–10 years, which provides a yield of 150–200 m^3 ha^{-1} (mean annual increment of 20–25 m^3 ha^{-1} per year) in block plantations and 12–20 m^3 ha^{-1} (mean annual increment of 2–3 m^3 ha^{-1} per year) in boundary plantations (Kishwan and Kumar, 2013). The wood of the tree is mainly used for plywood manufacturing in India. The branches, tops, and roots of the trees are also used by plywood industries as fuel, which helps reduce fossil fuel use. Due to its fast growth and wider adoptability, the tree has huge potential to sequester carbon and mitigate CO_2 from the atmosphere (Dhiman, 2009; Singh and Lodhiyal, 2009; Chauhan et al., 2010; Gera, 2012).

Comprehensive reports on biomass, productivity, structure, and functioning of *P. deltoides* plantations are available in the literature from India (Lodhiyal et al., 1995; Lodhiyal and Lodhiyal, 1997; Das and Chaturvdi, 2005). However, information pertaining to biomass, carbon

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stocks, and sequestration rates of plantations along an age series are scanty. The present study was therefore designed to test the hypothesis that *P. deltoides* plantations have potential to significantly support carbon stocks and carbon sequestration and thereby mitigate CO_2 from the atmosphere. The study was planned to estimate growth and biomass production, carbon capture potential and its distribution in the different pools (biomass and soil), and developing biomass and biomass carbon equations for *P. deltoides* along an age series.

2. Materials and methods

2.1. Site description

The study was conducted in a tanda forest in the Tarai Forest Division in Uttarakhand, India. The Tarai region is a wide low-lying strip of 15–18 km with a high water table adjacent to the western Himalayan foothills in the Shivalik range. The climate of Tarai is humid and subtropical. The area experiences hot, dry summers and cold winters. The dry season runs from early October to mid-June, and the monsoon season starts in the third or fourth week of June and lasts until September or the first week of October. The mean annual rainfall is 1364 mm, of which 80% to 90% occurs during monsoon season. The daily average minimum temperature in the coldest months varies from 0 to 9 °C, while during the summer the maximum temperature varies from 30 to 40° C. The soil of the tanda forest in Haldwani has developed from calcareous, medium to moderately coarse-textured materials under predominant influence of tall vegetation and well-drained conditions. The soil of the experimental field was sandy clay loam (Haldi series) with a weak-fine to fine-medium granular structure, classified under order Mollisol, suborder Udoll, great group Hapludoll, subgroup typic Hapludoll (Deshpande et al., 1971a, 1971b).

2.2. Tree establishment

The study was conducted in 1- to 11-year-old plantations raised consecutively from 2000 to 2010. The locations of the different sites, along with elevation, are given in Table 1. Care was taken to include sites as close as possible. Fields were prepared by plowing and leveling the land with a tractor. A G-48 clone was used in all the plantations to maintain clonal uniformity. During the second fortnight of January, 1-year-old transplants of the G-48 clone with bare roots were planted in the field. Pits 50 cm × 50 cm × 100 cm in size were dug manually, and 2 kg of well-decomposed farm yard manure and 100 g of single superphosphate were added to each pit with soil and then thoroughly mixed. The trees were planted at a spacing of 5 × 4 m (500 trees ha^{-1}). After establishment of the plantation, nitrogen in the form of urea was applied in 3 split doses of 75 g, 150 g, and 250 g per plant during the second weeks of June, July, and August, respectively.

Table 1. Location of the study sites.

Age (years)	Location	Elevation (m)
1	29°08′732″N 79°02′513″E	222
2	29°10′ 212″N 79°20′248″E	224
3	29°02′547″N 79°30′434″E	219
4	29°08′750″N 79°20′442″E	223
5	29°04′460″N 79°25′750″E	227
6	29°02′477″N 79°26′436″E	225
7	29°00′783″N 79°30′799″E	230
8	29°04′773″N 79°22′611″E	228
9	29°16′212″N 79°20′248″E	224
10	29°04′765″N 79°22′609″E	221
11	29°03′014″N 79°23′604″E	229

During the first and second years, flood irrigation was given at 10-day intervals by making irrigation channels until the onset of monsoon season (second fortnight of June). No irrigation was given after the second year. No special management practices except pruning of co-leader and large branches were followed after planting.

