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Carbon sequestration potential of poplar-based agroforestry using the CO2FIX model in the Indo-Gangetic Region of India

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Abstract: Poplar (*Populus deltoides*) is one of the dominant and most preferred agroforestry species of the farming community of the Indo-Gangetic Region (IGR). The species is maintained at different rotation lengths depending upon farmers' management needs. The objective of the study was to compare carbon sequestration potential of poplar-based agroforestry systems in different parts of IGR using the CO2FIX model. Growth of trees, and yield of associated crops along with soil carbon, and litter fall were measured at Ludhiana (upper-IGR), Pantnagar (middle-IGR) and Pusa (lower-IGR). These data were used as inputs for CO2Fix model. Two rotation ages (6 and 9 years) were simulated for 54 years. The simulation results showed that biomass decreased by 62.50% in the upper IGR when rotation was reduced by three years from 9 to 6 years. Similarly the decrease was 56.57% and 43.18% in middle and lower IGR. The initial soil carbon pools were 7.8, 19.5 and 6.9 Mg ha^{-1} for upper, middle and lower IGR, respectively, which increased to 15.9, 22.7 and 15.0 Mg ha^{-1} by the end of 9th year; and 10.4, 18.8 and 12.3 Mg ha^{-1} by the end of the sixth year in first rotation. The net carbon sequestered was 47.2%, 51.7% and 31.4% less in 6 year rotation in upper, middle and lower IGR, respectively, as compared to 9 year rotation when compared for 54 years. The result suggests that in lower IGR shorter rotation of 6 years should be preferred and in upper IGR 9 year rotation is beneficial for carbon sequestration.

Key words: Agroforestry, biomass carbon, CO2FIX model, carbon sequestration potential, rotation, simulation, soil carbon.

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Introduction

The Indo-Gangetic Region (IGR) is a large and fertile plain encompassing most of northern and eastern India, the most populous parts of Pakistan, parts of southern Nepal, and virtually all of Bangladesh. The Indian IGR represents eight agro-ecological regions (AERs) and 14 agro-

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ecological sub-regions (Joshi & Datta 2009). It covers the states of West Bengal, Bihar, Uttar Pradesh, Haryana, and Punjab along the Indian Himalayan ranges. It covers 15.3% of India and supports about 33% of the human and 35% of the livestock population of India (Pathak *et al.* 2014). The region has been heavily exploited for agriculture by the indiscriminate use of fertilizers, pesticides, and other chemicals, which have resulted in soil degradation and unsustainable use of natural resources. Declining productivity, soil quality, and water table, and increasing waterlogging and salinity have now become major problems in this region requiring immediate attention. Agroforestry in this region has high potential to address the issues of degradation and sustainability (Pal *et al.* 2009; Pathak *et al.* 2014).

Agroforestry, in India, has been promulgated to reduce the pressure on forest areas for fuel wood, diversify agriculture, and, more recently, aid carbon sequestration. In Indian IGR, poplar (*Populus deltoides*)-based agroforestry systems have been proven to be compatible with agriculture crops and profitable to farmers. The species is widely grown in Punjab, Haryana, Uttarakhand, and Uttar Pradesh states of India. Nearly 15 million poplar plants are raised every year in these states in agroforestry plantations covering roughly 30000 ha. A similar area of mature agroforestry plantations is harvested annually yielding about 0.36 million m^3 of wood supporting the safety match industry and a large number of veneer and plywood units (Pathak *et al.* 2014). Poplar is now linked to social, ecological, agricultural, and industrial applications in the region. An estimate revealed that 312000 ha are planted with poplar in India of which 60% is under block plantation (compact blocks with plants in square or rectangular planting pattern) and 40% as bund plantation (raised as single or double rows on agricultural field bunds) (ICFRE 2012).

