ANNALS OF FOREST RESEARCH
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Carbon allocation, sequestration and carbon dioxide mitigation under plantation forests of north western Himalaya, India

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Devi B., Bhardwaj D.R., Panwar P., Pal S., Gupta N.K., Thakur C.L., 2013. Carbon allocation, sequestration and carbon dioxide mitigation under plantation forests of north western Himalaya, India, Ann. For. Res. 56(1): 123-135, 2013.

Abstract. The organic carbon and soils of the world comprise bulk of the terrestrial carbon and serve as a major sink and source of atmospheric carbon. Increasing atmospheric concentrations of green house gases may be mitigated by increasing carbon sequestration in vegetation and soil. The study attempted to estimate biomass production and carbon sequestration potential of different plantation ecosystems in north western Himalaya, India. Biomass, carbon density of biomass, soil, detritus, carbon sequestration and CO_2 mitigation potential were studied under different plantation forest ecosystems comprising of eight different tree species: *Quercus leucotrichophora, Pinus roxburghii, Acacia catechu, Acacia mollissima, Albizia procera, Alnus nitida, Eucalyptus tereticornis* and *Ulmus villosa*. Above (185.57±48.99 tha^{-1}) and below ground (42.47±10.38 tha^{-1}) biomass was maximum in *Ulmus villosa*. The vegetation carbon density was maxium in *Albizia procera* (118.37±1.49 tha^{-1}) and minimum (36.50±9.87 tha^{-1}) in *Acacia catechu*. Soil carbon density was maximum (219.86±10.34 tha^{-1}) in *Alnus nitida*, and minimum (170.83±20.60 tha^{-1}) in *Pinus roxburghii*. Detritus was higher in *Pinus roxburghii* (6.79±2.0 tha^{-1}). Carbon sequestration (7.91±3.4 tha^{-1}) and CO_2 mitigation potential (29.09±12.78 tha^{-1}) was maximum in *Ulmus villosa*. Pearson correlation matrix revealed significant positive relationship of ecosystem carbon with plantation biomass, soil carbon and CO_2 mitigation potential. With the emerging threat of climate change, such assessment of forest and soil carbon inventory would allow to devise best land management and policy decisions for sustainable management of fragile hilly ecosystem.
Keywords Afforestation, carbon sequestration, plantation biomass, soil carbon, carbon dioxide mitigation.

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Manuscript received December 29, 2011; revised June 26, 2012; accepted July 6, 2012; online first November 16, 2012.

Introduction

To meet the food demands of growing population, in the last decade drastic changes in land use took place in tropical countries (Lambin et al. 2001). Emission of 1.7±0.8 Gt carbon yr^{-1} and 1.6 Gt carbon yr^{-1} during 1980s and 1990s has been attributed to the effects of land land-use changes (Houghton et al. 2000, Upadhyay et al. 2005). Conversion of forest to agriculture contributes significantly to global carbon budget (Lal 2002), because of considerable losses of carbon from vegetation and soil (Cuevas 2001). Sequestration of carbon in biomass is presently considered as the most promising approach to mitigate green house effect (Kimble et al. 2002). At global scales, forest contributes 80–90% of plant biomass carbon and 30–40% of soil carbon and hence requires special attention by researchers (Harvey 2000). Nutrient cycling in agroforestry is in between natural forest ecosystems of the tropics and most of the agricultural systems which are ‘‘leaky’’ having higher nutrient losses (Nair et al. 1995). For efficient forest management, budgeting of forest carbon cycle is of enormous significance (Liu et al. 2006).

About two-thirds of the carbon in terrestrial ecosystems comes from soil organic carbon (Eswaran et al. 1993). Soil organic matter is a key indicator of soil quality (Karlen et al. 1997, Haynes 2005). Soil biology, nutrient dynamics and degradation resistance are highly influenced by soil organic matter (Lal 2002). It has been reported that an increase in soil organic carbon by 0.01% could lead to the C-sequestration equivalent to annual increase of atmospheric carbon-di-oxide carbon (Lal et al. 1998). In tropical and subtropical regions, soil ecosystem is highly fragile and depleted of soil organic carbon, enhancement of organic carbon is very important (Sharma et al. 2005).

On a global mean basis terrestrial ecosystem has sequestered 12.0 Giga tonnes Carbon from atmosphere over a period from 1961 to 1991 (Goto & Yanagisava 1996). This estimate denotes the high carbon sequestration potential of forest sector. In spite of the increasing demand of forest product, India has been able to maintain approximately 64 M ha of forest cover during the last decade. In India forest were planted at the rate of 1.67 M ha yr^{-1} during 1990’s and currently it is 2 M ha per annum, which is one of the highest among tropical countries (Lal & Singh 2000). This rate of afforestation is considered to be one of the highest among the tropical countries. Shrinking natural forest necessitates us to look for potential of the man made plantation for sequestering carbon both in soil and biomass.

Keeping this in view, the present study attempts to monitor biomass production and carbon sequestration potential of 8 different plantation forest ecosystems (*Quercus leucotrichophora, Pinus roxburghii, Acacia catechu, Acacia mollissima, Albizia procera, Alnus nitida, Eucalyptus tereticornis* and *Ulmus villosa*) in north western Himalaya, India.