2.3. Biomass sampling

A single plot of 1 ha was sampled for each age group, which included 3 replicate subplots of 50 × 50 m (0.25 ha). The location of the 3 subplots was random. All the trees in each subplot were measured for their diameter at breast height (DBH) and height with tree caliper and Ravi's altimeter, respectively. Three trees (1 from each subplot) from each age group representing the average diameter and height were felled in October. In total, 33 trees were harvested. Aboveground components of bole, branches, twigs, and leaves were separated, and the fresh weight of all components was recorded in the field. Samples of each component were oven-dried to a constant weight at 65 °C. Using the fresh/dry weight ratio, dry weight of each component was determined. Leaf area index (LAI) was recorded with the AccuPAR LP-80, which is a menudriven, battery-operated linear PAR ceptometer that consists of an integrated microprocessor-driven data logger and a probe with 80 independent sensors. Three readings were taken in each plot.

2.4. Carbon stocks and sequestration

Carbon content in different components of the poplar trees was determined by combustion method and expressed in percent (Gallardo and Merino, 1993). Carbon stock in different tree components was obtained by multiplying the dry weight of the different components by their average carbon content. The carbon stock obtained in different tree components was then summed up to obtain total carbon stock in differently aged plantations. In India, economic rotation at 7–10 years of age is followed for harvesting *P. deltoides* to cater to the need of plywood industries. Carbon sequestration rates (CSRs) were therefore calculated for plantations of >7 years. The exact lifetime of wood products is poorly known, but a reasonable assumption is that wood product lifetime is at least equal to rotation length. The proportion of stemwood used as long-lived wood products is estimated to be 42% (Wang and Feng, 1995). Therefore:

long-lived carbon storage = carbon mass in stemwood × 42%.

Short-lived biomass is used as a fuel to replace fossil fuels. Carbon storage from coal combustion was calculated by considering the top portion of bole, branches, and roots of the trees, which are used as fuel by plywood industries in India. The weight of biomass fuel equals the total biomass weight minus the long-lived stemwood weight. Since the heat released per unit weight of biomass is taken as 18×10^9 J Mg^{-1}:

heat from biomass combustion = $[\text{biomass} - (\text{stemwood weight} \times 0.42)] \times 18 \times 10^9$.

The thermal efficiency of biomass combustion is only 60% of that achieved with fossil fuels. If the heat released from combustion of unit weight of coal is taken as 25×10^9 J Mg^{-1} and the carbon content of coal is 70%, then:

carbon storage from coal combustion = $(\text{heat of biomass combustion} \times 0.60 \times 0.70) / (25 \times 10^9)$.

The total amount of carbon sequestered in the agroforestry systems is the sum of the long-lived carbon storage in wood products and the carbon storage due to substituting biomass for coal.

2.5. Soil carbon stocks

Soil samples were randomly collected at 3 different places at 3 depths (0–30, 31–60, and 61–90 cm) in each plantation. At each sampling point, samples were collected below the tree canopy and outside the tree canopy in 4 cardinal directions around the tree. The samples were mixed to obtain a composite sample for each depth. In total, 99 samples (11 ages × 3 depths × 3 replicates) were collected. Soil samples were analyzed for soil organic carbon (SOC) by the Walkley and Black (1934) method. Bulk density was determined using metal core samplers of 4.0 cm in height and 5.0 cm in internal diameter at 3 depths (0–30, 31–60, and 61–90 cm). Samples were then oven-dried separately at 105 ± 10 °C for 48 h. The oven-dried weight of the sample divided by the volume of core sampler gave the bulk density of soil (Blake and Hartge, 1986). The amount of carbon stored per hectare was obtained by multiplying the values of soil depth (cm), bulk density (g cm^{-3}), and the percentage of SOC content (Joa Carlos et al., 2001).

2.6. Allometric relationships

The data obtained from all the harvested trees were subjected to the allometric model $Y = a \times D^b$, where Y = dry weight of the component (kg per tree) or biomass carbon (kg), D = diameter at breast height (cm), and a and b are model coefficients. Equation performance was monitored using goodness-of-fit statistics, namely the coefficient of determination (R^2) and standard error (SE) of estimates. Residuals for the estimated model were tested for normality using the Anderson–Darling test and for independence using the run test. The developed equations were used to estimate the aboveground biomass (AGB) and biomass carbon stocks of different tree components of the stands.

2.7. Statistical analysis

The data on growth, AGB, soil carbon, and bulk density were analyzed after one-way analysis of variance (ANOVA) using SAS 9.3 statistical software. Significant differences were tested at $P \leq 0.05$ using Tukey's least significant difference test.