Agroforestry has great potential for restoration of degraded lands and forests and mitigating the accumulation of carbon as CO_2 in the atmosphere by increasing land-based carbon sinks. The Intergovernmental Panel on Climate Change (IPCC) recognized agroforestry as having high potential for sequestering carbon under climate change mitigation strategies (Watson *et al.* 2000). The importance of agroforestry as a viable alternative to prevent and mitigate climate change has also been recognized widely in India. At the national level, planting of poplar may lead to carbon sequestration of more than 542 kt yr^{-1} when wood products are not accounted for and about 1 Mt yr^{-1} inclusive of wood products (Gera 2012). In Yamunanagar and Saharanpur districts of Haryana and Uttar Pradesh states of India, carbon storage was estimated to be 27–32 Mg ha^{-1} in boundary systems and 66–83 Mg ha^{-1} in agroforestry systems at a rotation period of 7 years (Rizvi *et al.* 2011) while Kanime *et al.* (2013) reported values of 4.51 Mg ha^{-1} in boundary plantation and 28.7 Mg ha^{-1} in block plantation at Pantnagar, India. In Punjab, India, Chauhan *et al.* (2010) reported that total biomass carbon storage after 7 years was equivalent to 62.48 Mg ha^{-1} (8.92 Mg ha^{-1} yr^{-1}). Arora *et al.* (2014) reported that average long-lived carbon sequestration rate and long + short-lived sequestration rate were 2.11 and 6.07 Mg ha^{-1} yr^{-1} respectively. Dhiman (2009) estimated that only 1.04 Mt out of 2.5 Mt carbon from poplar production systems in India is sequestered in wood-based products; the remainder is released to the atmosphere in the form of fuel and only a marginal fraction of 0.3 Mt carbon is added to soil through leaf litter every year. Ravindranath *et al.* (2002) estimated that the mitigation potential of the forestry sector, based on a biomass-demand-based scenario and using short or long-term commercial forestry options, is 122×10^6 Mt carbon for the period 2000–2012. Further, species-specific carbon sequestration potential studies have provided entirely different estimates depending upon various factors like weather conditions, location and management activities (Negi & Chauhan 2002; Negi *et al.* 2003; Singh 2003). Efforts are increasingly being made to generate data on potential of species for carbon sequestration in different regions.

Most of the studies estimating carbon stocks in India are based on measurement of tree biomass productivity through periodic harvesting which is time consuming and labour intensive. Moreover, in most of the reports, the simulation aspects of carbon sequestration have not been considered beyond the actual experiment duration. For such predictions, computer models are essential tools for evaluating the biomass stored and carbon sequestered both above ground and below ground including soil. Models can also help in long term prediction which can help policy makers in developing strategies. Accordingly, in this study, we employed the CO2FIX model to simulate and compare the carbon sequestration potential (CSP) of poplar-based systems in different parts of the IGR.

Table 1. Site characteristics and climatic data of the areas.

Location	State	Latitude and Longitude	Altitude (m)	Temp. (°C) (Max–Min)	Rainfall (mm)	Climate
UGR–Ludhiana	Punjab	30°54´N; 75°48´E	247	45–46; 4.2–8	768	Subtropical
MGR–Pantnagar	Uttarkhand	29°08´N; 79°20′E	223	30–40; 0–9	1364	Humid subtropical
LGR–Pusa	Bihar	25°59´N; 85°48´E	53	30–31.3; 16–20	1065	Subtropical

UGR–Upper Gangetic Region ; MGR–Middle Gangetic Region; LGR–Lower Gangetic Region.

Materials and methods

Description of the CO2FIX model

The CO2FIX model v3.2 (Masera *et al.* 2003), a process-based carbon estimation model, was used for simulations in this study. Detailed information on CO2FIX model is available at http://dataservices. efi.int/casfor/downloads/co2 fix3_1_description.pdf. CO2FIX was preferred over other models used in estimating changes in carbon stocks for forestry and plantation projects *viz.* PROCOMAP, CENTURY and ROTH since only CO2FIX can simulate the carbon dynamics of single or multiple species simultaneously, and can handle trees with varied ages. CO2FIX has been tested and validated for forests in the Phillipines, mixed pineoak forest of central Mexico, multi-strata agroforestry systems (AFS), tropical rainforest in Costa Rica and woodlots in Zambia (Kaonga & Smith 2012). In India, CO2FIX has been used to estimate the carbon storage and sequestration potential for agroforestry systems in the Indo-Gangetic plains (Ajit *et al.* 2013), sal (*Shorea robusta*), eucalyptus (*Eucalyptus tereticornis*), poplar (*Populus deltoides*), and teak (*Tectona grandis*) (Kaul *et al.* 2010).