Materials and methods

Site description

The area lies between 30° 50′30″ to 30°52′0″ N latitude and 77°8′30″ and 77°11′30″ E longitude and the climate is transitional between subtropical and moist temperate. The minimum and maximum temperature varies from 3°C during winter (January) to 33°C during summer (June), whereas mean annual temperature is 19°C. Annual rainfall varies from 1000-1400 mm, majority of which is received during monsoons, i.e. July-September. Soil of the experimental site is clay loam with about 28 percent clay with 31.02 per cent coarse fragments; pH ranges from 6.29 to 8.02 and organic carbon percentage is 0.83 to 2.96. The forest of the region are classified as 9 C_1-Lower Himalayan chir pine forests with *Pinus roxburghii* as a dominant species, as per Champion and Seth’s forest type classification (Khanna 1993). Eight tree species were planted in period 1988-1990 to see the performance of species with respect to growth and biomass production. The measurement of experimental parameters are taken in 2011. The detailed site characteristics of the plantation are given in Table 1. Stem density of all the plantations was found to have no statistical difference and hence the variation among the plantations will be because of the adaptive and production potential of the species.

Estimations

Above ground biomass of forest trees. To estimate stem biomass all the trees within a plot size of 31.62 m x 31.62 m were enumerated. The diameter at breast height (dbh) and height of the tree were measured. Local volume equations developed for specific tree species for the region were used for calculating the volume of the plantation (Devi 2011). Volume of *Ulmus villosa* was determined following the procedure of Kaul & Panwar (2008).

Specific gravity of wood. Specific gravity was determined by the standard procedure. Specific gravity was calculated from stem core measurement of wood, taking into account the variation in different parts of the tree. The biomass of the stem was measured using maximum moisture method as presented in equation 1 (Smith 1954).

$$G_f = \frac{1}{\frac{M_m - M_0}{M_0} + \frac{1}{GS_0}} \tag{1}$$

where: G_f - specific gravity of wood, M_m - constant weight of sample having maximum moisture content, M_o - oven dried constant weight of sample and GS_o - average density of wood, a constant having value of 1.53.

Biomass of wood. Stem biomass was the product between average specific gravity of stem wood and volume. Standing biomass of dead and fallen trees was estimated separately in a quadrate of 31.62 m x 31.62 m. Standing dead trees were assumed to fall under decay class “0”. Diameter of fallen trees was measured at 1.3 m from the larger end of the tree along with its length and was categorized in decay class 1-5. Decay class “0 to 5” refers to the progression of decay of the wood. Standing dead trees were not found to have initiation of decay hence were categorised as decay class

Table 1 Site characteristics of different plantation forest ecosystems.

Plantation forest ecosystems	Altitude (m)	No. of plots	Stem density (ha^{-1})	Average dbh (cm)	Volume/ (m^3 ha^{-1})	Specific gravity ($g\ cm^{-3}$)
Quercus leucotrichophora	1226-1229	3	2320 (5)[a]	14.88 (0.02)[ab]	221.30 (0.053)[ab]	0.740
Pinus roxburghii	1211-1236	3	1875 (175)[a]	16.54 (18.45)[ab]	266.34 (32.034[a]	0.470
Acacia catechu	1118-1180	3	1342 (477.38)[a]	10.49 (2.89)[b]	45.16 (23.91)[c]	0.670
Acacia mollissima	1205-1246	3	1216.67 (472.58)[a]	14.41 (1.07)[ab]	113.52 (26.84)[b]	0.780
Albizia procera	1196-1198	3	1602.7 (5.03)[a]	19.2 (0.056)[a]	236.64 (0.115)[ab]	0.750
Alnus nitida	1189-1191	3	458.67 (9.01)[a]	25.72 (0.79)[a]	217.7 (0.87)[ab]	0.682
Eucalyptus tereticornis	1188-1238	3	2233.33 (539.86)[a]	12.84 (0.45)[b]	193.27 (56.34)[b]	0.700
Ulmus villosa	1214-1231	3	1617 (301.6)[a]	12.94 (1.63)[a]	217.09 (63.091)[ab]	0.900

Note. Values in the columns followed by same letter(s) are not significantly different according to LSD test ($p < 0.05$). Values inside the parenthesis denote standard error.

"0". The decay classes 1-5 were identified on the basis of structural integrity, condition of bark, bole, leaves, color of wood, portion of log on ground invaded by roots etc. as assumed by Harmon et al. (1996) and Yan et al. (2006).

Branch biomass of forest trees. Total number of branches were counted on every sample tree and categorised into three groups, (<6 cm, 6-10 cm and >10 cm), on the basis of basal diameter. Fresh and dry weight of branches was determined following equation 2 (Chidumaya 1990).

$$B_{dwi} = B_{twi} / 1 + M_{cbdi,} \qquad (2)$$

where: B_{dwi} - oven dry weight of branch, B_{twi} - fresh/green weight of branches and M_{cbdi} - moisture content of branch on dry weight basis. The total branch biomass (fresh/dry) per sample tree was estimated by equation 3:

$$B_{bt} = n_1 bw_1 + n_2 bw_2 + n_3 bw_3 - n_i bw_i = \sum_{i=1}^{n} n_i bw_i \qquad (3)$$

where: B_{bt} - branch biomass (fresh/dry) per tree, n_i - number of branches in the i^{th} branch group, b_w - average weight of branch of i^{th} group.

Leaf biomass of forest trees. Leaves from selected branches were separated, weighed and oven dried at 80±5^0 C. Leaf biomass was derived by equation 4 (Chidumaya 1990):

$$L_{bt} = n_1 lw_1 + n_2 lw_2 + n_3 lw_3 - n_i lw_i = \sum_{i=1}^{n} n_i lw_i \qquad (4)$$

where: L_{bt} - leaf biomass dry per tree, n_i - number of branches in the i^{th} branch group, l_w - average weight of leaf in i^{th} group. The total tree biomass was the sum of stem biomass, branch biomass and leaf biomass.

