Carbon Sequestration: underexploited environmental benefits of *Tarai* agroforestry Systems

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ABSTRACT: The present investigation deals with effect of structural composition of agroforestry system, number of woody perennial involved in the system and the management practices plays a major role in influencing the biomass level, carbon storage, CO_2 mitigation potential and total carbon sequestration (in trees) of 70.59 tha^{-1}, 21.38 tha^{-1}, 116.29 tha^{-1} and 18.53 t C ha^{-1} in system S_1 followed by 68.53 tha^{-1}, 20.63 tha^{-1}, 113.03 tha^{-1} and 17.60 t C ha^{-1} in system S_4, respectively. It was also observed that all the agroforestry systems can sequester more carbon as compared to sole agricultural land use systems. It was also observed that *Populus deltoides* + wheat and *Populus deltoides* + lemon grass under block plantation have the maximum potential to sequester carbon than the boundary plantations of *Populus deltoides* and *Eucalyptus hybrid*.
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Key words: Biomass, Carbon sequestration, carbon stock, *Cymbopogon flexuosus*, *Populus deltoides*, *Tarai*.

Introduction

Emission of greenhouse gases has become a matter of great concern because of the future projection of the global warming and related effects on biological life. While nations struggle to lower the greenhouse gas emissions at source, complimentary efforts are required to enlarge the sinks of these gases. The reduction in concentration of CO_2 in the atmosphere can be achieved by reducing the demand for energy and by altering the way the energy is used, and by increasing the rates of removal of the atmospheric CO_2 through carbon sequestration. Carbon sequestration refers to the provision of long term storage of carbon in the terrestrial biosphere, underground or the ocean so that the buildup of carbon dioxide concentration in the atmosphere will be reduced or slowed in order to improve environmental conditions and check the processes of environmental degradation.

Agroforestry systems can be better climate change mitigation option than ocean, and other terrestrial options, because of the secondary environmental benefits such as food security and secured land tenure, increasing farm income, restoring and maintaining above ground and below ground biodiversity, maintaining watershed hydrology and soil conservation. By including trees in agricultural production systems, agroforestry can increase the amount of carbon stored in lands devoted to agriculture, while still allowing for growing of food crops (Kursten, 2000). The tree components in agroforestry systems can be significant sinks of atmospheric carbon due to their fast growth and high productivity. Thus, promoting agroforestry can be one of the options to deal with problems related to land use and global warming. The amount of carbon sequestrated, however, will largely depend on the agroforestry system, the structure and function of agroforestry systems which to a great extend, are determined by environmental and socio-economic factors. Also tree species and system management can influence carbon storage in agroforestry systems (Albrecht and Kandji, 2003)

Agroforestry practices also have wide and promising potential to store carbon and remove atmospheric carbon dioxide through enhanced growth of trees and shrubs. Average sequestration potential in agroforestry has been estimated to be 25t C ha^{-1} over 96 million ha of land in India and 6-15 t C ha^{-1} over 75.9 Mha in China (Sathaye and Ravindranath, 1998). Watson *et al*., (2000) estimated carbon gain of 0.72 Mg C ha^{-1} yr^{-1} on 4000 million ha land under agroforestry, with potential for sequestering 26 Tg C yr^{-1} by 2010 and 45 Tg C yr^{-1} by 2040.

MATERIALS AND METHODS

The field investigation was conducted at Bagawala, Udham Singh Nagar (Uttarakhand) in the year 2005-07. The climate of the area is humid sub-tropical with dry hot summers and severe winters. The dry season starts from early October to mid-June and wet season from mid-June to early October. Relative humidity remains highest during July-August and lowest during April-May. The average annual rainfall is about 1400mm. The soil of experimental fields was a typical Hapludoll derived from alluvium. It is a silty clay loam having pH of 6.8, the CEC (meq./100g) and free lime ($CaCO_3$)

content of the soil ranged between 9.9 to 16.2 and 1.2 to 1.5 per cent, respectively, while average organic carbon was 2.2 to 2.4 per cent. The average bulk density of soil has been 1.32 Mg/m^3 and moisture at field capacity ranges between 30.2 to 34.5 per cent, available N, P, and K were ranged between 272 to 277, 12.70 to 13.30 and 244.3 to 250.1 kg/ha, respectively.