Data required for running the CO2FIX model

For the purpose of simulating carbon stocks under poplar-based systems in different parts of Indian IGR, biomass, soil and carbon accounting modules were used. CO2FIX requires primary as well as secondary data on tree and crop components (called 'cohorts' in CO2FIX) for preparing the account of carbon sequestered. The primary data include number of trees per hectare, height, diameter at breast height (DBH) taken as per standard procedure, crops grown on farmlands along with their productivity, area coverage, soil carbon, and litter fall. The secondary data include the growth rates of tree biomass components (stem, branch, foliage and root) on an annual basis as well as the productivity of different crops grown in that region. In the present study wheat was the associated crop while in the middle IGR pure plantations of *P. deltoides* were raised without intercropping. Data for the present study were collected from three sites in Indian IGR (Table 1), which we refer to as lower (Pusa in Bihar), middle (Tanda Forest range near Pantnagar in Uttrakhand), and upper IGR sites (Ludhiana in Punjab). Average growth parameters *viz.,* height (m) and diameter at breast height (1.37 m above ground) and age of the trees at each study site were collected (Table 2). More details of the study site and methodology are found in Ajit *et al.* (2011) and Arora *et al.* (2014).

Table 2. Summary of growth data and parameters used in simulating carbon dynamics.

Location/ parameters	Height (m)	Diameter (cm)	Age (yrs)	System
Pusa	3.4– 23.4	1.8–40.5	1–9	Agro-forestry
Pantnagar	2.1–24.2	3.56–26.6	1–10	Sole plantation
Ludhiana	4.93–24.3	5.36–23.9	1–7	Agro-forestry

Stems ha^{-1} – 500; Rotation length – 6 and 9 years; Basic Wood Density – 0.61 (Mg m^{-3}); Turnover rates (yr^{-1}): Foliage–- 0.6; Branch – 0.02; Roots – 0.2.

Input parameters for the CO2FIX model

There were two cohorts for all three site *viz.* tree and crop, however simulation for middle-IGR was done only for trees as it did not have any crop component. The main input parameters in CO2FIX are the cohort values for the stem-CAI

Table 3. Product allocation after harvest.

	Log wood	Pulp wood	Slash
Stem	0.05	0.5	0.45
Branch	0.05	0.5	0.45
Foliage	0	0	1

(current annual increment in m^3 ha^{-1} yr^{-1}); relative growth of the foliage, branches, and root with respect to the stem growth over years; turnover rates for foliage, branches and roots; and climate data of the site (annual precipitation in mm and monthly values of minimum and maximum temperatures in °C). Other inputs to the model include initial surface soil organic carbon (Mg ha^{-1}), rotation length for the tree species, per cent carbon contents in different tree parts, wood density and initial values of baseline carbon (Mg ha^{-1}) in different tree parts. Competition, management mortality and thinning tools were not simulated as thinning is not practiced and management mortality is uncommon in poplar-based agroforestry. Further details on model parameters of tree and crop cohorts are given in Ajit *et al.* (2013).

To derive the incremental data on tree stem growth (i.e., the generalized equations), the volume equations published in India State of Forest Report-2013 (Ministry of Environment and Forests, Government of India, http://fsi.nic.in/cover_2013/annexure.pdf) were used. Data for wood density and turnover rates (Table 2) were obtained from previous studies on short rotation species (Bargali *et al.* 1992; Ajit *et al.* 2013)

Simulation approach

Model parameters were obtained for the simulations using field data. In biomass modules, stem growth had to be provided in the form of CAI as a function of age. Since poplar is a short rotation crop, thinning is generally not carried out, therefore rotations of 6 and 9 years were simulated to study the effect of continuous poplar cropping on carbon in soil and biomass. Lodhiyal *et al.* (1995) reported that in 5–8 year old poplar plantation, the relative allocation of biomass in logwood and roots ranged from 56–59% and 19–21% respectively. Given the small differences in biomass allocation in different aged plantations, biomass allocation for the present study was considered the same for both ages (Table 3). Biomass allocation is based on the information provided by the plywood units near to the study sites. A sensitivity analysis of CO2FIX was done by taking annual precipitation and monthly temperatures as site-specific factors which are liable to vary during the simulation period. CO2FIX model considers them as static throughout the simulation period and thus they are sources of uncertainty in model output. Based on secondary data of the previous 50 years, two groups of 10 and 20% in precipitation and one group of 0.5 °C in temperature were made to evaluate sensitivity (increase/decrease) to input parameters. It was observed that a change of 0.5 °C in monthly temperature may result in 0.7–2.46% change in per cent rate of C-sequestered, whereas a change of 20% in annual precipitation may lead to 5.39–10.88 % change in per cent rate of C-sequestered. Thus the rate of C-sequestration is more sensitive to precipitation than temperature (Ajit *et al.* 2013).