Shrub and grass biomass. The basal diameter and length of tiller of all shrubs falling within 5 m x 5 m quadrates were recorded. Species and region specific local volume equations were used for calculating the volume. The total grass biomass of collected samples was oven dried at 65±5^0 C to a constant weight.

Surface litter. Surface litter was collected within a 1 m x 1 m quadrate. Collected samples were weighed, dried at 65±5^0 C, ground and converted to ash. Ash corrected dry weight was assumed to contain 45% carbon.

Detritus carbon content was:

$$\textit{detritus carbon content} = \textit{dry biomass} \cdot 0.5 \qquad (5)$$

(assumed carbon concentration of 50%, as per standard procedure followed in numerous literature, e.g. Zhu et al. 2010). Detritus carbon density was calculated as a summation of carbon density of standing dead trees, fallen trees and forest floor biomass.

Below ground biomass. Below ground biomass of trees and shrubs was calculated by Cairns (1997) equation and as per the IPCC guidelines. Below ground biomass of the grasses and herbs were computed using the equation of Mokany et al. (2006):

$$\textit{belowground biomass} = \textit{above ground biomass} \cdot \textit{root: shoot ratio} \qquad (6)$$

C estimation. C sequestrated (t ha^{-1}) was the difference between C stored in the plantation and C present just outside the plantation ecosystem. Rate of carbon sequestration was the ratio between C sequestrated and the number of years.

Collection, preparation and analysis of soil samples

Soil samples were taken from three soil layers (0-20 cm, 20-40 and 40-100 cm), in three replications. Soil depth was measured as the vertical length from the soil surface and the samples were collected by auger. Soil samples were processed after passing through a 2 mm sieve. Soil pH was measured by combined glass–calomel electrode in 1:2.5 soil solution ratio. Electrical conductivity (dS m^{-1}) was determined by conductivity bridge (Richards 1954). Wet digestion method was used for estimating soil organic carbon (Walkley & Black 1934). Available nitrogen was measured by the alkaline permanganate method (Subbiah & Asija 1956). Bulk density of soil was estimated through specific gravity method (Singh 1980). Soil carbon (t ha^{-1}) was estimated following equation 7 (Nelson & Sommers 1996):

$$soil\ carbon = [soil\ bulk\ density\ (g\ cm^{-3}) \cdot soil\ depth\ (cm) \cdot carbon\ (\%)] \cdot 100 \quad (7)$$

Statistical analysis

Analysis of variance was performed for statistical analysis of data. Soil samples were collected randomly from three soil layers (0-20, 20-40 and 40-100 cm), in three replications. Measurements of sample trees were taken in replicates from different plantation systems. Statistical analyses were conducted using the SAS System software. The relationship between different parameters was determined by Pearson's correlation matrix using SPSS window version 14.0 (SPSS Inc., Chicago, USA).

Results and discussion

Biomass and biomass carbon density under plantation forest ecosystems

Above ground biomass production under different plantation is given in Table 2. Maximum above ground biomass was recorded in *Ulmus villosa* (185.57±48.99 t ha^{-1}, where number followed by ± indicates the standard deviation), closely followed by *Albizia procera* (180.61± 2.18 t ha^{-1}), *Eucalyptus tereticornis* (153.06 ±42.46 t ha^{-1}), *Quercus leucotrichophora* (149.59±5.85 ha^{-1}) and *Alnus nitida*

Table 2 Biomass and biomass carbon density (t ha^{-1}) under plantation forest ecosystems

Plantation forest ecosystem	Treeabove ground biomass (*A*) (t ha^{-1})	Tree below ground biomass (*B*) (t ha^{-1})	Total Tree biomass (*C = A+B*) (t ha^{-1})	Shrub biomass (above+ below) (*D*) (t ha^{-1})	Grass biomass (above+ below) (*E*) (t ha^{-1})	Vegetation biomass (above+ below) (*F=C+D+E*) (t ha^{-1})	Vegetation biomass carbon density (t ha^{-1})
Quercus leucotrichophora	149.59 (5.85)^{ab}	34.79 (1.23)^{ab}	184.44 (7.07)^{ab}	1.09 (0.03)^{c}	2.26 (0.06)^{d}	187.84 (7.08)^{abc}	93.88 (3.59)^{ab}
Pinus roxburghii	131.39 (15.19)^{b}	30.87 (3.30)^{b}	162.25 (18.49)^{b}	1.47 (0.93)^{c}	10.99 (1.63)^{a}	174.59 (18.34)^{bc}	87.37 (9.1)^{b}
Acacia catech)	46.84 (15.14)^{c}	11.87 (3.60)^{c}	58.71 (18.76)^{c}	4.18 (1.99)^{ab}	10.11 (1.08)^{a}	72.46 (20.62)^{d}	36.50 (9.87)^{c}
Acacia mollissima	109.06 (24.19)^{b}	25.97 (5.30)^{b}	135.03 (29.51)^{b}	2.47 (1.84)^{bc}	6.38 (3.68)^{c}	143.88 (29.83)^{c}	71.92 (13.93)^{b}
Albizia procera	180.61 (2.18)^{a}	41.53 (0.57)^{a}	222.51 (3.14)^{a}	4.66 (0.07)^{a}	9.53 (0.19)^{ab}	236.75 (2.91)^{a}	118.37 (1.49)^{a}
Alnus nitida	147.00 (2.00)^{ab}	34.27 (0.435)^{ab}	181.27 (2.44)^{ab}	4.97 (0.46)^{a}	7.29 (1.04)^{bc}	193.05 (2.00)^{abc}	96.78 (1.41)^{ab}
Eucalyptus tereticornis	153.06 (42.46)^{ab}	35.51 (9.19)^{ab}	188.58 (39.29)^{ab}	1.57 (0.17)^{c}	6.36 (0.45)^{c}	196.21 (51.37)^{ab}	98.27 (25.78)^{ab}
Ulmus villosa	185.57 (48.99)^{a}	42.47 (10.36)^{ab}	228.03 (59.34)^{a}	1.85 (0.68)^{c}	3.09 (0.73)^{d}	232 (59.96)^{a}	116.48 (30.39)^{a}
P - value	0.0002	0.0001	<0.0001	0.0009	0.0001	0.0002	0.0002