The experiment was laid out under four different agroforestry systems S_1 (*Populus deltoides* 'G-48' + wheat), S_2 (*Eucalyptus hybrid* + wheat in boundary plantation), S_3 (*Populus deltoides* + wheat boundary plantation) and S_4 (*Populus deltoides* + lemon grass) under already planted block and boundary plantations of nine year old *Populus deltoides* and Eucalyptus *hybrid* with wheat (*Triticum aestivum* cv UP-2425) and lemon grass (*Cymbopogon flexuosus* 'CKP-25'). Nitrogen, phosphorus and potassium (standard fertilizer doses) were applied in the form of urea, single super phosphate and muriate of potash, respectively. Nitrogen was divided in three equal doses, one third of which was given as basal dressing along with full doses of P and K and the remaining two third in two equal splits after emergence of wheat and at milky stage with irrigation. Disease free and healthy slips of lemon grass were transplanted in December, in plots already fertilized as required doses followed by a light irrigation. Agronomical operations like weeding and hoeing were done as and when required. Biomatric observations were taken at each harvest time. The grasses were harvested three times (April, July and October) in both the years.

Above and below ground biomass:

Diameter and height of all the trees in the study area were measured. Three trees representing the average diameter and height of the plantation area were selected randomly and felled. After felling, above ground parts viz. branches, twigs and leaves and below ground part (roots) was separated. The samples were cross cut into appropriate length depending upon the general form of the sample. Fresh weight of each sample was taken from each tree for determining moisture content. Moisture content of each sample was determined by drying the samples in the oven at 80^0C to constant weight. The moisture content of oven dried sample was expressed as a percentage on oven dry weight basis was calculated by the formula given by Husch *et al*., (1972). The following formula was used to calculate fresh weight of sample biomass into dry weight.

$$\mathbf{S_{wd} = S_{wf}/(1 + M_{cd})}$$

Where M_{cd} = Moisture content as a percentage of oven dry weight, S_{wf} = green/fresh weight (kg) of sample and S_{wd} = Oven dry weight (kg) of sample

The total biomass of each sample (Stem, branch and roots was determined by the formula given by Chidumayo, (1990).

$$\mathbf{B = n_1bw_1 + n_2bw_2 + n_3bw_3 + \ldots = \sum_{i=1}^{n} n_1bw_i}$$

Where B- sample biomass (fresh/dry) per tree, n_i- number of samples in the i^{th} sample group and bw_i – average weight of sample of i^{th} group.

Litter fall: Litter fall was collected at each site. Six trap of 1m x 1m were placed on each site for litter collection. Litter from traps was collected every ten days for two months. Fresh weight of the samples was taken with the help of digital balance. Samples were then oven dried at 80^0C to a constant weight, weighed and ground in a Wiley Mill. The litter fall biomass was calculated by adding the oven dried weight of all the samples collected at different time.

Crop and grass biomass: Biomass was estimated using 1m x1m quadrates. Crop/ grasses in the quadrates were cut at ground level. Fresh weight was taken using pan balance. Samples were taken to laboratory and were oven dried at 80^0C to a constant weight. Using Fresh/fry weight ratio, the dry weight of crop/grass biomass was estimated.

Carbon sequestration in plants:

Carbon concentration: Carbon concentration was determined by combustion method. Oven dried samples were grinded in Wiley mill, 20 g of the powdered sample was taken in silica crucible. The powdered material was then combusted in muffle furnace at 600^0C for 4-5 hours for ashing. Carbon was assumed to constitute 50% of ash free dry mass (Gallardo and Merino, 1993).