Parameterization of the soil module

Data on monthly temperature and precipitation were obtained from a local meteorological observatory situated at Pusa in Bihar, Pantnagar in Uttrakhand and Ludhiana in Punjab. These data were used as variables for the soil compartment of the model for the respective sites. The YASOO soil model is an integral part of CO2FIX that simulates decomposition and dynamics of soil carbon in well-drained soils (Liski *et al.* 2005). The soil module consists of three litter and five decomposition compartments. Litter is produced in the biomass module through biomass turnover. Litter is classified as non-woody (foliage and fine roots), fine woody (branches and coarse roots) and coarse woody (stems and stumps). Since the biomass module makes no distinction between fine and coarse roots, root litter is separated into fine and coarse roots in the same ratio as branch and foliage litter. Decomposed matter components are extractives, cellulose, lignin-like compounds, humus-1 and humus-2.

Results

Effect of rotation length and number on biomass production

Biomass accumulation under a 9 year rotation was highest in upper IGR and lowest in lower IGR (Table 4). At the 9th year the simulated tree biomass was 136.6 Mg ha^{-1} and tree plus crop biomass was 152.7 Mg ha^{-1} in upper IGR. In a similar way in lower IGR the biomass increased

Table 4. Simulated biomass accumulation with 9 year and 6 years rotations; values are Mg ha^{-1} of dry aboveground biomass. Initial density 500 stems ha^{-1}.

Rotation	UGR		MGR*	LGR	
	Tree	Crop	Tree	Tree	Crop
9 year rotations					
0	0.03	15.6	0.03	0.03	12.03
1	136.6	152.7	117.9	110.5	122.4
3	149.9	165.9	129.2	120.9	132.8
6	150.0	166.0	129.3	121.0	132.9
6 year rotations					
0	0.03	15.64	0.03	0.03	12.03
1	51.2	67.4	51.2	62.8	74.5
4	57.8	73.8	57.2	69.5	81.4
9	57.8	73.8	57.2	69.5	81.4

UGR- Upper Gangetic Region; MGR – Middle Gangetic Region; LGR – Lower Gangetic Region.

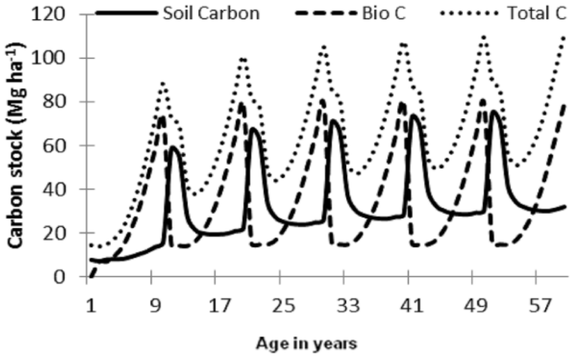
ABG– Above and below ground; *crop was not obtained.

from 110.5 to 122.4 Mg ha^{-1} when crop biomass was added. In upper IGR, biomass was 150.0 Mg ha^{-1} after 6 rotations (54 years) without a crop and 166.0 Mg ha^{-1} with a crop. It was least in lower IGR with a biomass of 121.0 and 132.9 Mg ha^{-1} without and with crops, respectively after 6 rotations.