3. Results

3.1. Tree growth, AGB, and carbon stocks

Tree growth parameters revealed that with increased age, a gradual increase in DBH and height was observed with maximum DBH (26.6 cm) and that maximum height (24.2 m) was attained at 11 years (Figure 1). The incremental rate of DBH and height was higher during years 1–6, after which the rate was slow. LAI also showed an increasing trend from 0.23 at 1 year of age to 1.49 at the age of 11 years (Figure 1). Positive and significant relationships between LAI and DBH ($r = 0.80$, $P < 0.001$, $n = 33$) and LAI and height ($r = 0.82$, $P < 0.001$, $n = 33$) indicate that DBH and height contribute to the biomass increment of poplar tree.

Mean carbon content in aboveground components varied from 39.7% to 51.7% (Table 2). The maximum carbon concentration was observed in stemwood (51.7%), followed by branch wood (45.3%), twigs (41.7%), and leaves (39.7%). Allometric models were developed between AGB components and biomass carbon with DBH (Table 3). All the models resulted in R^2 values of greater than 94%, thereby indicating that the models are well fitted (Figure 2). The normality of the residuals was tested using

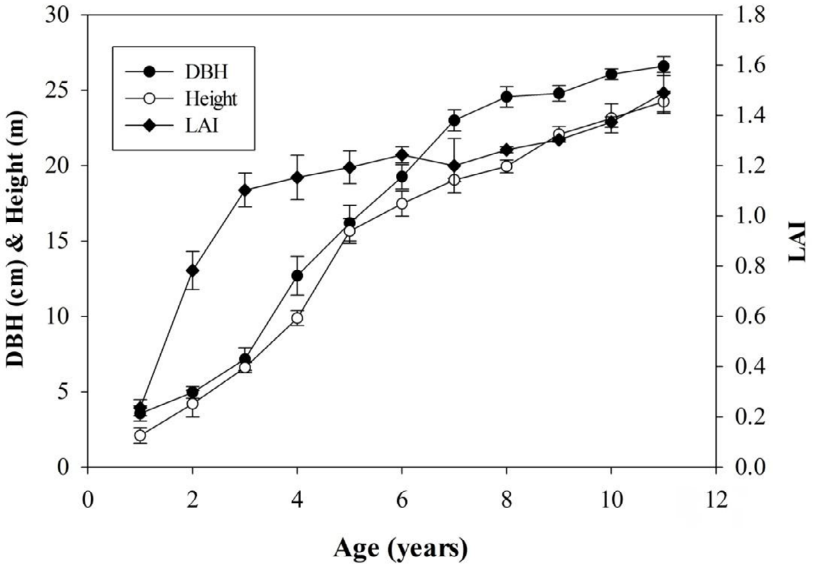

Figure 1. DBH, height, and LAI of the *Populus deltoides* stands at different ages. Error bars are ±SD, n = 3 for each age.

Table 2. Mean carbon (%) in different components of *P. deltoides.*

No.	Component and subcomponent	Carbon concentration
1	Stemwood	51.66 ± 0.28^{a}
2	Branch wood	45.33 ± 0.91^{b}
3	Twig	41.66 ± 0.48^{c}
4	Leaf	39.66 ± 0.57^{c}

Note: Values are mean ± standard deviation.

Table 3. Relationship between biomass (kg per tree) and biomass carbon (kg per tree) with DBH (cm).

Component	DBH versus biomass			DBH versus biomass carbon		
	Parameter estimate		R-square	Parameter estimate		R-square
	a	*b*		*a*	*b*	
Bole biomass	0.058 (0.023)	2.485 (0.125)	0.9835	0.022 (0.009)	2.585 (0.128)	0.9841
Branch biomass	0.037 (0.015)	2.478 (0.123)	0.9836	0.012 (0.005)	2.581 (0.126)	0.9844
Leaf biomass	0.003 (0.001)	2.764 (0.159)	0.9790	0.001 (0.004)	2.828 (0.160)	0.9802
Twig biomass	0.038 (0.019)	1.741 (0.146)	0.9483	0.011 (0.005)	1.859 (0.152)	0.9516
Total aboveground biomass	0.109 (0.043)	2.470 (0.124)	0.9834	0.039 (0.016)	2.572 (0.169)	0.9841

Equation used: $Y = a \times D^{b}$.
Values in the parentheses are the standard error of the parameter estimate.