Carbon stock/mass in plants: Carbon stock in different plant component was obtained by multiplying the dry weight of the different plant components by their average carbon concentration. The carbon stock in different plant components was then summed up to obtain total carbon stock.

Long lived carbon storage: The exact lifetime of wood products is poorly known, but a reasonable assumption is that wood product lifetimes are at least equal to the rotation length. The proportion of stem wood used as long-lived wood products is estimated to be 42%. Long-lived carbon storage was therefore estimated by the formula (Wang and Feng, 1995).

Long-lived carbon storage = carbon mass in stem wood x 42%.

Heat from biomass combustion: Short lived biomass is generally used as fuel which can replace fossil fuels. The weight of biomass fuel equals the total biomass weight minus the long lived stem weight. Since the heat released per unit weight of biomass is taken as 18 x 10^9 J/ton. Heat from biomass combustion was estimated by the formula (Wang and Feng, 1995).

Heat from biomass combustion = [biomass-(stem wood weight x 0.42) x 18 x 10^9

Carbon storage from coal combustion: The thermal efficiency of biomass combustion is only 60% of that achieved with fossil fuels. If the heat release from combustion of unit weight of coal is taken as 25 x 10^6 J/ton and the carbon content of coal is 70%, then carbon storage from coal substitution can be estimated. Carbon storage from coal substitution was estimated by the formula (Wang and Feng, 1995).

Total amount of carbon sequestration in woody component was estimated by adding long lived carbon storage in wood products and the carbon storage due to substitution biomass for coal. Total carbon sequestration was expressed in tha^{-1}.

RESULTS AND DISCUSSION

A. Biomass Production:

The data in table (1) shows the variation in biomass level for different tree components, viz., stem, branch, leaves, litter as well as in crop and lemon grass in different agroforestry systems. The maximum stem biomass (tha^{-1}) was recorded (47.3 tha^{-1}) in system S_1 (*Populus deltoides* 'G-48' + wheat) followed by (45.55 tha^{-1}) in system S_4 (*Populus deltoides* + lemon grass) while the minimum value of biomass was recorded 12.04 tha^{-1} in system S_3 (*Populus deltoides* + wheat boundary plantation). The maximum branch wood, leaf and litter biomass (tha^{-1}) were observed in system S_1 (*Populus deltoides* 'G-48' + wheat) 2.05, 1.65 and 0.46tha^{-1} while minimum biomass were recorded in system S_2 (*Eucalyptus hybrid* + wheat in boundary plantation) 0.36, 0.15 and 0.04 tha^{-1}, respectively.

The biomass of tree in different components, viz., stem, branch wood and leaf depends upon number of factors, viz., growth habit of the species, site quality, soil on which trees are growing, age of the tree, management practices, frequent intercultural operations and moisture conservation and its interaction with below ground crops have also contributed towards increasing height and diameter at breast height of poplar trees. The highest biomass in system S_1 (*Populus deltoides* + wheat) can be attributed to high density plantation of tree species. More number of trees per hectare further resulted in higher branch and leaf biomass. Swamy *et al*., (2003) reported that in nutrient rich soil, more of biomass is allocated to above ground parts. Lowest stem biomass in system S_3 (*Populus deltoides* + wheat boundary plantation) can be attributed due to less number of trees/ha. Lowest branch wood, leaf and litter biomass in system S_2 (*Eucalyptus hybrid* + wheat in boundary plantation) can be attributed due to self pruning ability and evergreen nature of these plant species. Values of above ground biomass in the present study are comparable with those obtained by Lodhiyal *et al*., (1995) for *Populus deltoides* and Pandey *et al*., (1987) for *Eucalyptus* species.