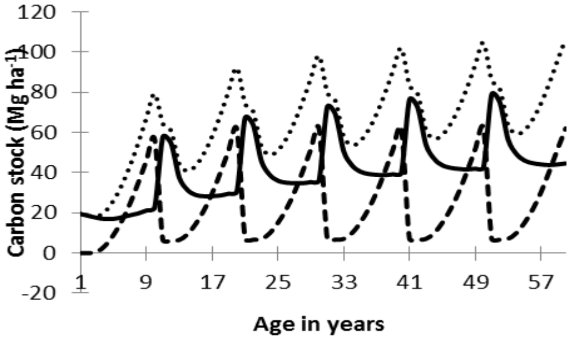
To investigate the effect of reducing rotation length on dry matter and carbon sequestration, a 6 year rotation was simulated (Table 4). After one rotation, biomass accumulation was 62.5% less than in the 9 year rotation in upper IGR. Similarly, the reduction was 56.6% and 43.2% in middle and lower IGR. For combined tree and crop biomass after 9 six-year rotations (54 years), biomass accumulation was 73.8, 57.2 and 81.4 Mg ha^{-1} which were 55.5%, 55.8% and 38.7% less than accumulated after 6 nine-year rotations in upper, middle and lower IGR respectively.

Effect of rotation length and number on carbon sequestration

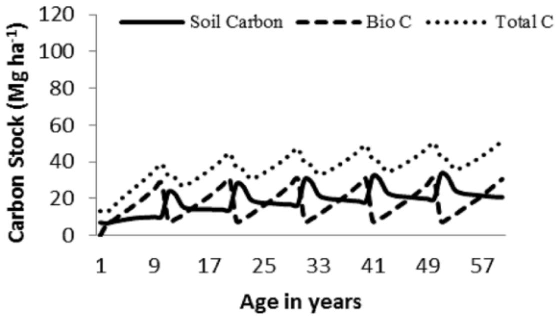
The initial soil C pools were 7.8, 19.5 and 6.9 Mg ha^{-1} for upper, middle and lower IGR, respectively, which increased to 15.9, 22.7 and 15.0 Mg ha^{-1} by the end of the first rotation of 9 years. After 6 rotations (54 years) the soil carbon increased by 312.3, 129.0 and 451.2 % in upper, middle and lower IGR, respectively. For the 6 year rotation soil carbon increased to 10.4, 18.8 and 12.3 Mg ha^{-1} by the end of the first rotation. After 9 rotations (54 years) soil carbon accumulation followed the order middle>lower>upper IGR.



Upper Gangetic plain



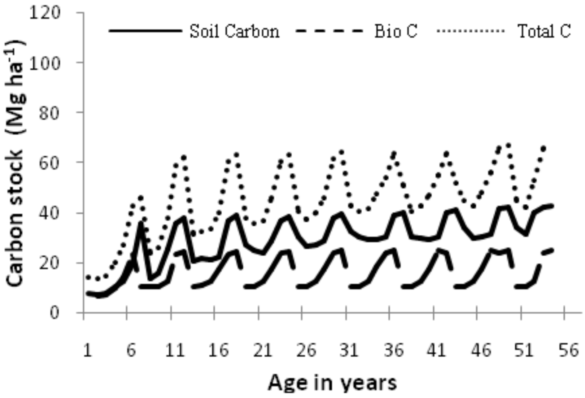
Middle Gangetic plain



Lower Gangetic plain

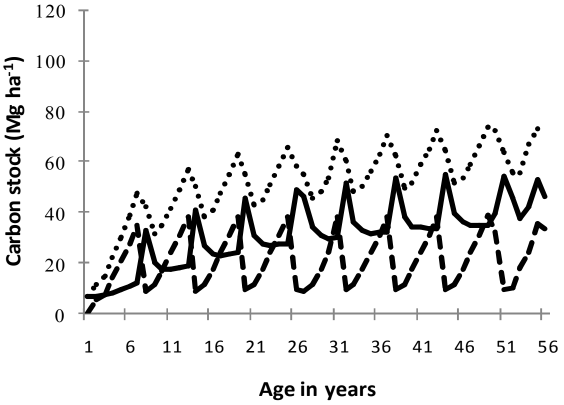
Fig. 1. Simulated carbon stocks at upper, middle and lower Gangetic plains with 6 year rotation length.

The long-term average carbon stocks in soil and tree biomass revealed that after three and six 9-year rotations, soil carbon was highest in middle IGR (Fig. 1). The biomass carbon was intermediate in upper IGR (78.83 and 78.9 Mg ha^{-1} of carbon at 3rd and 6th rotation respectively) and least in lower IGR. Total carbon followed the trend upper> middle>lower IGR (Fig. 1). Simulation was also done to compare carbon sequestration potential when rotation length is reduced to 6 years. After four and nine rotations, soil carbon was highest in middle IGR followed by lower IGR and then upper



Upper Gangetic Region

Middle Gangetic Region



Lower Gangetic Region

Fig. 2. Simulated carbon stocks at upper, middle and lower Gangetic plains with 9 year rotation length.