Note. Values in the columns followed by same letter(s) are not significantly different according to LSD test ($p < 0.05$). Values inside the parenthesis denote standard error.

(147±2 t ha^{-1}). The minimum above ground biomass accumulation was found in *Acacia catechu* (46.84 t ha^{-1}), which was significantly lower than all other tree species. Belowground biomass was maximum in *Ulmus villosa* (42.47±10.36 t ha^{-1}) and minimum in *Acacia catechu* (11.27±3.6 t ha^{-1}).

Total biomass of trees was maximum in *Ulmus villosa* (228.030±59.34 t ha^{-1}). Total tree biomass in *Pinus roxburghii* (165.25±18.49 t ha^{-1}) was statistically at par with *Acacia mollisima* (135.027±29.51 t ha^{-1}), *Alnus nitida*, *Quercus leucotrichophora* and *Eucalyptus tereticornis*. Minimum tree biomass accumulation was found in *Acacia catechu* (58.71±18.76 t ha^{-1}).

Maximum shrub biomass (4.97±0.46 t ha^{-1}) was in *Alnus nitida* plantation whereas, the grasses were maximum (10.99±1.63 t ha^{-1}) under the *Pinus roxburghii* plantation. Minimum biomass of shrub (1.096±0.029 t ha^{-1}) and grasses (2.26±0.062 t ha^{-1}) was found in *Quercus leucotrichophora* plantation.

Vegetation biomass production of plantation was maximum in *Albizia procera* (236.75±2.91 t ha^{-1}) and minimum in *Acacia catechu* (72.46±20.62 t ha^{-1}). Vegetation biomass carbon density followed a similar trend, being maximum in *Albizia procera* (118.37±1.49 t ha^{-1}) and minimum (365 t ha^{-1}) in *Acacia catechu* (Table 2).

Geographical region, plant species and age are the major determinants of biomass and carbon stock in forest stand (Van Noordwizk et al, 1997). The above-ground biomass of the ban oak forest is found to be much lesser than reported for other oak forests (Negi et al. 1983, Johnson & Risser 1974, Rawat & Singh 1988, Sharma et al. 2010). However, the above ground biomass in oak forest in our study falls well within the average range of above ground biomass as reported by the several workers for Himalayan region (Sharma et al. 2010, Tiwari & Singh 1987, Singh et al. 1985, Negi et al. 1983). Above ground biomass production in ban oak forest is higher than the value reported by Sharma et al. (2010) for lower western Himalayan *Quercus leucotrichophora* forest.

The above ground biomass production of chir pine forest falls in the range reported by Chaturvedi & Singh (1987), but it is higher than those reported by Sharma et al. (2010) for Himalayan *Pinus roxburghii*. The above ground biomass production in the oak and pine forest is much lower than value reported by Rana et al. (1989) for mixed oak-pine forest but falls within the range of average values reported by Sharma et al. (2010) for north-west Himalayan forests. Minimum vegetation carbon density was found in *Acacia catechu*. Vegetation carbon density in present result is in accord with the result reported by Sharma et al. (2010), Tiwari & Singh (1987) and Singh et al. (1985) for adjoining Himalayan forest ranges. This difference in biomass production in different trees is related to their leaf area index and canopy architecture.

Soil carbon density of plantation forest ecosystems

In humus layer, maximum soil carbon density was under *Acacia catechu* (12.69±1.124 t ha^{-1}) followed by *Albizia procera*, *Eucalyptus tereticornis*, *Acacia mollissima and Ulmus villosa,* respectively in descending order (Table 3). At 0-20 cm soil depth soil carbon density was maximum in *Acacia catechu* (64.06±6.67 t ha^{-1}) plantation and minimum under *Eucalyptus tereticornis* (40.027±5.48 t ha^{-1}). Carbon density in 20-40 cm soil layer did not vary significantly among tree species. At the lowest soil depth, highest value of soil carbon density was in recorded in *Alnus nitida* (121.1±8.84 t ha^{-1}) and minimum under *Quercus leuoctrichophora* (70.47±23.88 t ha^{-1}). The total soil carbon density (0–100 cm) was maximum in *Alnus nitida* (213±9.16 t ha^{-1}), and minimum under *Albizia procera* (163±26.1 t ha^{-1}) plantation. A comparison of the total soil carbon density did not show any statistically significant difference under different plantations.