Biomass of wheat crop was recorded maximum in system S_3 (6.49 tha^{-1}) followed by system S_1 (6.23 tha^{-1}) and the minimum value of 6.00 tha^{-1} in system S_2. Biomass of lemon grass was recorded 7.68 tha^{-1}. Total above ground biomass was found maximum in system S_1 (57.69 tha^{-1}) followed by system S_4 (56.38 tha^{-1}) while the minimum biomass value was recorded in system S_3 (19.32 tha^{-1}).

Under different land systems, the maximum crop biomass of wheat was found in system S_3 (*Populus deltoides* + wheat boundary plantation). Minimum crop biomass was observed when wheat was grown with Eucalyptus hybrid under boundary plantation; yield reduction under trees is a common phenomenon. The reason for reduction in crop biomass may be the allelopathic effect, competition between trees and crop for the sharing of resources, viz., light, water and nutrients at the same times hence causing reduction in dry matter accumulation. Reduction in yield of wheat below tree have also been recorded by Sharma (1992), Puri and Bangarwa (1992), Dhillon *et al*., (1998) and Nadal and Singh (2001).

Lemon grass biomass recorded 7.68tha^{-1} under system S_4 (*Populus deltoides* + lemon grass), the difference can be attributed largely to the net biomass production per unit area due to higher fertility status of the soil in respect to N, P and K (Afridi *et al*., 1992; Pal *et al*., 1992). Lemon grass grows well under partial shade, warm and humid (higher rainfall) conditions (Yadava, 2001). The increase, in fresh herbage yield has been in the range of 0.02-29.38 per cent and 2.53-37.45 per cent in first and second year, respectively (Patra *et al*., 1989).

Maximum below ground biomass was recorded in system S_1 (12.90 tha^{-1}) followed by system S_4 (12.15 tha^{-1}) and the minimum biomass was recorded in system S_3 (3.37 t ha^{-1}). The maximum root biomass was observed in system S_1 *(Populus deltoides* + wheat), can be attributed to high density plantation, the variation in the distribution of root biomass may be due to variation in the genetic nature, growth habit of the species, soil/ site on which tree is growing, intercultural operations and fertilizer application to the wheat crop (Huck, 1983; Swamy *et al*., 2003).

B. Carbon stock and CO_2 mitigation through biomass:

Carbon concentration in different plant components was determined by burning the sample in muffle furnace. Carbon concentration in above ground components varied from 44.1-45.6 per cent. The maximum carbon concentration of 45.6 per cent was observed in stem wood of system S_3. In branch wood maximum carbon concentration was recorded in 45.4 per cent in system S_2. In leaf samples, maximum carbon concentration observed in system S_2 (44.2 per cent). In litter samples, maximum carbon concentration of 45.3 per cent was recorded in system S_3 & S_4. In wheat crop, maximum carbon concentration of 45.2 per cent was observed in system S_2. In lemon grass, carbon concentration was recorded 44.9 per cent. In below ground component, carbon concentration varied from 45.1- 45.4 per cent. Carbon concentration was higher in stem followed by branch wood and leaves. A similar trend was observed by Singh and Singh (1991) for dry tropical forests of India and Swamy and Puri (2005) for *Gmelina arborea*. Carbon concentration in different parts of various species depends upon the ash content which further varies in different components of the trees viz., stem, branch, leaf etc. (Negi *et al*., 2003)

Above and below ground biomass carbon stocks (tha^{-1}) in different systems are given in table no. 2. The maximum carbon stock was observed in system S_1 for stem (21.38 tha^{-1}), branches (0.92 tha^{-1}), leaf (0.73 tha^{-1}) and litter (0.20 tha^{-1}) followed by S_4 for stem (20.63 tha^{-1}), branches (0.68 tha^{-1}), leaf (0.53 tha^{-1}) and litter (0.20 tha^{-1}). Minimum carbon stock in stem was recorded 5.49 tha^{-1} in system S_3 and 0.16 tha^{-1} (in branch wood), 0.07 tha^{-1} (in leaf) and 0.02 tha^{-1} (in litter) in system S_2.