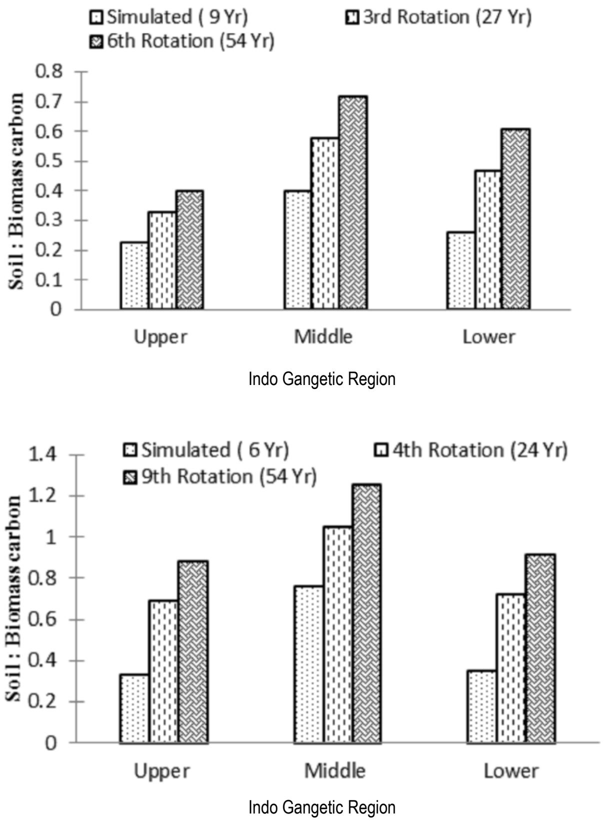


Fig. 3. Ratio of soil and biomass carbon with increasing number of rotation: (a) 9 year rotation length; (b) 6 year rotation length.

IGR. Biomass carbon was higher in lower and middle IGR at the 4th and 9th rotations and least in upper IGR. Total carbon followed the trend lower > upper > middle IGR (Fig. 2).

Simulated net carbon sequestered (biomass + soil carbon) under 6 and 9 year rotations was 47.2%, 51.7% and 31.4% less in 6-year compared to 9 year rotations in upper, middle and lower IGR, respectively after 54 years of simulation. Soil carbon to biomass carbon ratio increased with rotation length. Soil carbon ratio in middle IGR reached 0.7 for 9 year rotation length after six rotations (54 years), whereas this ratio was 1.2 after nine rotations (54 years) when rotation length was kept at 6 years (Fig. 3).

Discussion

The simulated total biomass at the end of a single 9 year rotation ranged from 110.5 to 136.6 Mg ha^{-1} without a crop and 122.4 to 152.7 Mg ha^{-1} when crop production was included (Table 4). The simulated biomass is comparable to the 128.6 Mg ha^{-1} reported by Rizvi *et al.* (2011) at the 7th year of a plantation with similar density. Lodhiyal *et al.* (1995) reported biomass of 134.3 Mg ha^{-1} in 8 year old plantation though plant density was low. In contrast, Dar and Sundrapandian (2015) reported higher values of biomass (254.3 Mg ha^{-1}) and carbon in poplar forest in the temperate Himalayas which can be attributed to high plant

Table 5. Comparisons of aboveground biomass and aboveground biomass carbon stocks of *P. deltoides* plantations in India.

Age (year)	Density (ha^{-1})	Aboveground biomass (Mg ha^{-1})	Aboveground biomass carbon stock (Mg ha^{-1})	References
1–4	666	7.4–89.3		Lodhiyal & 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 & Lodhiyal (2009)
8	500	50.1	22.8	Kanime *et al.* (2013)
9	500	48.7–51.5	22.0–23.2	Yadava (2010)
14		44.50		Raizada & Srivastava (1989)
1–11	500	1.26–180.2	0.51–90.12	Arora *et al.* (2014)
10	1111	14.74–48.97		Singh (1998)
-	1201	241.9	108.8	Dar & Sundarapandian (2015)

