Potential of agroforestry systems in carbon sequestration for mitigating climate changes in *Tarai* region of central Himalaya

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ABSTRACT: Carbon sequestration refers to the provision of long term storage of carbon in the terrestrial biosphere 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. The experiment was initiated in October, 2005 under six different agroforestry systems, viz., S_1: (*Populus deltoides* 'G-48' + wheat in block plantation), S_2: (*Eucalyptus hybrid* + wheat in boundary plantation), S_3: (*Populus deltoides* + wheat boundary plantation), S_4 : (*Populus deltoides* + lemon grass in block plantation), S_5 : (*Dalbergia sissoo* + wheat in block plantation) and S_6 : (*Dalbergia sissoo* + Lemon grass in block plantation) under nine years old block and boundary plantations of *Populus deltoides* and *Eucalyptus hybrid* and ten year old block plantation of *Dalbergia sissoo* with wheat (*Triticum aestivum* cv UP-2425) and lemon grass (*Cymbopogon flexuosus* 'CKP-25'). 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}, 113.15 tha^{-1} and 17.60 t C ha^{-1} in system S_4, respectively. It was observed that *Populus deltoides* + wheat, *Populus deltoides* + lemon grass, *Dalbergia sissoo* + wheat and *Dalbergia sissoo* + 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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INTRODUCTION

There is much concern that the increasing concentration of greenhouse gases (GHGs) and carbon dioxide in the atmosphere contributes to global warming by trapping long-wave radiation reflected from the earth's surface. Carbon sequestration, i.e. capturing and securing carbon that would otherwise be emitted and remain in the atmosphere might be a suitable alternative to control atmospheric emission of carbon. Plants capture CO_2 during photosynthesis and transform it to sugar and subsequently to dead organic matter. As the trees grow, they sequester carbon in their tissues, and as the amount of tree biomass increases, the increase in atmospheric CO_2 is mitigated. The area under forests, including part of the area afforested is increasing and currently 67.83 mha of area is under forest cover. Assuming that the current trend continues, the area under forest cover is projected to reach 72 mha by 2030. Estimates of carbon stock in Indian forests in both soil and vegetation range from 8.58 to 9.57 GtC (Ravindranath *et al*., 2008).

The significance of agroforestry with regards to C sequestration has been widely recognized with an estimated global potential of between 12 and 228 $Mgha^{-1}$ (Albrecht *et al.* 2003). However, variability can be high within various agroforestry systems as biomass C stock depends on several factors including environmental conditions, soil type, magnitude of land degradation and the length of fallow period (Batjes and Sombroek, 1997; Albrecht *et al.* 2003; Kaonga *et al.* 2009). Residue quality differences among agroforestry species further play a key role in regulating long term C build up, as the rate of soil organic matter decomposition is dependent on residue chemical quality which is mainly defined using various ratios of carbon, nitrogen, lignin and polyphenols (Vanlauwe *et al.* 1997).

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 (Kursten and Burschel, 1993). 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 tC ha^{-1} over 75.9 Mha in China (Sathaye and Ravindranath, 1998; Ravindranath *et al*., 2008). 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. Proper design and management of agroforestry practices can make them effective carbon sink. As in other land-use systems, the extent of C sequestered will depend on the amount of C in standing biomass, recalcitrant C remaining in the soil and C sequestered in wood products. Average carbon storage by agroforestry practices has been estimated as 9, 21, 50 and 63 Mg C ha^{-1} in semiarid, subhumid, humid and temperate regions (Montagnini and Nair, 2004).

However, there is limited data available on impact of C dynamics by agroforestry species, as previous research has focused on agricultural productivity. Therefore, knowing the sizes of carbon pools in agroforestry systems is important to promoting the land use system as a C sink. The present study has been undertaken with the following objectives (i) to study the above and below ground biomass and (ii) to study the carbon stock and carbon sequestration potential of different agroforestry systems in *Tarai* region of Uttarakhand.