Among different tree components, stem showed maximum CO_2 mitigation potential (table 3). Maximum CO_2 mitigating (tha^{-1}) in system S_1 for stem, branch, leaf, litter and root was recorded 78.04, 3.36, 2.66, 0.73 and 21.28 tha^{-1}, respectively followed by system S_4 75.30, 2.48, 1.93, 0.73 and 20.00 tha^{-1}, respectively. Minimum CO_2 mitigation was recoded in stem 20.04 tha^{-1} (in system S_3), in branch (0.58 tha^{-1}) leaf (0.26 tha^{-1}) and litter (0.07 tha^{-1}) in system S_2 and in root (5.58 tha^{-1}) in system S_3.

The CO_2 mitigation in wheat crop was maximum in system S_3 (10.66tha^{-1}) followed by S_1 (10.22tha^{-1}) and minimum in S_2 (9.89tha^{-1}). In lemon grass CO_2 mitigation was recorded in 12.59$tha^{-1.}$

Carbon stocks are dependent on the higher tree density and carbon concentration in different components. Carbon storage in plant can be high in complex agroforestry systems and productivity depends on several factors such as age, structure and way how the systems are managed (Swamy and Puri, 2005; Oelbermann *et al*., 2004). The results comparable with the findings of Albrecht and Kandji (2003) reported that agroforestry can store carbon in the range of 12-228 $Mgha^{-1}$.

CO_2 mitigation by above ground parts varied from 31.97 -95.01 tha^{-1}. Total above ground CO_2 mitigation recorded higher value of 95.01 tha^{-1} in system S_1 followed by system S_4 (93.03 tha^{-1}). Minimum above ground value observed in system S_3 (31.97tha^{-1}).

Below ground CO_2 mitigation biomass varied from 5.58 – 21.28tha^{-1}. The maximum below ground value observed in system S_1 (21.28tha^{-1}) followed by system S_4 (20.00 tha^{-1}) with the minimum value of 5.58tha^{-1} in system S_3.

A perusal of data in table no. 3 further shows that total above and below ground CO_2 mitigation by plant biomass was highest in system S_1 followed by system S_4, where the respective values of 116.29 and 113.03tha^{-1} were recorded. The minimum value recorded in system S_3 (37.55tha^{-1}).

CO_2 mitigation by plant is directly related to biomass production of the different plant components. Higher mitigation value of system S_1 can be attributed to more biomass and more carbon stock in agroforestry system as compare to sole agriculture system

D. Carbon sequestration by tree components:

Long lived carbon storage in stem and carbon storage from coal substitution through branches and twigs/leaves have been calculated in table no. 4. Maximum values in long lived carbon storage, heat from biomass combustion and carbon storage from coal substitute was observed in system S_1, the values were 8.98 $tCha^{-1}$, 568.69 x 10^9 and 9.55 $tCha^{-1}$ while the minimum values observed in system S_3 were 2.31 $tCha^{-1}$, 139.92 x 10^9 and 2.35 t Cha^{-1}.

The carbon sequestration ranged from 4.66 to 18.53 t Cha^{-1}. Maximum value was recorded in system S_1 (18.53 t Cha^{-1}) which was followed by system S_4 (17.60 $tCha^{-1}$). Minimum carbon sequestration was recorded in System S_3 (4.66 $tCha^{-1}$). Annual carbon sequestration was maximum in system S_1 (2.06 $tCha^{-1}yr^{-1}$), which was followed by system S_4 (1.96$tCha^{-1}yr^{-1}$). The minimum annual carbon sequestration was observed in system S_3 (0.52 $tCha^{-1}yr^{-1}$).

Considering only the woody components of various agroforestry systems, for long term storage and for coal substitution, the value of carbon sequestration was highest in system S_1 followed by system S_4. Higher allocation of biomass in stems of *Populus deltoides* sequester higher amount of carbon for a life time of the species. In addition to the above after completing the life cycle, the carbon stored in stem is resistant to microbial attack, i.e., decomposition due to higher lignin content. Thus, it sequesters the carbon for longer time after felling as compared to the carbon stored in leaves and branch biomass. The results are again in line with the findings of Wang and Feng (1995) and Chesney and Nygren (2002) also reported similar results with different tree species of Poplar and *Erythrina poeppigiana*.