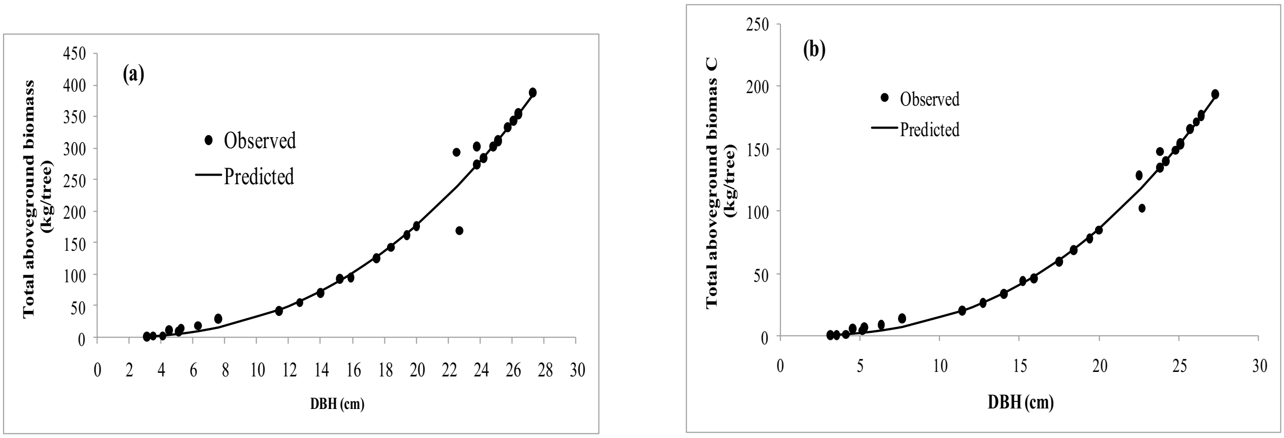

Figure 2. Allometric model fitted to the observed dataset of a) total AGB versus DBH and b) total AGB carbon versus DBH.

Anderson–Darling tests, with the null hypothesis that the residuals are normally distributed. The test statistic for the Anderson–Darling test was 0.413 ($p = 0.320$) for AGB and 0.550 ($p = 0.613$) for biomass carbon, which indicates the acceptance of the null hypothesis. The run test was performed to test the independence of the residuals with the null hypothesis that the residuals are independent. The probability value for the residuals of total AGB and biomass carbon was 0.592 and 0.967, respectively. Nonsignificant values in both of the tests indicate that the residuals are independent and follow normal distribution.

The AGB and biomass carbon stock estimated using the developed equation increased with age and reached maximum at 11 years of age (Table 4). Total AGB increased from 1.26 Mg ha^{-1} at 1 year of age to 180.24 Mg ha^{-1} at 11 years of age. A positive and significant correlation was observed between total AGB and age ($r = 0.97$, $P < 0.001$, $n = 33$). The contribution of bole to the total AGB varied from 53.9% to 55.9%. Aboveground carbon stocks in *P. deltoides* increased from 0.51 Mg ha^{-1} at 1 year to 90.12 Mg ha^{-1} at 11 years (Table 4). The contribution of bole C was maximum compared to total biomass carbon. In general, contributions by bole, branch, and twig carbon stocks to the total carbon stocks increased with the advancement of plantation age from 1 to 11 years. However, contribution by leaf carbon stocks followed a decreasing trend with an increase in age. There was a positive correlation between total biomass carbon and age

Table 4. Estimated biomass and carbon stocks in the *P. deltoides* plantation, by age.

Age (years)	Biomass (Mg ha^{-1})					Carbon stock (Mg ha^{-1})				
	Bole	Branch	Leaf	Twig	Total	Bole	Branch	Leaf	Twig	Total
1	0.68	0.43	0.05	0.17	1.26	0.29	0.16	0.02	0.06	0.51
2	1.56	0.98	0.13	0.31	2.86	0.69	0.38	0.05	0.11	1.20
3	3.87	2.44	0.35	0.59	7.06	1.79	0.97	0.13	0.21	3.09
4	16.05	10.06	1.69	1.59	29.03	7.85	4.24	0.66	0.62	13.46
5	29.38	18.38	3.31	2.42	52.95	14.72	7.94	1.32	0.97	25.17
6	45.20	28.24	5.34	3.28	81.26	23.05	12.42	2.15	1.35	39.31
7	70.19	43.81	8.71	4.46	125.85	36.43	19.62	3.55	1.87	62.00
8	82.68	51.58	10.45	5.00	148.10	43.20	23.26	4.27	2.11	73.45
9	84.65	52.80	10.72	5.09	151.60	44.26	23.84	4.39	2.15	75.26
10	95.80	59.74	12.31	5.55	171.45	50.35	27.11	5.05	2.36	85.55
11	100.75	62.81	13.02	5.75	180.24	53.05	28.56	5.35	2.45	90.12

