Indian Journal of Agricultural Sciences **80** (2): 129–35, February 2010

Yield and carbon sequestration potential of wheat (*Triticum aestivum*) -poplar (*Populus deltoides*) based agri-silvicultural system

SANJEEV K CHAUHAN[1], S C SHARMA[2], V BERI[3], RITU[4], S YADAV[5] and N GUPTA[6]

Punjab Agricultural University, Ludhiana 141 004

Received: 17 April 2009; Accepted: 29 October 2009

ABSTRACT

A study was conducted during 2004–06 to assess the carbon storage by the poplar-based agri-silvicultural system and change in the soil organic carbon. There was a dire need to quantify the carbon sequestration potential of poplar-based agri-silvicultural model, besides the productivity of the system. At sixth year, total biomass in agri-silvicultural system was 25.2 tonnes/ha, which was 113.6% higher than sole wheat cultivation. Poplar tree stem alone contributed 21.99 tonnes/ha, which is very significant proportion and goes to the durable products. Net carbon storage (soil + tree/crop biomass) was 34.61 tonnes/ha in wheat–poplar interface compared to 18.74 tonnes/ha in sole wheat cultivation (soil + crop biomass). After 6 years of poplar planting, organic carbon increased in soil (0–15 cm) by 35.6% than pure wheat crop. Though there was substantial loss in wheat crop yield under poplar but the decrease in wheat yield has been compensated by the poplar trees in terms of biomass, economics and the carbon mitigation potential.

Key words: Agri-silvicultural system, Carbon allocation, Poplar, System productivity, Wheat

Tree provides an assurance to the farmers towards agricultural production in normal rainfall year, while in famines and drought year they provide top feed for livestock. Trees improve soil productivity through ecological and physio-chemical changes depending upon the quantity and quality of litter reaching the soil surface and the rate of litter decomposition and nutrient release (Singh and Sharma 2007). In addition, introduction of trees in agricultural farms is a useful tool to lock up the carbon in tree components and increase the soil carbon status because the presence of trees affect carbon dynamics directly or indirectly (Singh 2005, Khan and Chaturvedi 2007, Newaj and Dhyani 2008). Various interacting factors through which a tree influences carbon stock in the soil under agroforestry are addition of litter, maintenance of higher soil moisture content, reduced surface soil temperature, proliferated root system, enhanced biological activities and decreased risk of soil erosion (Singh and Rathod 2002, Schultz *et al.* 2004, Singh and Sharma 2007).

Populus deltoides Bartr. based agroforestry system is one of the viable alternate land-use systems to prevent further degradation and obtain biological production on sustainable basis. Poplar being a deciduous tree, enters in dormancy during winter and the leaf fall coincides with the time of wheat sowing (Zomer *et al.* 2007). The cultivation of poplar under agroforestry system improves the physico-chemical properties of soil through addition of organic matter in the soil (Singh and Sharma 2007, Gupta *et al.* 2009). However, some adverse effect has also been reported by various workers (Singh *et al.* 2001, Nandal and Dhillon 2007). Leaf fall at sowing poses physical barrier to germinating seeds and may affect the availability of nutrients to developing seedlings. Addition of leaves, changes the C: N ratio of the soil which can effect the crop growth. There is need to increase the level of soil organic carbon not only to maintain land productivity but also to provide a sink for atmosphere CO_2 in the terrestrial carbon pool. The carbon sequestration in above ground biomass and soils under agroforestry from biomass turnover have been expected to be greater than under conventional agricultural operations (Montagnini and Nair 2004). Very limited actual data are available to understand the carbon storability in the system (tree-crop-soil). The present study aimed to assess the carbon storage by the poplar, the

[1]Associate Professor (e mail: chauhanpau@rediffmail.com), Department of Forestry and Natural Resources

[2]Director, RRSKA, Ballowal Saunkhri (e mail: subhash38 @yahoo.com)

[3]Professor and Head (Retd), Department of Soils (e mail: vberi@pau.edu), [4]Assistant Scientist, RRS Bathinda (e mail: ritubabuta@gmail.com)

[5]Research Fellow, Department of Forestry and Natural Resources (e mail: sudhir_ydv@yahoo.com), [6]Research Fellow, Department of Soils (e mail: naveen_pau@rediffmail.com).

associated agricultural crop (wheat) and change in the soil organic carbon so that the carbon sequestration potential of poplar-based agroforestry system is acknowledged.