density (1201 ha^{-1}). Arora *et al.* (2014) reported 180.2 Mg ha^{-1} of biomass production in 11 year old plantation (Table 5). When the simulated rotation length was decreased to 6 years, biomass production ranged from 51.2 to 62.8 Mg ha^{-1} without a crop and 67.4 to 74.5 Mg ha^{-1} with a crop (Table 4). The estimated values in the present study are comparable (67.4 Mg ha^{-1} at 5 years) with those of Lodhiyal *et al.* (1995); Tandon *et al.* (1991) also reported similar biomass of 65.8 Mg ha^{-1} at seven years. In contrast, high biomass of 89.3 Mg ha^{-1} was reported by Lodhiyal and Lodhiyal (1997) at four years which can be attributed to a high tree density of 666 ha^{-1} as against 500 ha^{-1} in the present study.

Simulated biomass production varied from upper to lower IGR which may be attributed to the favourable conditions of better soil aeration and lesser humidity for poplar growth in upper IGR. Lower IGR has high soil fertility and ample soil moisture which results in good initial growth of poplar. However, after 6 years the biomass production in lower IGR is less as the roots of six year old plants of poplar extend into the high water table prevailing in the region and hence root growth is restricted and plant growth is affected. Contrary to this scenario, in upper IGR such root restriction does not occur and plants continue to grow rapidly, surpassing growth in lower IGR after 6 years.

Simulated carbon stocks for 6 and 9 year rotations in the present study ranged from 41.9 to 47.5 Mg ha^{-1} and 73.2 to 88.4 Mg ha^{-1}, respectively. Carbon stocks as low as 23.2 Mg ha^{-1} at 9 year of age have been reported (Yadava 2010). At 9 years, comparable carbon stocks of 75.3 Mg ha^{-1} have been reported by Arora *et al.* (2014) and 75.7 Mg ha^{-1} by Singh & Lodhiyal (2009) (Table 5). Gera (2012) suggested that the variations in the sequestration potential can be attributed to the mean annual increment, which varies with site, age, density, and plantation, as well as the quality of planting stock.

In the present study the total carbon stock increased with increase in number of rotations (Fig. 1 and 2) and rotation age. Kaul *et al.* (2010) also reported that the total carbon stock in the forest ecosystem increased with increasing rotation length. A 30 year increase in the rotation length from the recommended 120 years increased the average carbon stock of the forest ecosystem (trees + soil) by 12%. Increase in rotation age led to more biomass accumulation and higher carbon. The addition of litter in soil for an additional three years (from 6 to 9 year) from full grown trees adds high amounts of carbon to soil therefore, carbon stocks in 9 year rotations were higher.

Soil-to-biomass carbon ratio in the present study ranged from 0.2 to 1.2 depending on rotation length and duration of cropping. Ravindranath *et al.* (1997) reported that the ratio of soil and biomass carbon was 1.25 while Kaul *et al.* (2010) reported a ratio between soil and biomass carbon in the range of 0.7 to 2. Post *et al.* (1990) reported that the ratio between soil and biomass carbon is 2.5 to 3 in the terrestrial ecosystem. However, in tropical forest, the carbon in the soil is less than or equal to the above-ground biomass due to rapid decomposition (Ramachandran *et al.* 2007). Poplar is deciduous and shed its leaves annually during winter. Ralhan *et al.* (1996) reported that poplar trees on average add 3.5 Mg ha^{-1} of litter to the soil every year. The increase in soil carbon with increasing number of rotations therefore is due to the increase in litter production and harvest residues thus substantially enhancing the carbon sink function of agroforests.

Conclusions

Biomass accumulation is more rapid in lower than in upper IGR at early stages. However, if rotation length is longer, the biomass accumulation and carbon sequestration in upper IGR catches up to and exceeds that in lower IGR. The increase in soil carbon is greater in middle IGR and less in upper IGR. Opting for a 50% increase in rotation age of (9 year as compared to 6 year), increases the net carbon sequestration by 30 to 50 per cent. The simulation studies further reveal that with current management practices, if the rotation age is kept at 9 years and poplar cultivation is continued over a long period, it will improve the soil carbon pool along with production of more biomass as compared to 6 year rotation. The results of the study thus suggest that continuous short rotation commercial tree cultivation will improve soil health besides having environmental and economic benefits.

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