(r = 0.97, P < 0.001, n = 33). Estimated carbon storage and sequestration rates by trees are given in Table 5. Long-lived carbon storage increased with age from 15.30 Mg ha^{-1} in the 7th year to 22.28 Mg ha^{-1} in the 11th year. The total CSR of the plantation increased from 44.44 to 63.99 Mg C ha^{-1}. Rate of sequestration was highest in the 8th year (6.55 Mg C ha^{-1} per year).

3.2. Soil carbon stocks

The difference in SOC due to age was significant (Table 6). SOC showed a decreasing trend with soil depth in the entire plantation. Carbon concentration was highest in surface soil (0–15 cm depth) as compared to subsurface soil (15–30 and 30–60 cm depth). In surface soil, SOC was 27.72% higher in the 11-year-old plantation than in the 1-year-old plantation. Bulk density showed a decreasing trend with an increase in the age of the trees. In surface soil, it decreased from 1.34 g cm^{-3} at 1 year to 1.27 g cm^{-3} at 11 years. Bulk density increased with an increase in soil depth at all ages (Table 6).

SOC stocks increased with tree age, irrespective of soil depth (Table 7). In the surface layer (0–30 cm), SOC stocks were 23.74% higher at 11 years. Not many variations were observed in the subsurface soil layer (at 30–60 and 60–90 cm soil depths). The CSR in the 0–30 cm soil profile was 0.75 Mg ha^{-1} per year at 7 years and 1.81 Mg ha^{-1} per year at 11 years compared to initial values. Correlation between soil carbon and age was positive and significant at the 0–30 cm soil depth (r = 0.87, P < 0.001, n = 33). No significant

Table 5. Estimated carbon storage and sequestration rate in *P. deltoides* in relation to tree age.

Age (years)	Long-lived C storage (Mg C ha^{-1})	Carbon storage from coal substitution (Mg C ha^{-1})	Carbon sequestration (Mg C ha^{-1})	Carbon sequestration rate (Mg C ha^{-1} per year)
7	15.30	29.14	44.44	6.35
8	18.14	34.28	52.43	6.55
9	18.59	35.09	53.68	5.96
10	21.15	39.68	60.83	6.08
11	22.28	41.71	63.99	5.82
Average	19.09	35.98	55.07	6.15

Table 6. Organic carbon and bulk density in age series *P. deltoides* plantation.

Age (years)	OC (%)			BD (g cm^{-3})		
	0–30 cm	31–60 cm	61–90 cm	0–30 cm	31–60 cm	61–90 cm
1	1.59 ± 0.12^{d}	1.39 ± 0.05^{b}	1.31 ± 0.07^{a}	1.34 ± 0.02^{a}	1.44 ± 0.03^{a}	1.53 ± 0.02^{a}
2	1.58 ± 0.03^{d}	1.38 ± 0.03^{bc}	1.27 ± 0.05^{bcd}	1.33 ± 0.03^{a}	1.44 ± 0.02^{a}	1.52 ± 0.01^{ab}
3	1.64 ± 0.10^{d}	1.35 ± 0.06^{cd}	1.27 ± 0.07^{bcd}	1.33 ± 0.04^{a}	1.44 ± 0.03^{a}	1.52 ± 0.01^{ab}
4	1.70 ± 0.05^{cd}	1.33 ± 0.05^{d}	1.25 ± 0.08^{d}	1.33 ± 0.02^{a}	1.42 ± 0.02^{ab}	1.52 ± 0.03^{ab}
5	1.80 ± 0.04^{c}	1.35 ± 0.03^{cd}	1.25 ± 0.04^{d}	1.32 ± 0.02^{ab}	1.42 ± 0.01^{ab}	1.52 ± 0.02^{ab}
6	1.81 ± 0.08^{c}	1.35 ± 0.06^{cd}	1.26 ± 0.06^{cd}	1.32 ± 0.03^{ab}	1.42 ± 0.04^{ab}	1.5 ± 0.02^{abc}
7	1.85 ± 0.08^{c}	1.36 ± 0.03^{bcd}	1.29 ± 0.06^{abc}	1.30 ± 0.02^{bc}	1.41 ± 0.03^{abc}	1.5 ± 0.03^{abc}
8	1.91 ± 0.06^{c}	1.36 ± 0.08^{bcd}	1.27 ± 0.09^{bcd}	1.29 ± 0.04^{cd}	1.41 ± 0.02^{abc}	1.49 ± 0.02^{bc}
9	1.97 ± 0.07^{bc}	1.37 ± 0.04^{bc}	1.27 ± 0.04^{bcd}	1.28 ± 0.01^{cd}	1.41 ± 0.03^{abc}	1.48 ± 0.04^{c}
10	2.07 ± 0.06^{b}	1.38 ± 0.07^{bc}	1.25 ± 0.08^{d}	1.28 ± 0.02^{cd}	1.40 ± 0.03^{bc}	1.48 ± 0.02^{c}
11	2.20 ± 0.17^{a}	1.43 ± 0.04^{a}	1.30 ± 0.06^{ab}	1.27 ± 0.03^{d}	1.38 ± 0.02^{c}	1.47 ± 0.03^{c}