MATERIALS AND METHODS

A field experiment was conducted for 3 years on the farmer's field at Balachaur, SBS Nagar (Punjab). The experimental site is situated at 31°6′5″N and 76°23′26″E at 355 m above the mean sea level. The site is characterized by sub-tropical climate with hot and dry summers from April to June, hot and humid from July to September and cold winter from December to January. The average annual rainfall during 2004–06 was 571 mm, which was more or less equal to the normal (586 mm). The soil was loam (0–15 cm), sandy loam (15–30 cm) and loamy sand (30–60 cm) in texture. The soil was found slightly alkaline in reaction (7.49) and low in organic carbon (0.31%), low in alkaline $KMnO_4$ – extractable N (180 kg/ha), medium in 0.5 N $NaHCO_3$ – extractable P (17.1 kg/ha) and medium in NH_4OAc–extractable K (136.8 kg/ha).

The experiment was started during 2003–04 in 1 to 4–years-old poplar plantations adjacent to each other. One-year-old poplar plants of Australian clone 'G 48' were transplanted in January in 2000, 2001, 2002 and 2003 as block plantation at a row distance of 4.5 m (along north-south row direction) and tree-to-tree distance of 3 m. Data were collected from 4 replications (0.4 ha area/replication) in different age plantations. There was no other special management practices followed for poplar except pruning of the tree from second year after transplantation (during 2/3 year one third, 4/5 year half and 6 year 2/3 of the tree stem was pruned). The poplar tree rows were dry tilled once with discs plough and twice with cultivator and leveled with a wooden plank. The 'PBW 343' wheat was sown with seed drill at a row-to-row distance of 22.5 cm in the first week of November. All other recommended practices of Punjab Agricultural University, Ludhiana were followed for crop cultivation. The crop was harvested in April. Data of sole wheat crop was also recorded from the adjacent field as control, where the traditional crop rotation of wheat (winter season) - paddy (summer season) was followed.

The field was divided into 4 blocks and each block was treated as a replication. From each replication, the height of randomly selected plants in each quadrat was recorded from ground level to the tip of plant at the time of harvesting stage. Ear length and number of grains/ear of the representative ear heads were also recorded at the time of harvesting from each and every quadrat.

The grain yields were recorded from 1 m^2 quadrat from 9 spots and mean of these values were used to represent each replication. The average grain yield of 1 m^2 was extrapolated to give yield in tonnes/ha by bringing the produce at 14% grain moisture content. The weight of straw produced in each quadrat was recorded and straw yield was also computed in tonnes/ha on dry weight basis.

The trees were measured for their top height, diameter at breast height (DBH) and crown spread. The total height was measured with Altimeter (m) from ground to top of the trees. The clear bole was maintained at the time of pruning. The diameter at breast height (1.37 m above the ground level) was taken with the help of digital caliper. Crown spread was measured using metre tape and 2 poles holding straight touching to the outmost tip of the opposite sides of the tree. The distance between these 2 poles were recorded with the help of measuring tape. Similarly, it was repeated at perpendicular to measure the other direction.

The standard timber volume of the tree was measured using the locally developed regression equation; $V = 0.003487 + 0.268366 \times D^2H$, where V, D and H are timber volume, diameter at breast height and height of the tree, respectively (Dhanda and Verma 2001). The randomly collected plant samples (poplar and wheat) were analyzed for C content. The carbon content in different tree/crop components (above and below ground) was estimated on CHNS analyzer to calculate the carbon storage in each component of poplar (stem, branch, bark, leaves and root) and wheat crop (straw, grain and root). The total carbon storage was computed by using the carbon values of respective component and multiplying the same with the biomass of each component derived through the regression equations developed in prevailing agro-climatic zone by Sharma *et al.* (2007). The carbon stored was converted to CO_2 fixation by multiplying the total carbon storage with factor 3.67 (Dury *et al*. 2002).