MATERIALS AND METHODS

The field investigation was conducted at Bagawala, Udham Singh Nagar (Uttarakhand) in the year 2006-08. The climate of the area is humid sub-tropical with dry hot summers and severe winters. The meteorological data for the experimental period indicate that the monthly maximum temperature range from 21.42^{0}C during January to 36.16^{0}C during April and the monthly minimum from 6.40^{0}C during December to 25.07^{0}C during July. 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 0.89-1.12 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 initiated in October, 2006 under six different agroforestry systems, viz., S_1: (*Populus deltoides* 'G-48' + wheat in block plantation), S_2: (*Eucalyptus hybrid* + wheat in boundary plantation), S_3: (*Populus deltoides* + wheat boundary plantation), S_4: (*Populus deltoides* + lemon grass in block plantation) S_4 : (*Populus deltoides* + lemon grass in block plantation), S_5 : (*Dalbergia sissoo* + wheat in block plantation) and S_6 : (*Dalbergia sissoo* + Lemon grass in block plantation) under nine years old block and boundary plantations of *Populus deltoides* and *Eucalyptus hybrid* and ten year old block plantation of *Dalbergia sissoo.* Five hundred trees of *Populus deltoides* in block plantation at the spacing of 4m x 5m and 130 trees *at the spacing of 2.5m* in boundary plantations, 625 trees of *Dalbergia sissoo* in block plantation at the spacing of 4m x 4m and 192 trees of *Eucalyptus hybrid at the spacing of 2m* with wheat (*Triticum aestivum* cv UP-2425) at the spacing of 10cm x7cm and lemon grass (*Cymbopogon flexuosus* 'CKP-25') at the spacing of 40cm x 40cm. Nitrogen (120 $kgha^{-1}$), phosphorus (40 $kgha^{-1}$) and potassium (40 $kgha^{-1}$) 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, 2006 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 with the help of power chain saw. After felling, above ground parts viz. branches, twigs and leaves were separated from the main stem. The stems were cross cut into appropriate length depending upon the general form of the stem. Fresh weight of each log was taken in the field for each sample tree with the help of heavy weight spring balance. Three cross sectional discs representing top, middle and bottom portion of trees were 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 a 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 from October 15th onwards in both the years from 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/dry 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.

CO_2 mitigation:

CO_2 mitigation by different agroforestry systems was estimated by multiplying the values of carbon stock by factor of 3.66.

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 18×10^9 J/ton. Heat from biomass combustion was estimated by the formula (Wang and Feng, 1995).

Heat from biomass combustion ($Jton^{-1}$) = [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 25×10^6 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).

$$\textbf{Carbon Storage from coal combustion } (tCha^{-1}) = \frac{\textbf{(Heat of biomass combustion} \times 0.60 \times 0.70)}{25 \times 10^9}$$

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}.

Statistical analysis was not done for different biomass parameters due to lesser error degree of freedom.