Table no. 1. Biomass production (tha^{-1}) of different agroforestry systems.

Systems	Treatments	No. of trees	Age of Trees (years)	Above ground biomass production (tha^{-1})				Above ground tree biomass	Crop (grain + straw	Grasses	Total above ground biomass	Below ground biomass
				Stem	Branch	Leaf	Litter					
Populus deltoides + Wheat	S_1	500	09	47.3	2.05	1.65	0.46	51.46	6.23	-	57.69	12.9
Eucalyptus hybrid + wheat Boundary Plantation	S_2	192	09	21.12	0.36	0.15	0.04	21.67	6.00	-	27.67	4.13
Populus deltoides + wheat Boundary Plantation	S_3	130	09	12.04	0.38	0.29	0.12	12.83	6.49	-	19.32	3.37
Populus deltoides + Lemon grass	S_4	500	09	45.55	1.5	1.2	0.45	48.7	-	7.68	56.38	12.15

Table no. 2. Biomass carbon stock (tha^{-1}) under different agroforestry systems.

Systems	Treatments	Above ground biomass production (tha^{-1})				Total above ground Biomass	Crop	Grasses	Roots	Grand Total
		Stem	Branch	Leaf	Litter					
Populus deltoides + Wheat	S_1	21.38	0.92	0.73	0.20	23.23	2.80	-	5.83	31.86
Eucalyptus hybrid + wheat Boundary Plantation	S_2	9.59	0.16	0.07	0.02	9.84	2.71	-	1.87	14.42
Populus deltoides + wheat Boundary Plantation	S_3	5.49	0.17	0.13	0.05	5.84	2.92	-	1.53	10.29
Populus deltoides + Lemon grass	S_4	20.63	0.68	0.53	0.20	22.04	-	3.45	5.48	30.97

Table 3. CO_2 mitigation by different agroforestry systems.

Systems	Treatments	Above ground biomass production (tha^{-1})				Total tree biomass	Crop	Grasses	Total above ground	Below ground	Grand Total
		Stem	Branch	Leaf	Litter						
Populus deltoides + Wheat	S_1	78.04	3.36	2.66	0.73	84.79	10.22	-	95.01	21.28	116.29
Eucalyptus hybrid + wheat Boundary Plantation	S_2	35.00	0.58	0.26	0.07	35.91	9.89	-	45.80	6.83	52.63

Populus deltoides + wheat Boundary Plantation	S_3	20.04	0.62	0.47	0.18	21.31	10.66	-	31.97	5.58	37.55
Populus deltoides + Lemon grass	S_4	75.30	2.48	1.93	0.73	80.44	-	12.59	93.03	20.00	113.03

Table no. 4. Biomass production and carbon sequestration by tree components in different agroforestry systems.

Systems	Treatments	Stem biomass (tha^{-1})	Carbon storage (tha^{-1})	Long lived C storage (ton C ha^{-1})	Heat from biomass combustion ($x10^9$)	Carbon storage from coal substitute (ton Cha^{-1})	Total carbon sequestration (ton C ha^{-1})	Carbon sequestration (t C $ha^{-1}yr^{-1}$)
Populus deltoides + Wheat	S_1	47.3	21.38	8.98	568.69	9.55	18.53	2.06
Eucalyptus hybrid + wheat Boundary Plantation	S_2	21.12	9.59	4.03	230.39	3.87	7.90	0.88
Populus deltoides + wheat Boundary Plantation	S_3	12.04	5.49	2.31	139.92	2.35	4.66	0.52
Populus deltoides + Lemon grass	S_4	45.55	20.63	8.66	532.24	8.94	17.60	1.96

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