The soil samples were collected from different age plantations and sole wheat plots at 0–15, 15–30 and 30–60 cm depths. Soil was analyzed for total carbon by Walkley and Black method (Jackson 1973) after crop harvesting in 2006. The results of net carbon accumulation in the agroforestry system have been determined by subtracting the quantities from the carbon stored in the control plot (sole wheat). In this study, the above ground, below ground, litter biomass and soil organic carbon has been taken into consideration for calculating the carbon pool. These all 4 carbon pools are essential for the quantification of carbon in the system for perspective environmental benefits. The comparison of carbon storage in sole wheat crop (traditional agriculture) and poplar–wheat interface has also been attempted. The total carbon storage in standing trees was computed by adding the carbon stored in foliage, stem, branch and roots, whereas the total carbon storage in the system was estimated by adding the carbon accumulated in vegetation (poplar + wheat above and below ground biomass) and soil compartments in different age plantations. The net carbon accumulation was calculated by subtracting total carbon in sole wheat plot (crop plant + soil) from the carbon accumulated in agroforestry system (tree-crop-soil).

The average of the crop and tree parameters of respective ages have been computed for better understanding and clarity of the data. The crop and tree data for first and sixth year plantation are one year data, second and fifth year values are average of 2 years and values of third and fourth are average of 3 years because the experimental plantations entered in the respective years accordingly. The average data in 4 replications on growth, biomass and carbon and allocation in poplar/wheat crop and soil were suitably analyzed after following the established procedures on computer. Significant differences among the treatment means (different age plantations) for growth, biomass and carbon storage were tested at $P \leq 0.05$ using least significant difference values as described by Panse and Sukhatme (1978).

RESULTS AND DISCUSSION

Plant height, ear length and number of grains/ear

The plant height of the wheat crop decreased significantly with advancement of the age of the poplar trees (Table 1) and the maximum average crop plant height (85.58 cm) was recorded under control plots (97.26, 76.23 and 83.27 cm during 2004, 2005 and 2006, respectively). The lower height under poplar plantation might be due to the shading or increase in competition for different resources with increasing age of poplar trees and presence of poplar leaf litter mulch. Poplar leaves contain secondary compounds, which may act as allelo-chemicals and inhibit shoot and root growth of wheat crop (Singh *et al.* 2001, Mughal and Khan 2005, Nandal and Dhillon 2007). Sharma *et al*. (2005) also recorded similar observations for crop plant height and ear length due to poplar mulch and reported that the shading caused by poplar clone (G3) had negative effect on growth of wheat crop. The lower plant height and ear length may be due to lower production of photosynthates under low light conditions in comparison to sole wheat crop (Miah *et al.* 1999). The reduction in the light intensity in present study, ie 23.9, 35.1, 46.7, 54.9, 59.8 and 61.3% in first to sixth year plantation, respectively than open condition resulted in reduced plant growth. The reduction in light intensity was significantly more during initial years than the later years (Fig 1). LAI values of 1.98, 3, 59 and 3.72 under 4, 5 and 6- year old plantation recorded through the canopy analyzer (model CI 110, US made) and the corresponding co-efficient for diffusion penetration values of 0.284, 0.129, and 0.112 reflected substantial shade for the under-storey crop. The reduction in photosynthetically active radiation (PAR) becomes much drastic due to canopy shade than the actual light intensity (Chauhan *et al.* 2007, 2009).

1st yr 6th yr

Fig 1 Canopy structure of first and sixth year of poplar plantation

The ear length and number of grains/ear followed the same trend as of plant height during all the 3 years (Table 1). The ear length was significantly higher in control plots (9.30 cm) and it decreased with advancement of age of poplar. Similar trend was observed for number of grains/ear, which contributed directly to the grain yield. Gill *et al.* (2009) also recorded declining trend in tiller height, number of tiller and spike length in wheat crop with increase in age of poplar plantation.

Grain yield and straw yield

The average grain yield of wheat crop was maximum under control plots, ie 4.55 tonnes/ha (5.35, 4.48 and 4.53 tonnes/ha during 2004, 2005 and 2006, respectively), which was statistically higher than the crop under block poplar plantations (Table 1). The crop yield declined significantly with advancement of age of poplar trees. The rate of decrease in grain yield of wheat crop was sharp during initial years (first to third year) and got more or less constant after 4 years of poplar plantation. The year-wise relative performance of