RESULTS AND DISCUSSION

A. Biomass Production:

The data shows the biomass for different agroforestry systems in kg/tree (table 1) and the variation in biomass level for different tree components, viz., stem, branch, leaves, litter as well as in wheat crop and lemon grass in different agroforestry systems (table 2). The maximum stem biomass (tha^{-1}) was recorded (47.3 tha^{-1}) in the system S_1 (***Populus deltoides*** 'G-48' + wheat block plantation) followed by (45.55 tha^{-1}) in the system S_4 (***Populus deltoides*** + lemon grass block plantation) while the minimum value of biomass was recorded 8.11 tha^{-1} in the system S_2 (*Eucalyptus hybrid* + wheat in boundary plantation). The maximum branch wood and leaf biomass (tha^{-1}) were observed in the system S_5 (*Dalbergia sissoo* + wheat block plantation) 4.06 and 1.94 tha^{-1} while minimum biomass were recorded in the system S_2 (*Eucalyptus hybrid* + wheat in boundary plantation) 0.14 and 0.06 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 and *Dalbergia sissoo* trees. The highest biomass in the system S_1 (***Populus deltoides*** + wheat block plantation) 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) and Yadava (2010_a) reported that in nutrient rich soil, more of biomass is allocated to above ground parts. Lowest stem biomass, branch wood, leaf and litter biomass in the system S_2 (*Eucalyptus hybrid* + wheat in boundary plantation) can be attributed due to less number of trees/ha, 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 the system S_5 (6.57 tha^{-1}) followed by the system S_3 (6.49 tha^{-1}) and the minimum value of 6.00 tha^{-1} in the system S_2. Biomass of lemon grass was recorded 7.79 tha^{-1} in the system S_6. Total above ground biomass was found maximum in the system S_1 (57.69 tha^{-1}) followed by the system S_4 (56.38 tha^{-1}) while the minimum biomass value was recorded in the system S_2 (14.35 tha^{-1}). Under different land systems, the maximum crop biomass of wheat was found in the system S_5 (*Dalbergia sissoo* + wheat block plantation). Minimum crop biomass was observed when wheat was grown with *Eucalyptus hybrid* under boundary plantation the reason for reduction in crop biomass may be the allelopathic effect (Kohli and Singh, 1991; Ahmed ***et al***., 2008), 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 Nadal and Singh (2001) and Yadava ($2010_{a\&b}$). Lemon grass biomass recorded 7.79 tha^{-1} in the system S_6 (***Dalbergia sissoo*** + Lemon grass block plantation followed by 7.68 tha^{-1} in the system S_4 (***Populus deltoides*** + lemon grass block plantation), 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 (Pal ***et al***., 1992). Lemon grass grows well under partial shade, warm and humid (higher rainfall) conditions. 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 the system S_1 (12.90 tha^{-1}) followed by the system S_4 (12.15 tha^{-1}) and the minimum biomass was recorded in the system S_2 (1.59 t ha^{-1}). The maximum root biomass was observed in the system S_1 ***(Populus deltoides*** + wheat block plantation) 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 the system S_3. In branch wood maximum carbon concentration was recorded in 45.4 per cent in the system S_2. In leaf samples, maximum carbon concentration observed in the system S_2 (44.2 per cent). In litter samples, maximum carbon concentration of 45.3 per cent was recorded in the system S_3 & S_4. In wheat crop, maximum carbon concentration of 45.2 per cent was observed in the 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 also observed by Swamy and Puri (2005). 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 3. The maximum carbon stock was observed in the system S_1 for stem (21.38 tha^{-1}) and litter (0.20 tha^{-1}), system S_5 for branches (1.82 tha^{-1}), leaf (0.87 tha^{-1}) followed by S_4 for stem (20.63 tha^{-1}) and system S_6 for branches (1.79 tha^{-1}), leaf (0.83 tha^{-1}). Minimum carbon stock was recorded 3.65 tha^{-1} (in stem), 0.06 tha^{-1} (in branch wood), 0.03 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 4). Maximum CO_2 mitigating (tha^{-1}) in the system S_1 for stem (78.04 tha^{-1}), litter (0.73 tha^{-1}) and root (21.28 tha^{-1}) and in system S_5 for branch (6.69 tha^{-1}) and leaf (3.20 tha^{-1}) was recorded. Minimum CO_2 mitigation was recoded in stem (13.38 tha^{-1}), in branch (0.23 tha^{-1}), leaf (0.10 tha^{-1}), litter (0.07 tha^{-1}) and in root (2.62 tha^{-1}) in system S_2. The CO_2 mitigation in wheat crop was maximum in system S_5 (10.84 tha^{-1}) followed by S_3 (10.70 tha^{-1}) and minimum in S_2 (9.90tha^{-1}). In lemon grass CO_2 mitigation was recorded in 12.85 tha^{-1} in S_6 followed by 12.59tha^{-1} in S_4.

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) and Montagnini and Nair (2004) reported that agroforestry can store carbon in the range of 12-228 Mgha^{-1} (Sathaye and Ravindranath, 1998; Ravindranath *et al*., 2008).

CO_2 mitigation by above ground parts varied from 32.01 -95.01 tha^{-1}. Total above ground CO_2 mitigation recorded higher value of 95.01 tha^{-1} in the system S_1 followed by the system S_4 (93.11 tha^{-1}) with the minimum value of (23.68 tha^{-1}) observed in the system S_2. The maximum below ground value observed in the system S_1 (21.28tha^{-1}) followed by the system S_4 (20.04 tha^{-1}) with the minimum value of 2.62 tha^{-1} in the system S_2. A perusal of data in table 4, further shows that total above and below ground CO_2 mitigation by plant biomass was highest in the system S_1 followed by the system S_4, where the respective values of 116.29 and 113.03tha^{-1} were recorded. The minimum value recorded in the system S_2 (26.3tha^{-1}).

CO_2 mitigation by plant is directly related to biomass production of the different plant components. Higher mitigation value of the system S_1 can be attributed to more biomass and more carbon stock in agroforestry system as compare to sole agriculture system. (Montagnini and Nair (2004) and Yadava, 2010_b)

C. Carbon sequestration by tree components:

Long lived carbon storage in stem and carbon storage from coal substitution through branches and twigs/leaves have been recorded in table 5 and Graph 1. Maximum values in long lived carbon storage, heat from biomass combustion and carbon storage from coal substitute was observed in the 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 the system S_2 were 1.53 tCha^{-1}, 89.10 x 10^9 and 1.5 t Cha^{-1} .