Table 3 Soil carbon density (t ha^{-1}) of plantation forest

	Soilcarbon density (t ha^{-1})					
Plantation forest ecosystem	Humus layer (*A*)	0-20 cm depth (*B*)	20-40 cm depth (*C*)	40-100 cm depth (*D*)	0-100 cm depth (*E*)	Total soil carbon density (*F* =*A*+*B*+*C*+*D*+*E*)
Quercus leucotrichophora	5.86 (0.61)^{d}	60.76 (7.78)^{ab}	34.09 (10.20)^{a}	70.47 (23.88)^{c}	165.00 (29.10)^{b}	170.87 (29.30)^{a}
Pinus roxburghii	7.19 (1.26)^{cd}	53.41 (4.62)^{ab}	31.86 (6.60)^{a}	78.37 (13.5)^{bc}	165.00 (19.50)^{b}	170.83 (20.60)^{a}
Acacia catech)	12.69 (1.12)^{a}	64.06 (6.67)^{a}	38.75 (6.37)^{a}	77.55 (17.26)^{bc}	18.00 (18.50)^{ab}	193.08 (19.09)^{a}
Acacia mollissima	5.66 (0.79)^{d}	50.12 (6.31)^{abc}	39.32 (9.72)^{a}	105.81 (31.6)^{ab}	195.00 (39.30)^{ab}	200.60 (40.01)^{a}
Albizia procera	8.34 (0.38)^{b}	49.16 (16.75)^{bc}	36.58 (10.08)^{a}	76.96 (10.92)^{bc}	163.00 (26.10)^{b}	171.04 (26.01)^{a}
Alnus nitida	6.60 (1.66)^{cd}	49.80 (1.04)^{abc}	42.35 (1.34)^{a}	121.10 (8.84)^{a}	213.00 (9.16)^{a}	219.86 (10.34)^{a}
Eucalyptus tereticornis	7.70 (0.68)^{cd}	40.03 (5.48)^{c}	31.83 (3.47)^{a}	91.90 (17.08)^{abc}	164.00 (21.10)^{b}	171.50 (21.7)^{a}
Ulmus villosa	3.01 (1.69)^{e}	49.80 (7.67)^{abc}	41.30 (1.48)^{a}	115.45 (5.17)^{a}	207.00 (4.28)^{a}	209.56 (2.61)^{a}
p - value	< 0.0001	0.0343	0.776	0.0444	0.28	0.1907

Note. Values in the columns followed by same letter(s) are not significantly different according to LSD test ($p < 0.05$). Values inside the parenthesis denote standard error.

The soil carbon stock exhibits considerable spatial variability, both horizontally according to land use and vertically within the soil profile. Soil carbon density of 161.9 t ha^{-1} for the soil depth of 1 m has been reported by Chhabra et al. (2003) for montane temperate forest. Soil organic carbon declines with depth irrespective of vegetation type and soil texture (Trujilo et al. 1997). The soil organic carbon stock in cacao+gliricidia (*Gliricidia sepium*) agroforestry systems in Indonesia amounted to 155 Mg C ha^{-1} at 0–100 cm soil depth (Smiley & Kroschel 2008). Singh (2005) demonstrated the usefulness of tree species in improving the carbon stock. The positive impact of higher litter addition on soil organic carbon accumulation has been reported earlier (Negi et al. 2006).

Detritus carbon density under different plantations

Total detritus carbon density of different plantations is given in Table 4. It was observed that total detritus carbon density was maximum in *Pinus roxburghii* (6.79±2.0 t ha^{-1}) of which 0.77±0.20 t ha^{-1} was of standing dead trees, 2.14±3.58 t ha^{-1} of fallen trees and floor material contributed 3.88±2.19 t ha^{-1}. The minimum total detritus carbon density was found in *Alnus nitida* (2.88±0.10 t ha^{-1}) where maximum contribution was of floor material (1.82±0.08 t ha^{-1}). The detritus material is more in stronger light demander species like *Pinus roxburghii* as those individual which are left behind in competition dies because of lack of light.

Carbon density of plantation forest ecosystems

Carbon density of plantation forest ecosystem is presented in Table 5. Maximum carbon density was in *Ulmus villosa* (330.07±31.21 t ha^{-1}), followed by *Alnus nitida* (319.52±9.79 t ha^{-1}) and *Albizia procera* (292.39±27.40 t ha^{-1}). Minimum value of carbon density was in *Acacia catechu* plantation (234.08±27.99 t ha^{-1}). Maximum contribution toward carbon density was from soil followed by biomass and least

Table 4 Detritus carbon density (t ha^{-1}) of plantation

Plantation forest ecosystems	Detritus carbon density (t ha^{-1})			
	Standing dead tree (above + below) (*A*)	Fallen tree (above + below) (*B*)	Floor material (*C*)	Total detritus (*D*= *A*+*B*+*C*)
Quercus leucotrichophora	0.79 (0.042)b	0.36 (0.07) a	1.95 (0.03)c	3.098 (0.02)c
Pinus roxburghii	0.77 (0.20)b	2.14 (3.58)a	3.88 (2.19)a	6.79 (2.0)a
Acacia catech)	0.77 (0.06)b	0.17 (0.05)a	3.57 (0.05)ab	4.52 (0.10)b
Acacia mollissima	0.78 (0.01)b	0.67 (0.11)a	1.86 (0.53)c	3.33 (0.47)bc
Albizia procera	1.30 (0.07)a	0.02 (0.01)a	1.67 (0.04)c	2.99 (0.04)c
Alnus nitida	0.75 (0.03)b	0.31 (0.04)a	1.82 (0.08)c	2.88 (0.101)c
Eucalyptus tereticornis	0.78 (0.15)b	0.59 (0.07)a	2.24 (0.29)bc	3.60 (0.38)bc
Ulmus villosa	1.16 (0.05)a	0.69 (0.03)a	2.19 (0.01)bc	4.03 (0.03)bc
P - value	<0.0001	0.5939	0.0227	0.0393

Note. Values in the columns followed by same letter(s) are not significantly different according to LSD test ($p < 0.05$). Values inside the parenthesis denote standard error.