Table 1 Performance of wheat crop under poplar-based agri-silvicultural system

Age of plantation	Plant height (cm)	Ear length (cm)	Grains/ ear	Grain yield (tonnes/ha)	Straw yield (tonnes/ha)
Control	85.58	9.30	40.43	4.55	6.61
1st yr	85.98	9.56	46.01	4.61	6.90
2nd yr	77.52	8.42	37.10	3.41	5.35
3rd yr	74.24	8.04	29.07	3.09	4.77
4th yr	73.79	8.13	28.06	2.34	4.14
5th yr	72.47	7.56	27.83	2.08	3.99
6th yr	72.33	8.10	28.10	2.03	3.50
CD (P=0.05)	3.98	0.97	2.60	0.40	0.77

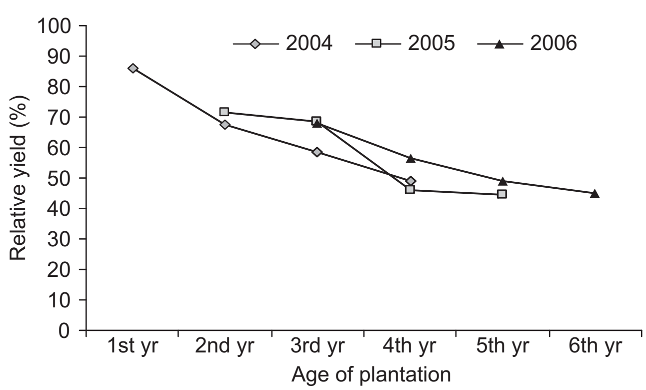

Fig 2 Relative yield of wheat crop under different age poplar plantations than in open condition

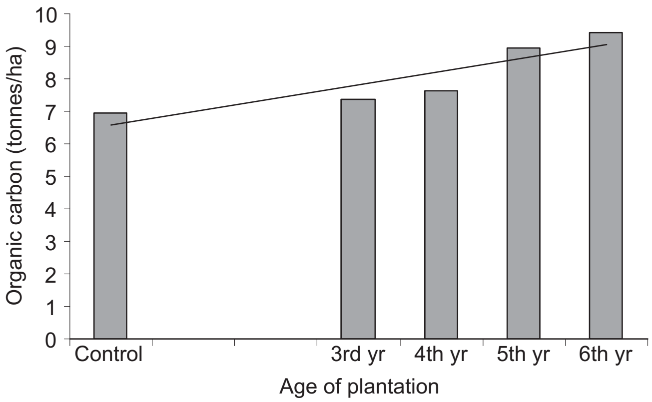

Fig 3 Soil carbon (t ha^{-1}) builds up with agri-silvicultural system

the crop has been depicted in Fig 2, which shows decreasing trend in crop yield behavior during 2004–06, however, the slight decrease in yield over the years may be because of prevailing climatic conditions during the particular year. The average straw yield of 3 years was also higher in control plots, ie 6.61 tonnes/ha (7.94, 6.52 and 5.37 tonnes/ha during 2004, 2005 and 2006, respectively). The straw yield followed the trend of grain yield and declined with the advancement of age of poplar plantation up to fourth year and after that the straw yield was statistically at par (Table 1). However, the rate of decrease in straw yield was comparatively lower than grain yield.

The winter cereals are normally suited to partner deciduous poplar trees. The crop grows strongly during the initial period (November to mid March), when shading is not a problem and by the time, poplar have developed their foliage, the wheat crop has virtually completed its vegetative growth. The reproductive phase is affected by the shade and even the ripening of the crop is delayed by a fortnight. That's why the effect on the straw yield was comparatively less than the grain yield. The straw : grain ratio was estimated to be 1.4 under control, whereas, the values ranged from 1.5 to 1.83 under poplar canopy. These results are also in conformity with the findings of Gill *et al.* (2007, 2009), where the decrease in biological yield has been reported with increase in age of plantations. They reported that increase in age of poplar is associated with root and canopy development, this causes intense competition for light, nutrients and water, thus, reducing the wheat yield with increase in age of poplar plantation. Also with the increasing age, the amount of poplar leaf litter mulch also increases, which hinders the germination of seed and comparatively the tiller number per unit area are less under the tree canopy. Das and Chaturvedi (2005) also observed negative relationship of increased litter biomass with crop biomass.