The total carbon sequestration ranged from 3.03 to 18.53 t Cha^{-1}. Maximum value was recorded in the system S_1 (18.53 t Cha^{-1}) which was followed by the system S_4 (17.60 tCha^{-1}). Minimum carbon sequestration was recorded in the system S_2 (3.03 tCha^{-1}). Annual carbon sequestration was maximum in the system S_1 (2.06 tCha^{-1}yr^{-1}), which was followed by the system S_4 (1.96 tCha^{-1}yr^{-1}). The minimum annual carbon sequestration was observed in the system S_2 (0.34 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 the system S_1 followed by the 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 (Vanlauwe *et al.* 1997). 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); Montagnini and Nair (2004) and Chesney and Nygren (2002) also reported similar results with different tree species of Poplar and *Erythrina poeppigiana*.

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Table no. 1. Biomass (dry weight) kg/tree of different agroforestry systems.

Systems	Treatments	No. of Trees	Age of trees (years)	Stem (kg/tree)	Branch (kg/tree)	Leaf (kg/tree)	Total above ground tree biomass (kg/tree)	Root biomass (kg/tree)
Populus deltoides + Wheat Block Plantation	S_1	500	09	94.6	4.10	3.30	101.20	25.80
Eucalyptus hybrid + wheat Boundary Plantation	S_2	192	09	42.24	0.72	0.30	43.34	8.26
Populus deltoides + wheat Boundary Plantation	S_3	130	09	88.70	2.91	2.32	93.93	23.6
Populus deltoides + Lemon grass Block Plantation	S_4	500	09	91.10	3.00	2.40	97.40	24.30
Dalbergia sissoo + Wheat Block Plantation	S_5	625	10	37.3	6.5	3.1	46.9	10.16
Dalbergia sissoo + Lemon grass Block Plantation	S_6	625	10	37.2	6.4	3.0	46.6	10.18

Table no. 2. Biomass production (tha^{-1}) of different agroforestry systems.

Systems	Treatments	No. of trees	Age of Trees (years)	Above ground tree biomass production (tha^{-1})				Above ground tree biomass (tha^{-1})	Crop (grain + straw (tha^{-1})	Grasses (tha^{-1})	Total above ground biomass (tha^{-1})	Below ground tree biomass
				Stem	Branch	Leaf	Litter					
Populus deltoides + Wheat Block Plantation	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	8.11	0.14	0.06	0.04	8.35	6.00	-	14.35	1.59
Populus deltoides + wheat Boundary Plantation	S_3	130	09	11.53	0.38	0.30	0.32	12.53	6.49	-	19.02	3.07
Populus deltoides + Lemon grass Block Plantation	S_4	500	09	45.55	1.5	1.2	0.45	48.7	-	7.68	56.38	12.15
Dalbergia sissoo + Wheat Block Plantation	S_5	625	10	23.31	4.06	1.94	0.15	29.46	6.57	-	36.03	6.35
Dalbergia sissoo + Lemon grass Block Plantation	S_6	625	10	23.25	4.0	1.87	0.14	29.26	-	7.79	37.05	6.36

Table no. 3. Biomass carbon stock (tha^{-1}) under different agroforestry systems.