Values are mean ± standard deviation, n = 3 for each age.
Means followed by the same letters are not significantly different at a 5% probability level.

Table 7. Effect of different age trees on soil carbon stocks at different soil depths (cm).

Age (years)	Soil organic carbon stock (Mg ha^{-1})			
	0–30 cm	3–60 cm	61–90 cm	Mean
1	63.92^{ef}	60.05^{a}	59.74^{a}	61.23^{bc}
2	63.04^{f}	59.62^{ab}	58.29^{ab}	60.32^{c}
3	65.44^{ef}	57.51^{c}	57.91^{b}	60.29^{c}
4	67.83^{de}	57.46^{c}	57.00^{bcd}	60.76^{c}
5	71.28^{cd}	57.51^{c}	56.25^{cd}	61.68^{bc}
6	71.68^{cd}	57.51^{c}	57.46^{bc}	62.21^{bc}
7	72.15^{c}	57.53^{c}	57.28^{bc}	62.32^{b}
8	73.92^{bc}	57.53^{c}	56.77^{bcd}	62.74^{b}
9	75.65^{ab}	57.95^{bc}	57.15^{bcd}	63.58^{b}
10	79.49^{a}	57.96^{c}	55.50^{d}	64.32^{b}
11	83.82^{a}	59.20^{abc}	57.33^{bc}	66.78^{a}

Means followed by the same letters are not significantly different at a 5% probability level.

correlation was observed between age and soil carbon stock at 30–60 cm and 60–90 cm soil depths.

3.3. Total carbon stocks

Total C stock (biomass C + soil C) was only considered up to the 30 cm soil depth, as per the guidelines of the Intergovernmental Panel on Climate Change (IPCC) (Table 8). The amount of total carbon (biomass and soil) increased from 64.43 Mg ha^{-1} at 1 year of age to 173.94 Mg ha^{-1} at 11 years of age. Carbon stock from the vegetation became almost equivalent to SOC stock at the age of 8 and 9 years. Total carbon stocks also showed a positive correlation with the age of the stand ($r = 0.91$, $P < 0.001$, $n = 33$).

Table 8. Total carbon stocks in different ages among the *P. deltoides* plantation.

Age (years)	Carbon stock (Mg ha^{-1})		
	Aboveground	Soil organic carbon	Total
1	0.51	63.92	64.43
2	1.20	63.04	64.24
3	3.09	65.44	68.53
4	13.46	67.83	81.29
5	25.17	71.28	96.45
6	39.31	71.68	110.99
7	62.00	72.15	134.15
8	73.45	73.92	147.37
9	75.26	75.65	150.91
10	85.55	79.49	165.04
11	90.12	83.82	173.94