Table 5 Carbon density (t ha^{-1}) of plantation forest

Plantation forest ecosystems	Carbon density (t ha^{-1})				
	Vegetation (*A*)	Soil (*B*)	Detritus (*C*)	Ecosystem (*D*= *A*+*B*+*C*)	Soil: vegetation ratio
Quercus leucotrichophora	93.88 $(3.59)^{ab}$	170.87 $(29.30)^{a}$	3.098 $(0.02)^{c}$	267.84 $(29.05)^{dc}$	1.8^{bc}
Pinus roxburghii	87.37 $(9.10)^{b}$	170.83 $(20.60)^{a}$	6.79 $(2.00)^{a}$	265.00 $(16.50)^{dc}$	1.96^{bc}
Acacia catech)	36.50 $(9.87)^{c}$	193.08 $(19.09)^{a}$	4.52 $(0.10)^{b}$	234.08 $(27.99)^{d}$	5.28^{a}
Acacia mollissima	71.92 $(13.93)^{b}$	200.60 $(40.01)^{a}$	3.33 $(0.47)^{bc}$	275.86 $(35.72)^{bdc}$	2.79^{b}
Albizia procera	118.37 $(1.49)^{a}$	171.04 $(26.01)^{a}$	2.99 $(0.04)^{c}$	292.39 $(27.40)^{abc}$	1.44^{c}
Alnus nitida	96.78 $(1.41)^{ab}$	219.86 $(10.34)^{a}$	2.88 $(0.10)^{c}$	319.52 $(9.79)^{ab}$	2.27^{b}
Eucalyptus tereticornis	98.27 $(25.78)^{ab}$	171.5 $(21.70)^{a}$	3.60 $(0.38)^{bc}$	273.39 $(15.69)^{bdc}$	1.75^{c}
Ulmus villosa	116.48 $(30.39)^{a}$	209.56 $(2.61)^{a}$	4.03 $(0.029)^{bc}$	330.07 $(31.1)^{a}$	1.80^{bc}
P - value	0.0002	0.1907	0.0393	0.0149	0.0523

Note. Values in the columns followed by same letter(s) are not significantly different according to LSD test ($p < 0.05$). Values inside the parenthesis denote standard error.

by detritus. Soil: vegetation ratio in plantation forest ecosystem varied significantly. Highest soil : vegetation ratio (5.28) was under *Acacia catechu* plantation and minimum (1.8) in *Ulmus villosa* and *Quercus leucotrichophora* plantations.

The total carbon in the system and its allocation between soil and plant and even in humus depends on inter-relationship between vegetation and carbon dynamics. Input from leaf litter and/or fine roots and their decomposition rates are controlled by microbial activity. The vegetation composition determines residence time of organic carbon in soil (Rasse et al. 2006). Such variation in rates leads to difference in carbon density in soil and plant. Those ecosystems/tree species which have more capacity to store the carbon in mineral soil layer have got more carbon mitigation potential than those which do so in the organic soil layer because in the mineral soil layer the carbon is in stable carbon pool. Maximum detritus carbon density in the plantation ecosystem was in the *Pinus roxburghii,* which is 2-3 times more over other plantation tree species. Similar trends of carbon densities were also seen in the standing dead tree, fallen tree and floor material. These variations in the detritus carbon density among various vegetation types/plantation ecosystems can be explained on the basis of their light requirements, leaf-shedding habit and stem density. In the natural ecosystems most of the trees like *Quercus, Pines roxburghii, Acacia catechu, Bombax ceiba, Acacia*, etc. are strong light demander hence, trees and/or branches dies because of natural pruning and natural thinning leading to more carbon density in the dead pool. In addition, they regularly shed leaves leading to building up of leaf-litter on the forest floor. Singh (2005) demonstrated the usefulness of tree species in improving the carbon stock. The higher litter addition had positive influence on soil organic carbon accumulation (Negi et al. 2006). Higher soil: vegetation carbon ratio indicates that in the near future if any accident or conversion takes place then this system can be the major source of CO_2 flux into the atmosphere. Soil organic carbon density ranges are more or less same as reported by Raina et al. (1999) and Singh et al. (1987) but lower than the range of Chaudhary et al. (1973).

Carbon sequestration potential of plantation forest

Total carbon density under plantation ecosystem had been discussed above and was found to be maximum in *Ulmus villosa* and minimum in *Acacia catechu.* Carbon density outside plantation ecosystem (natural vegetation) in soil, vegetation and total varied significantly among plantation. Maximum carbon density outside the plantation was near *Alnus nitida* (193.12 ±20.88 t ha^{-1}) and minimum was near *Acacia catechu* (119.6±44.07 t ha^{-1})(Table 6). Data in Table 6 demonstrates that carbon sequestration potential varied significantly under different plantation forest ecosystem. Maximum carbon sequestration in soil was under *Acacia catechu* (90.51±61.03 t ha^{-1}) and minimum in *Eucalyptus tereticornis* (12.91±27.91 t ha^{-1}), whereas, in vegetation *Albizia procera* (100.92±1.44 t ha^{-1}) showed maximum carbon sequestration potential and minimum was found in *Acacia catechu* (23.92±7.58 t ha^{-1}). The sequestration rate is estimated by diving the total carbon sequestration by age of the tree.