Trees growth and biomass

The tree growth and biomass estimates revealed that all the parameters varied significantly ($P \leq 0.05$) with age

Table 2 Tree growth parameters under poplar block plantations

Age of plantation	Height (cm)	DBH (cm)	Crown spread (m^2)	Volume (m^3)
1st yr	4.93	5.37	8.38	0.0073
2nd yr	10.48	10.48	26.36	0.0353
3rd yr	15.33	14.52	27.79	0.0918
4th yr	17.78	18.67	35.10	0.1698
5th yr	21.14	19.25	40.60	0.2138
6th yr	22.05	19.71	43.21	0.2334
CD (P=0.05)	1.17	1.58	5.13	0.0041

(Table 2). The mean height and DBH of poplar increased from 4.93 cm and 5.37 cm (1 year-old plantation) to 22.05 cm and 19.71 cm (6 year-old plantation), respectively. The mean annual increment of tree height and diameter was high during the initial years (up to fourth year age) but at later stage, the increase was at the decreasing rate. Sharma *et al.* (2007) and Chauhan *et al.* (2009) also reported the similar trend in growth of poplar under irrigated agro-ecosystem. Since, the volume is dependent upon the tree height and diameter growth, the trend in estimated standing tree values was also same (Table 2).

Crown spread exhibited variation with respect to length of lateral branches. It ranged from 8.38 m^2 (1st yr) to 43.21 m^2 (6th yr). Crown spread increased with age and the increase was statistically significant. Though, the crown spread depends on growth of lateral branches, but depending upon inter-cultivation practices in agri-silvicultural system, pruning of the lateral or side branches facilitate more solar radiation for inter-cropping. Since, no standard pruning schedules are available, therefore, the schedule as per the suitability, variable at each site, age and at each farm level is followed. The rate of decrease in crop yield is directly related to the canopy structure, which depends upon the intensity of pruning followed.

On system basis, the trees and cereals can generate higher returns on unit area basis. The silvo-arable agroforestry for Europe (supported by European Union) has shown that one hectare planted with alternate strips of poplars and wheat will produce the same output as 0.9 ha of wheat and 0.4 ha of poplars (Brelivet 2006). The additional biomass production under agroforestry absorbs tonnes of green house gas, CO_2 and farm income is also increased through carbon trading (Albrecht and Kandji 2003, Pandey 2007).

Soil organic carbon

As perceived, a decreasing trend in soil organic carbon was observed with soil depth in all the poplar plantations and plots without poplar trees. Soil organic carbon was comparatively low in control plot than the plots under different age poplar plantations at 3 different soil layers. In the poplar-associated plots, the differences in soil organic carbon at different age plantations were significant ($p \leq 0.05$),

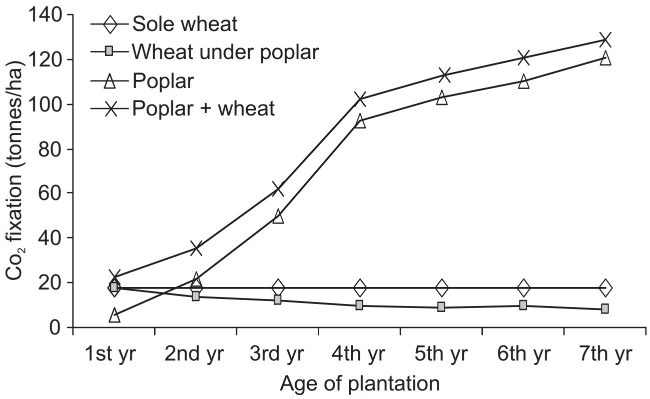

Fig 4 Total CO_2 assimilation (tonnes/ha) by poplar-wheat (above and below-ground biomass) in agroforestry system and sole wheat plot.

the concentration, however, was significantly high in 0–15 cm soil layer than the lower depths (15–30 and 30–60 cm). The organic carbon through litter, pruning material and roots of crops/trees increased the organic build-up in the top layer. An increase from 7.39 to 9.41 tonnes/ha was observed in 3–6 year plantation, than the control plot (6.94 tonnes/ha). The increase in soil organic carbon under agroforestry plantation than a site without trees was on account of recycling of organic matter was in the order of 6.48, 9.80, 29.11 and 35.59% over the control (Fig 3). Gupta *et al.* (2009) reported higher soil organic carbon in 0–30 cm profile during the initial years than the subsequent years.