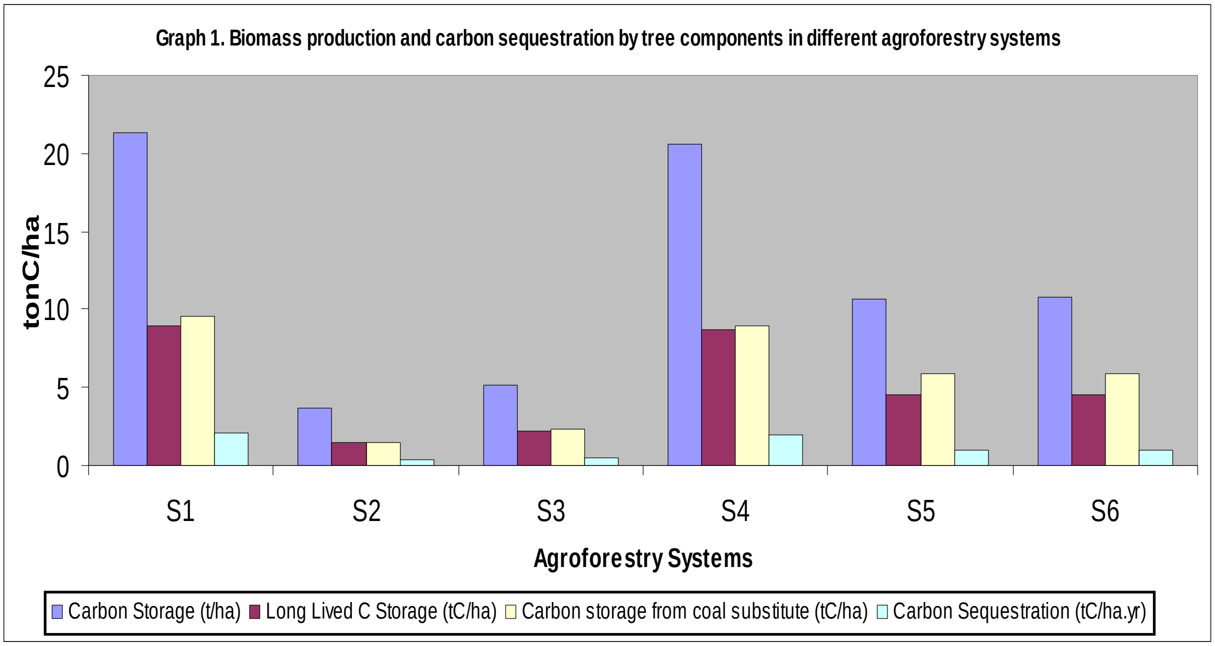
Systems	Treatments	Above ground tree biomass carbon stock. (tha^{-1})				Total above ground tree Biomass (tha^{-1})	Crop (tha^{-1})	Grasses (tha^{-1})	Tree Roots (tha^{-1})	Grand Total (tha^{-1})
		Stem	Branch	Leaf	Litter					
Populus deltoides + Wheat Block Plantation	S_1	21.38	0.92	0.73	0.20	23.23	2.80	-	5.83	31.86
Eucalyptus hybrid + wheat Boundary Plantation	S_2	3.65	0.06	0.03	0.02	3.76	2.71	-	0.71	7.18
Populus deltoides + wheat Boundary Plantation	S_3	5.19	0.17	0.13	0.14	5.63	2.92	-	1.38	9.93
Populus deltoides + Lemon grass Block Plantation	S_4	20.63	0.68	0.53	0.20	22.04	-	3.45	5.48	30.97
Dalbergia sissoo + Wheat Block Plantation	S_5	10.76	1.82	0.87	0.06	13.51	2.83	-	2.80	19.14
Dalbergia sissoo + Lemon grass Block Plantation	S_6	10.74	1.79	0.83	0.06	13.42	-	3.38	2.82	19.62

Table 4. CO_2 mitigation (tha^{-1}) by different agroforestry systems.

Systems	Treatments	Above ground tree CO_2 mitigation (tha^{-1})				Total tree CO_2 mitigation	Crop	Grasses	Total above ground	Below ground	Grand Total
		Stem	Branch	Leaf	Litter						
Populus deltoides + Wheat Block Plantation	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	13.38	0.23	0.10	0.07	13.78	9.90	-	23.68	2.62	26.30
Populus deltoides + wheat Boundary Plantation	S_3	20.04	0.62	0.47	0.18	21.31	10.70	-	32.01	5.06	37.07
Populus deltoides + Lemon grass Block Plantation	S_4	75.30	2.48	1.93	0.73	80.44	-	12.67	93.11	20.04	113.15
Dalbergia sissoo + Wheat Block Plantation	S_5	38.46	6.69	3.20	0.25	48.6	10.84	-	59.44	10.47	69.91
Dalbergia sissoo + Lemon grass Block Plantation	S_6	38.36	6.60	3.08	0.23	48.27	-	12.85	61.12	10.49	71.61

Table no. 5. 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 ($x10^9$) $Jton^{-1}$	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 Block Plantation	S_1	47.3	21.38	8.98	568.69	9.55	18.53	2.06
Eucalyptus hybrid + wheat Boundary Plantation	S_2	8.11	3.65	1.53	89.10	1.50	3.03	0.34
Populus deltoides + wheat Boundary Plantation	S_3	11.53	5.19	2.18	138.42	2.32	4.50	0.50
Populus deltoides + Lemon grass Block Plantation	S_4	45.55	20.63	8.66	532.26	8.94	17.60	1.96
Dalbergia sissoo + Wheat Block Plantation	S_5	23.31	10.76	4.51	354.06	5.94	10.45	1.04
Dalbergia sissoo + Lemon grass Block Plantation	S_6	23.25	10.74	4.51	350.91	5.89	10.40	1.04



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