Maximum value of total carbon sequestration potential was in *Ulmus villosa* (148.8±62.89 t ha^{-1}) plantation, which, however remained statistically at par with *Albizia procera*, *Quercus leucotrichophora*, *Pinus roxburghii* and *Alnus nitida*. Minimum value of total carbon sequestration potential was in *Eucalyptus tereticornis* (93.58±55.56 t ha^{-1}), which, remained statistically at par with *Acacia catechu*, *Alnus nitida*, *Pinus roxburghii* and *Quercus leucotrichophora*.

In one of the study in Uttar Pradesh, approximately 20 million t of carbon has been estimated to be sequestered by the farm forestry plantations (Singh et al. 2000). Gera et al. (2006) reported 115, 64 and 56 tha^{-1} carbon sequestration potential under poplar block, poplar boundary and *Eucalyptus* boundary plantations, respectively under irrigated agroecosystem on farmer's fields. Lal & Singh (2000) emphasized that with the increase in

Table 6 Carbon sequestration potential (t ha^{-1}) of plantation forest

Plantation forest ecosystems	Carbon density (t ha^{-1}) under plantation ecosystem			Carbon density (t ha^{-1}) outside plantation ecosystem			Carbon sequestration potential (t ha^{-1})		
	Soil	Plant	Total	Soil	Plant	Total	Soil	Vegetation	Total
Quercus leucotrichophora	170.87 (29.30)^{a}	96.98 (3.60)^{ab}	267.84 (29.05)^{dc}	120.58 (8.26)^{b}	19.53 (0.97)^{bc}	140.11 (6.70)^{b}	50.59 (35.03)^{b}	77.44 (2.7)^{abc}	128.04 (39.6)^{ab}
Pinus roxburghii	170.83 (20.60)^{a}	92.17 (11.19)^{b}	263.00 (16.50)^{dc}	117.48 (6.00)^{b}	18.83 (1.76)^{bc}	136.31 (7.54)^{bc}	53.35 (26.38)^{b}	73.34 (9.4)^{bc}	126.69 (39.66)^{ab}
Acacia catech)	193.08 (19.09)^{a}	40.95 (9.70)^{c}	234.08 (27.99)^{d}	102.57 (21.67)^{b}	17.03 (2.13)^{cd}	119.60 (44.07)^{c}	90.51 (61.03)^{a}	23.92 (7.58)^{d}	114.43 (72.86)^{b}
Acacia mollissima	200.60 (40.01)^{a}	75.26 (13.46)^{b}	275.86 (35.72)^{bdc}	143.72 (11.64)^{ab}	18.60 (1.30)^{bc}	162.32 (10.51)^{ab}	56.88 (49.22)^{b}	56.66 (12.31)^{c}	113.54 (63.98)^{b}
Albizia procera	171.04 (26.01)^{a}	121.36 (1.50)^{a}	292.39 (27.40)^{abc}	130.24 (13.16)^{b}	20.43 (0.91)^{bc}	150.67 (20.89)^{b}	40.80 (35.41)^{b}	100.92 (1.44)^{a}	141.73 (37.82)^{a}
Alnus nitida	219.86 (10.34)^{a}	99.66 (1.50)^{ab}	319.52 (9.79)^{ab}	179.72 (17.85)^{a}	14.00 (3.04)^{d}	193.82 (20.89)^{a}	40.04 (28.9)^{b}	85.66 (3.2)^{ab}	125.70 (32.73)^{ab}
Eucalyptus tereticornis	171.50 (21.70)^{a}	101.87 (25.59)^{ab}	273.39 (15.69)^{bdc}	158.73 (60.86)^{b}	21.20 (2.01)^{b}	179.79 (8.27)^{a}	12.91 (27.96)^{c}	80.66 (23.59)^{abc}	93.58 (55.56)^{b}
Ulmus villosa	209.56 (2.61)^{a}	120.51 (30.40)^{a}	330.07 (31.10)^{a}	150.73 (25.63)^{a}	30.47 (4.05)^{a}	181.20 (29.58)^{a}	58.83 (28.41)^{b}	90.04 (31.93)^{ab}	148.80 (62.89)^{a}
P - value	0.1907	0.0003	0.0149	0.2396	<0.0001	0.11985	0.1465	0.0006	0.1894

Note. Values in the columns followed by same letter(s) are not significantly different according to LSD test ($p < 0.05$). Values inside the parenthesis denote standard error.

sustainable annual plantation of 0.5 M ha, our forests are expected to act as a net C sink in future.

Carbon sequestration rate and carbon dioxide mitigation under different plantation forest ecosystems

Carbon sequestration rate under different plantations is given in Table 7. Higher rates of total carbon sequestration was in *Ulmus villosa* (7.91±3.4 t ha^{-1} yr^{-1}) and least in *Eucalyptus tereticornis* (4.4±2.64 t ha^{-1}yr^{-1}). In all the plantations contribution of biomass towards total sequestration rate, as compared to soil, was higher except *Acacia catechu* where rate of carbon sequestration in soil was higher than biomass.

Total carbon dioxide mitigation rate followed similar trend of sequestration rate. It was higher in *Ulmus villosa* (29.09±12.78 t ha^{-1} yr^{-1}), and minimum in *Eucalyptus tereticornis* (16.00±9.71 t ha^{-1} yr^{-1}) plantation (Table 7).