4. Discussion

Tree growth parameters and biomass in different tree components increased with age. The mean annual increment of tree height and DBH slowed with an increase in age. Chauhan et al. (2011) also reported a similar trend in growth of *P. deltoides* under agroforestry in the Indo-Gangetic plains. The AGB and carbon stock estimates in *P. deltoides* obtained in other comparable studies are summarized in Table 9. The present estimates are much higher than those reported by Yadava (2010), Raizada and Srivastava (1989), and Kanime et al. (2013). The estimates of total AGB, however, fall within the range of those reported by Lodhiyal et al. (1995), Tandon et al. (1991), and Rizvi et al. (2011) for *P. deltoides*. The present estimate, however, is lower than the estimate of Lodhiyal and Lodhiyal (1997) for 1–4-year-old plantations of *P. deltoides.* As compared to other short- and long-rotation species, the estimates of total AGB in the present study are comparable with 95 Mg ha^{-1} at 7 years and 54.1–101.8 Mg ha^{-1} at 5–8 years for *Eucalyptus* hybrid, 263 Mg ha^{-1} for oak forest, 50.3–122.7 for *Dalbergia sissoo*, and 113–283 Mg ha^{-1} for *Pinus roxburghii* (Chaturvedi, 1983; Negi and Sharma, 1985; Bargali et al., 1992; Lodhiyal and Lodhiyal, 2003). The variations in tree biomass as compared to other studies are attributed to a number of factors, such as growth conditions, site quality, age, density, structure, and management practices (Oelbermann et al., 2004; Swamy and Puri, 2005; Kanime et al., 2012; Goswami et al., 2013).

Total AGB and contribution by different components to total AGB was, in order, bole > branch > twig > leaf. The contribution of bole to the total AGB in the present study was within the range reported for *P. deltoides* by Lodhiyal et al. (1995) and other woody species (52%–70%) in West Himalaya, India (Toky et al., 1989). The contribution, however, was lower compared to the study of Swami et al. (2006), who reported that stemwood accounted for 60.4%–68.9% of the total biomass, followed by branches (12.3%–15%) in 6-year-old *P. deltoides* clones G3, G48, D121, and S7C1.

Carbon content in different components varied from 40.8% to 53.56%, which is within the range reported by Chauhan et al. (2009) and Zebek and Prescott (2006) for *P. deltoides*. The literature also revealed that carbon content in different tree parts has been generally assumed to be 45%–50% of the dry weight (Wang and Feng, 1995; Rizvi et al., 2011). In the present study, aboveground carbon stocks in *P. deltoides* increased from 3.9 Mg ha^{-1} at 1 year to 94.7 Mg ha^{-1} at 11 years. These observed values are comparable to the estimates of Chauhan et al. (2010) for *P. deltoides* (62.5 Mg ha^{-1}) and Kaul et al. (2010) for fast-growing short-rotation forests (101–134 Mg C ha^{-1}). The aboveground carbon stocks were also comparable to the findings of Rizvi et al. (2011) for *P. deltoides* at a 7-year rotation (65.62 Mg ha^{-1} and 52.11 Mg ha^{-1} at 2 different locations). The values were also comparatively lower than the estimates of 96.2 Mg ha^{-1} by Singh and Lodhiyal (2009) and 72 Mg ha^{-1} by Fang and Tang (2007). The variation in carbon stocks may be attributed to age class distribution. Gera (2012) suggested that the variations in the sequestration potential can be attributed to the mean annual increment, which varied with site, age, density, and plantation, as well as the quality of planting stock. In the present study, the contribution of bole accounted for the largest amount of carbon (nearly 50%) from total tree biomass, which is comparable with other findings for different species (Redondo, 2007; Fonseca et al., 2012).

Large C stock does not necessarily mean a large C sequestration potential. Carbon stock refers to the absolute

Table 9. Comparisons of aboveground biomass and aboveground biomass carbon stocks of *P. deltoides* plantations in India.

Age (year)	Density (ha^{-1})	Aboveground biomass (Mg/ha)	Aboveground biomass carbon stock (Mg/ha)	References
1–4	666	7.4–89.3		Lodhiyal and Lodhiyal (1997)
3–7	500	63–128.6	26.10–65.62	Rizvi et al. (2011)
3–7		26.91–65.8		Tandon et al. (1991)
5–8	400	67.4–134.3		Lodhiyal et al. (1995)
8	-	202.69	75.7	Singh and Lodhiyal (2009)
8	500	50.1	22.8	Kanime et al, (2012)
9	500	48.7–51.5	22.0–23.2	Yadava (2010)
14	-	44.50		Raizada and Srivastava (1989)
1–11	500	1.26–180.2	0.51–90.12	Present study