Trees in association with agricultural crops increase the soil carbon status, though the change depends upon the quality and quantity of litter input, decomposition and carbon release. The changes in micro-environment under tree canopy (soil moisture/temperature), proliferation of root system and enhanced biological activity also favour the carbon stock in the soil. However, the continuity in the system is essential; otherwise the build-up in organic carbon may revert back to its original under commercial agriculture. Similar observations of higher carbon sequestration in soils under agroforestry than conventional agricultural operations have been reported earlier (Paul *et al.* 2002, Peichl *et al.* 2006, Sauer *et al.* 2007).

Carbon Storage and CO_2 assimilation

The biomass estimates revealed that all the tree components varied in terms of carbon stock with age (Table 3). The carbon concentration in stem, branches and root+leaves+bark was 45.67, 46.56 and 45.51%, respectively. Among different tree components, at the age of 6 years, stem wood contributed 96.4% carbon, followed by litter+roots (2.20%) and branch wood (1.35%). The stem wood mentioned here still contains about 10–15% of wood, which will not go to durable products but as fuel-wood (lops and tops/wastage from industries).

The carbon stock in different carbon pools under study indicated that vegetation stock, above-ground biomass, followed by below-ground biomass has contributed the maximum towards aggregate carbon pool under agroforestry system. The litter (include roots here) contributed the least towards the aggregate C-stock, which was almost negligible in comparison to other pools. Gera *et al.* (2006) had also presented similar results in poplar and eucalyptus. The incremental carbon potential, however, depends upon the productivity of the components (poplar and wheat here). Till the fourth year, the annual increment in carbon stock increased with increasing rate and then decreased (Table 3). The poplar contributes the maximum carbon in the system. The carbon sequestrated in soils under agroforestry from biomass turnover was greater than under conventional agricultural operation (Fig 3). The organic carbon change in the control (sole crop) remains almost constant because of very less addition of above ground biomass in the soil (straw and grains are harvested and not incorporated in the soil). In the sixth year plantation, the timber carbon content was estimated to be 21.99 tonnes/ha, whereas the contribution of the roots, leaves and bark was 4.05 tonnes/ha. The branches in total (first to sixth years) can fix carbon to the tune of 9.46 tonnes/ha but this huge amount is released back to the atmosphere on using branch wood for fuel. In the wheat crop itself, the contribution of straw + grain is substantially higher (97.3%) but the straw and grains are taken away from the system and in due course of time the carbon assimilated by the crop would be released back in the atmosphere. The roots contribute only 2.67% of the total biomass. A constant trend

Table 3 Carbon storage (tonnes/ha) by different components of poplar and wheat

Age of plantation	Poplar				Wheat			
	Timber	Branch wood	Roots, leaves and bark	Total	Straw	Grain	Roots	Total
1st yr	0.65	0.51	0.039	0.74	2.78	1.92	0.111	4.81
2nd yr	4.01	0.75	0.126	4.21	2.15	1.42	0.097	3.67
3rd yr	9.67	1.56	0.230	10.05	1.93	1.29	0.091	3.31
4th yr	17.93	2.88	0.430	18.65	1.63	1.01	0.080	2.72
5th yr	20.51	2.93	0.468	21.27	1.57	0.88	0.074	2.52
6th yr	21.99	3.08	0.501	22.80	1.49	0.85	0.066	2.40
CD (P=0.05)	3.15	0.21	0.180	3.74	0.39	0.21	NS	0.61

in CO_2 assimilation was observed in sole wheat crop, which was though more than the wheat under poplar but the combined contribution of poplar and wheat was substantially high (~4.5 times). Thevalthasan and Gordon (2004) also concluded that the annual carbon sequestration in a hybrid poplar-based intercropping field was 4 times higher than that found in sole cropping agricultural fields. Higher carbon sequestration in intercropping systems compared to sole cropping system has also been reported by Peichl *et al.* (2006) in poplar-based system. The higher carbon pools within the intercropping systems compared to those from the sole cropping system were due to the additional carbon pool in the trees and an increased soil carbon pool as a result of carbon from litter fall and fine root turnover. The higher carbon storage within poplar intercropping system can be explained by higher growth and assimilation rates compared to the sole cropping system. Moreover, the poplar timber, which is the major carbon assimilator component in the system would remain lockup in the wood product (plywood) for a long time. Therefore, in comparison to traditional agricultural system, poplar-based agroforestry system offers the best land-use option for carbon sequestration, where the timber is used in wood-based industries. Pandey (2007) also emphasized the potential of agroforestry to remove significant amount of CO_2 from atmosphere, if the tree harvesting is accompanied by regeneration and stored carbon is locked through non-destructive (non-carbon dioxide emitting) use of wood.