The rate of carbon sequestration by different tree species in the soil varied between 0.6-3.98 t ha^{-1} yr$^{-1.}$ These results similar to the report of Post & Kwon (2000), who reported that the average rate of soil C sequestration ranged between 0-3 t C ha^{-1} yr^{-1} (0.3 t C ha^{-1} yr^{-1} average values) across different climatic zones.

Acacia catechu showed maximum CO_2 mitigation potential in soil followed by *Ulmus villosa*. Whereas, in trees maximum CO_2 mitigation potential was in *Alnus nitida* followed by *Ulmus villosa*. The total CO_2 mitigation potential (soil + vegetation) was maximum in *Ulmus villosa* followed by *Alnus nitida, Quercus leucotrichophora* and *Acacia mollissima.* The varying rate of CO_2 mitigation potential of plantations can be attributed to their rate of photosynthesis.

Pearson correlation matrix (Table 8) revealed significant and positive relationship of ecosystem carbon with tree above ground biomass

Table 7 Rate of carbon sequestration (t ha^{-1} yr^{-1}) and CO_2 mitigation (t ha^{-1} yr^{-1}) of different plantation forest ecosystems

Plantation forest ecosystems	Rate of carbon sequestration (t ha^{-1} yr^{-1})			Rate of CO_2 mitigation (t ha^{-1} yr^{-1})		
	Soil	Vegetation	Total	Soil	Vegetation	Total
Quercus leucotrichophora	2.29 (1.59)^{b}	3.47 (0.16)^{ab}	5.76 (1.8)^{bc}	8.40 (5.84)^{b}	12.7 (0.6)^{ab}	21.1 (6.61)^{ab}
Pinus roxburghii	1.96 (0.95)^{bc}	2.78 (0.71)^{b}	4.74 (1.42)^{c}	7.19 (3.49)^{bc}	10.2 (2.6)^{b}	17.39 (5.21)^{b}
Acacia catech)	3.98 (2.68)^{a}	0.97 (0.35)^{c}	4.95 (3.2)^{bc}	14.60 (9.87)^{a}	3.54 (1.3)^{c}	18.14 (11.78)^{b}
Acacia mollissima	2.84 (2.46)^{ab}	2.9 (0.67)^{b}	5.677 (3.19)^{bc}	10.42 (9.03)^{ab}	10.6 (2.47)^{b}	21.02 (11.7)^{ab}
Albizia procera	1.77 (1.53)^{bc}	4.42 (0.07)^{a}	6.16 (1.64)^{b}	6.49 (5.65)^{c}	16.2 (0.24)^{a}	22.60 (6.03)^{c}
Alnus nitida	2.1 (1.48)^{b}	4.68 (0.08)^{a}	6.78 (1.72)^{b}	7.70 (5.44)^{bc}	17.2 (0.29)^{a}	24.9 (6.32)^{a}
Eucalyptus tereticornis	0.6 (1.33)^{c}	3.76 (1.22)^{ab}	4.4 (2.64)^{c}	2.20 (4.88)^{d}	13.8 (4.47)^{ab}	16.00 (9.71)^{bc}
Ulmus villosa	3.26 (1.56)^{a}	4.65 (0.72)^{a}	7.91 (3.4)^{a}	11.99 (5.75)^{ab}	17.1 (2.65)^{a}	29.09 (12.78)^{a}
P - value	0.1465	0.0006	0.2575	0.1465	0.0006	0.2575

Note. Values in the columns followed by same letter(s) are not significantly different according to LSD test ($p < 0.05$). Values inside the parenthesis denote standard error.

carbon, below ground biomass, total carbon and total CO_2 mitigation. Total detritus carbon did not show any significant relationship with any of the soil and plant parameters.

Conclusions

The plant biomass and biomass carbon density followed the trend *Albizia procera*> *Ulmus villosa* > *Eucalyptus tereticornis*> *Alnus nitida* > *Quercus* > *Pinus roxburghii* > *Acacia mollissina* > *Acacia catechu*. The carbon density in humus layer was maximum in *Acacia catechu* plantation; however, total soil carbon density was highest in *Alnus nitida*. Total carbon sequestration was maximum in case of *Ulmus villosa*, followed by *Albizia procera*, *Quercus, Pinus roxburghii, Alnus nitida, Acacia catechu, Acacia mollissina* and *Eucalyptus tereticornis*. A nearly similar trend was found for rate of CO_2 mitigation. Pearson correlation matrix revealed significant and positive relationship of ecosystem carbon with tree above ground

Table 8 Pearson correlation matrix between different soil and plant parameters

	Ecosystem	Tree AGB	Tree BGB	Total H+S	Total detritus	Total CO_2 mitigation rate
Ecosystem	1.000	0.774*	0.773*	0.554*	NS	0.850**
Tree AGB		1.000	1.000**	NS	NS	0.525*
Tree BGB			1.000	NS	NS	0.520*
Total H+S				1.000	NS	0.663*
Total detritus					1.000	NS
Total CO_2 mitigation rate						1.000

Note. Abbreviations: AGB - above ground biomass, BGB - below ground biomass, H + S - carbon density of humus and soil (0-100 cm depth). * significant at $p < 0.05$, ** significant at $p < 0.01$ level.

biomass carbon, below ground biomass, total carbon density and rate of CO_2 mitigation. With the emerging threat of climate change, a comprehensive measurement of forest and soil carbon inventory would allow for more robust impact assessment of afforestation aiding future land management and policy decisions.

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