quantity of C held at the time of inventory, whereas C sequestration refers to the process of removing carbon from the atmosphere and depositing it in a reservoir (Takimoto et al., 2008). In short-rotation forestry, fast-growing trees are harvested at a short rotation; as a result, carbon is lost. However, when wood of these species is used for ply, packaging, or furniture making, carbon is again locked. The proportion of stemwood used as long-lived wood products is estimated to be 42% (Wang and Feng, 1995). In the present study, the CSR of 7– to 11-year-old plantations varied from 5.8 and 6.2 Mg C ha^{-1} per year, respectively. The estimates of CSRs in the present study are lower than that reported by Kaul et al. (2010) for poplar (8 Mg C ha^{-1} per year) but higher than that of moderate-growing teak forests (2 Mg C ha^{-1} per year) and slow-growing long-rotation sal forests (1 Mg C ha^{-1} per year). The values for carbon sequestration by bole (1.98–2.2 Mg C ha^{-1} per year) recorded in the present study are higher than the estimates of 1.1 Mg C ha^{-1} per year for natural forest cover (Lal and Singh, 2000) and 0.5 and 3.4 Mg Cha^{-1} per year for community-based teak forests in the Harda Forest Division of Madhya Pradesh, India (Poffenberger et al., 2001). The estimates are, however, comparable to the estimates of Gera et al. (2006), Hooda et al. (2007), and Gera et al. (2011) for *P. deltoides*, but lower than the 3.2 Mg C ha^{-1} per year reported by Lal and Singh (2000) for plantations. Dhiman (2009) estimated that only 1.04 Mg C out of 2.5 Mg C from the poplar production system in India is locked in wood-based products for different durations; the remaining is released back in the form of fuel and only a marginal fraction of 0.3 Mg C is added to soil through leaf litter every year.

Carbon sequestration potential (CSP) of any plantation is meaningful when it is based on area covered by the species (Nair et al., 2010; Ajit et al., 2013). An attempt was therefore made to supplement the CSP with the preliminary estimates of the area of *P. deltoides*. In India about 312,000 ha are planted with P. deltoides, of which 60% is planted as block plantation. Utilizing the above data on the extent of plantation and average values of carbon sequestration from the present study, it is estimated that at national level, *P. deltoides* as block plantation leads to sequestration of 0.40 Tg C per year when only long-lived C storage (storage in bole) is considered. However, when short-lived biomass (branches and leaves) is also considered, poplar block plantation may lead to the sequestration of 1.15 Tg C per year.

SOC concentration and stocks increased with tree age at the 0–30 cm soil depth. The increase in SOC stocks at the surface soil layer is attributed to greater carbon input from litterfall, dead roots, and root exudates (Ralhan et al., 1996; Chauhan et al., 2009; Kaushal et al., 2012). Poplar trees on average add 3.5 Mg ha^{-1} of litter fall every year (Ralhan et al., 1996). Gupta et al. (2009) also reported that SOC increased significantly with tree age in the 0–15 cm soil layer and was 18% higher under 3-year plantations than in the soils under 1-year plantations. It further increased by 18.5% in soils under 6-year plantations. The SOC sequestration rate in soil was determined as the ratio of the difference in total SOC pools at different ages and initial value to the tree age (years). The CSR of the soils in the present study in mature plantations (7–11 years) varied from 1.18 to 1.81 Mg ha^{-1} per year, which is comparable to the values (1.95 Mg ha^{-1} per year in 6 years) of Gupta et al. (2009).

In the present study, the ratio of SOC to biomass carbon was in the range of 0.7 to 2, thereby indicating that carbon content in the soil was higher at initial plantation ages and gradually decreased with advancement in growth of the trees, increasing to 0.75 to 0.97 over the rotation period of 7 years, which is attributed to the fast growth of poplar. The IPCC (2000) reported that, globally, carbon stocks in the soils exceed carbon stocks in vegetation by a factor of about 5. The ratio ranges from 1:1 in tropical forests to 5:1 in boreal forests, and by much larger factors in grasslands and wetlands. Post et al. (1990) reported the ratio of SOC to biomass carbon to be 2.5 to 3 times in the terrestrial ecosystem. However, in the tropical forest, the carbon in the soil is roughly equivalent to or less than the AGB, due to degradation (Ramachandran et al., 2007; Kaul et al., 2010). Ravindranath et al. (1997) reported that the ratio of SOC to biomass carbon was 1.25.

P. deltoides varies in the ability to sequester carbon at different ages. The species is very useful for carbon accumulation in a short span of time and thereby provides additional revenue in terms of the carbon market. In addition, these plantations also hold promise for higher organic matter production and meeting the demand for plywood and fuel due to fast growth and greater biomass accumulation. Allometric equations developed from this study can be safely used for the standard spacing (5 × 4 m) in the Tarai region of India where poplar is widely grown. Thus, this study recommends planting *P. deltoides* as a viable option for sustainable production and carbon mitigation. However, while considering the CSP, the end use of the wood must be taken into account.

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