The total carbon dioxide (CO_2) assimilated by the biomass in the agroforestry system was estimated to be 90 against 15 tonnes/ha (Fig 4) for agricultural system. Therefore, even when only the accumulation of biomass carbon is considered, an agri-silvicultural system is almost 6 times more efficient than an agricultural system. However, these figures depend upon the assumption that the harvested product goes to durable products, litter is completely added in the soil and not released back to the atmosphere as fuel, which actually needs further thorough investigations. Increasing carbon storage requires a large portion of the carbon fixed through photosynthesis to be released to the soil, which is not economically viable since it means reduced product output relative to inputs.

The observations in the present study stressed the usefulness of tree-crop interface in improving the carbon stock in irrigated agro-ecosystem. Agroforestry can give the landowner the biggest direct net gain through biomass productivity and indirectly through carbon storage on per unit land area, generally without compromising agricultural output. Similar views have been expressed by Schoeneberger (2009) that agroforestry can sequester significant amount of carbon while leaving the bulk of the land for crop production. None-theless agroforestry remains under recognized as a green house mitigation option for agriculture. Very limited data on carbon sequestration through agroforestry interventions are available today in comparison to the agronomy and forestry. The concept of carbon sequestration through agroforestry has been brought to the discussion table and its potential has been acknowledged. Today the financial viability of the system is at the central stage but it will become a powerful tool as soon the detailed scientific information on carbon sequestration through tree-crop interface are generated. Simultaneous to direct output/product and CDM benefits from intercropping system, the system will help in reducing the deforestation from the forests to meet the immediate domestic and industrial requirements and help indirect carbon sequestration in conventional forests.

ACKNOWLEDGEMENTS

Authors are thankful to the Indian Council of Agricultural Research, New Delhi for providing the financial support for conducting the investigations. The support of Shri O P Chaudhary, Progressive Farmer and Shri Paramjeet Singh, Research Fellow, are also gratefully acknowledged.

REFERENCES

Albrecht A and Kandji S T. 2003. Carbon sequestration in tropical agroforestry systems. *Agricultural Ecosystems and Environment* **99**: 15–27.

Brelivet S. 2006. Wheat under the trees. 4pp. South East NSW Private Forestry Newsletter (www.thebegavalley.org.au).

Chauhan S K, Beri V and Sharma S C. 2007. Studies on carbon sequestration under different farm/agroforestry interventions. 130pp. *Research Report* submitted to ICAR, New Delhi, Department of Forestry and Natural Resources, PAU, Ludhiana.

Chauhan S K, Nanda R K and Brar M S. 2009. Adoption of poplar based agroforestry as an approach for diversified agriculture in Punjab. *Indian Forester* **135** (5): 671–7.

Das D K and Chaturvedi O P. 2005. Structure and function of *Populus deltoides* agroforestry stystem in eastern India: 1. Dry matter dynamics. *Agroforestry Systems* **65**: 215–21

Dhanda R S and Verma R K. 2001. Timber volume and weight tables of farm-grown poplar *(Populus deltoides* Bartr. Ex Marsh) in Punjab (India). *Indian Forester* **127** (1): 115–29.

Dury S J, Polglase P J and Vercoe T. 2002. Greenhouse resource kit for private forest growers. 95pp. Agriculture, Fisheries and Forestry- Australia (AFFA), Canberra.

Gera M, Mohan G, Bisht N S and Gera N. 2006. Carbon sequestration potential under agroforestry in Roopnagar District of Punjab. *Indian Forester* **132**: 543–55.

Gill R I S, Singh B, Kaur N and Luna R K. 2007. Evaluation of crops in poplar plantation with three spacing in two row directions. *Indian Forester* **133**A: 45–57.

Gill R I S, Singh B and Kaur N. 2009. Productivity and nutrient uptake of newly released wheat varieties at different sowing times under poplar plantation in north-western India. *Agroforestry Systems* **76** (3): 579–90.

Gupta N, Kukal S S, Bawa S S and Dhaliwal G S. 2009. Soil Organic Carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. *Agroforestry Systems* **76**: 27–35.

Jackson M L. 1973. *Soil Chemical Analysis*. 498pp. Prentice Hall of India Pvt Ltd, New Delhi.

Khan I A and Chaturvedi O P. 2007. Agroforestry and carbon sequestration: global scenario. *Journal of Tropical Forestry* **23** (3&4): 1–15.

Miah M G, Rahaman M A and Haque M M. 1999. Performance of onion under different reduced light levels for intercropping and intercropping systems. *Bulletin of Institute of Tropical Agricultural Kyushu, University* **22**: 31–8.

Montagnini F and Nair P K R. 2004. Carbon sequestration: an underexploited environmental benefit of agroforestry systems. *Agroforestry Systems* **61**: 281–95.

Mughal A H and Khan M A. 2005. *Prospects of Populus deltoides in Agroforestry Systems*: An allelopathic point of view. *Agroforestry in 21*st *Century*, pp 170–3. Chauhan S K, Gill S S, Sharma S C and Rajni Chauhan (Eds), Agrotech Publishing Academy, Udaipur.

Pandey D N. 2007. Multifunctional agroforestry systems in India. *Current Science* **92** (4): 455–63.

Panse V G and Sukhatme P V. 1978. *Statistical Methods for Agricultural Workers*. 347 pp. ICAR, New Delhi.

Nandal D P S and Dhillon A. 2007. Allelopathic effect of poplar *(Populus deltoides* Bartr. Ex Marsh) : An assessment on the response of wheat varieties under laboratory and field conditions. *Indian Journal of Agroforestry* **9**: 125–7.

Newaj R and Dhyani S K. 2008. Agroforestry systems for carbon sequestration: present status and scope. *Indian Journal of Agroforestry* **10** (1): 1–9.

Paul K I, Polglasse P J, Nyakuengama J G and Khanna P K. 2002. Change in soil carbon following afforestation. *Forest Ecology and Management* **168**: 241–57.

Peichl M, Thevathasan N V, Gordon A M, Huss J and Abohassan R A. 2006. Carbon sequestration potential in temperate tree-based intercropping system, southern Ontario, Canada. *Agroforestry Systems* **66**: 243–57.

Sauer T J, Cambardella C A and Brandle J R. 2007. Soil carbon and tree litter dynamics in a red cedar-scotch pine shelterbelt. *Agroforestry Systems* **71**: 163–74.

Schoeneberger M M. 2009. Agroforestry: working trees for sequestering carbon on agricultural lands. *Agroforestry Systems* **75**: 27–37.

Schultz R C, Isenhart T M, Simpkios W W and Colletti J P. 2004. Riparian forest buffers in agroecosystem -lessons learned from the Bear Creek watershed, central Iowa, USA. *Agroforestry Systems* **61**: 35–50.

Sharma N K, Samra J S and Dadhwal K S. 2005. Effect of poplar leaves incorporation on growth and yield of wheat in relation to fertilizer application.*Indian Forester* **131**: 563–72.

Sharma S C, Dogra A S, Upadhayay A and Chahal G S. 2007. Carbon stock and productivity assessment of *Populus deltoides* Bartr. Ex Marsh in Punjab. *Indian Forester* **133**: 8–16.

Singh B and Sharma K N. 2007. Tree growth and nutrient status of soil in a poplar *(Populus deltoides* Bartr.) –based agroforestry system in Punjab, India. *Agroforestry Systems* **70**: 125–34.

Singh G. 2005. Carbon sequestration under an agri-silvicultural system in the arid region. *Indian Forester* **131**: 543–52.

Singh G and Rathod T R. 2002. Plant growth, biomass production and soil water dynamics in a shifting dune of Indian desert. *Forest Ecology and Management* **171**: 309–20.

Singh H P, Kohli R K and Batish D R 2001. Allelopathic interference of *Populus deltoides* with some winter season crops. *Agronomie* **21**: 139–46.

Thevathasan N V and Gordon A M. 2004. Ecology of tree intercropping systems in the North temperate region: experiences from southern Ontario, Canada, *Agroforestry Systems* **61**: 257–68.

Zomer R J, Bossio D A, Trabucco A, Yuanjie L, Gupta D C and Singh V P 2007. Trees and water: smallholder agroforestry on integrated lands in northern India. 47pp. *Research Report 122*, IWMI Colombo, Srilanka.