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Long term effects of natural and plantation forests on carbon sequestration and soil properties in mid-hill sub-humid condition of Himachal Pradesh, India

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Abstract

Natural forests of Quercus, *Pinus roxburghii*, Oak and pine, mixed broad leaved, *Acacia catechu*, scrub and grassland and eight different planted tree species *viz., Quercus leucotrichophora, P. roxburghii, Acacia catechu, Acacia mollissima, Albizia procera, Alnus nitida, Eucalyptus tereticornis* and *Ulmus villosa* were studied for carbon sequestration and soil properties. In natural forest, maximum and minimum biomass was produced in *P. roxburghii* (214.90 t ha^{-1}) and grasslands (10.87 t ha^{-1}), respectively. Maximum carbon sequestration was in *P. roxburghii* (107.5 2.43 tha^{-1}) and minimum in grassland (5.44 t ha^{-1}). In natural forest, detritus carbon sequestration varied from 0.49 t ha^{-1} in grassland to 12.24 t ha^{-1} in mixed broad leaved. Soil carbon sequestration ranged from 156.64 t ha^{-1} in grassland to 238.53 t ha^{-1} in natural forest of *A. catechu*.

Key words: Carbon sequestration, Grassland, Himalayan ecosystem, Land use system, Natural forest, Plantation, Soil properties

Introduction

The land-use systems play a tremendous role in influencing the nutrient availability and cycling and may also influence secondary succession and biomass production. Natural forest ecosystems of the tropics represent self-sustaining, efficient and ‘closed’ nutrient cycling systems with relatively little loss or gain of the actively cycling nutrients, and with high rates of nutrient turnover within the system. In contrast, most of the agricultural systems represent ‘open’ or ‘leaky’ system with comparatively high nutrient losses. Nutrient cycling in agroforestry systems falls between these extremes (Nair *et al*., 1995).

Tree litter and pruning improve soil fertility not only through the release of nutrients in the soil by mineralization but also by adding soil organic matter (Kohli *et al*., 2007). The increasing atmospheric concentrations of carbon (CO_2, CH_4, CO *etc.*) may be mitigated by increasing C sequestration in vegetative biomass and in soils. Soils are of major significance for carbon sequestration, as they contain an estimated 2400 to 2500 Gt (Gigatons) of OC to a depth of 2 m, which is about 3 times that contained in living biomass (Kirschbaum, 2000).

Carbon sequestration in terrestrial ecosystems, especially in soil, is a win–win strategy for developing countries, where land use change and agricultural intensification is most frequent (Lal, 2004). These stocks are dynamic, depending upon various factors and processes operating in the systems, the most significant being land use, land-use changes, soil erosion, and deforestation. The objective of study was to assess the long term effects of natural and plantation forests on carbon sequestration and soil properties in Indian sub-Himalayas.

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. 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, with annual rainfall from 1000-1400 mm. Soil of the experimental site is clay loam with about 28 per cent 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 forests of the region are classified as 9 C_1-Lower Himalayan *P. roxburghii* forests with *P. roxburghii* as a dominant species, as per Champion and Seth’s forest type classification (Khanna, 1993). Eight tree species were planted in the year 1985 to see the performance of species with respect to growth and biomass production. The detailed site characteristics of the plantation are given in table 1.

Table 1. Site Characteristics of natural and planted forest ecosystems

Forest type	Altitude (m)	Stem density (ha^{-1})	Average dbh (cm)	Volume(M^3 ha^{-1})
Natural forest				
T_1 (*Quercus* forest)	1298-1303	859.3 ± 5.03^{ab}	20.38 ± 0.59^{a}	104.07 ± 1.389^{b}
T_2 (*Pinus roxburghii* forest)	1375-1380	1048.7 ± 233.59^{a}	25.48± 1.28^{a}	324.45 ± 19.81^{a}
T_3 (Oak and Pine forest)	1228-1298	908.33 ± 125.83^{a}	22.81± 2.83^{a}	211.24 ± 99.54^{a}
T_4 (Mixed Broad leaved forest)	1203-1207	1620.67 ± 49.54^{a}	15.59 ± 1.22^{b}	251.02 ± 2.96^{a}
T_5 (*Acacia catechu* forest)	1207-1215	699.33 ± 13.31^{bc}	15.83± 0.015^{b}	110.3 ± 3.45^{b}
T_6 (Scrub)	1362-1365	233.33 ± 57.74^{c}	14.59 ± 3.34^{b}	9.02 ± 8.51^{c}
T_7 (Grassland)	1248-1250	65 ± 15.72^{c}	17.49 ± 0.52^{ab}	1.154 ± 0.35^{c}
Planted forest				
T_1 (*Quercus leucotrichophora)*	1226-1229	2320 ± 5^{a}	14.88 ± 0.02 ^{ab}	221.30 ± 0.053^{ab}
T_2 (*Pinus roxburghii)*	1211-1236	1875 ± 17^{a}	16.54 ± 18.45^{ab}	266.34 ± 32.03^{a}
T_3 (*Acacia catechu)*	1118-1180	1342 ± 477.38^{a}	10.49 ± 2.89^{b}	45.16 ± 23.91^{c}
T_4 (*Acacia mollissima)*	1205-1246	1216.67 ± 472.58^{a}	14.41 ± 1.07^{ab}	113.52 ± 26.84^{b}
T_5 *(Albizia procera)*	1196-1198	1602.7 ± 5.03^{a}	19.2 ± 0.056 ^{a}	236.64 ± 0.115^{ab}
T_6 (*Alnus nitida)*	1189-1191	458.67 ± 9.01^{a}	25.72 ± 0.79^{a}	217.7 ± 0.87^{ab}
T_7 (*Eucalyptus tereticornis)*	1188-1238	2233.33 ± 539.86^{a}	12.84 ± 0.45^{b}	193.27 ± 56.34^{b}
T_8 (*Ulmus villosa)*	1214-1231	1617 ± 301.6^{a}	12.94 ± 1.63^{a}	217.09 ± 63.09^{ab}

Values in the columns followed by same letter (s) are not significantly different (P < 0.05) according to LSD test. Values suffixing ± denote standard error.

Above ground biomass of forest trees: In both plantation and natural ecosystem, three sample plots of 31.62×31.62 m^2 (0.1 ha) size were selected randomly for estimation of tree species biomass. All the trees falling under the sample plots were enumerated. The diameter, height and form factor were estimated for each tree falling within the plot, so as to estimate the volume. In each main plot, two 5×5 m^2 sub-plots were laid out within the main plot (31.62×31.62 m^2) on the opposite corners randomly. Within these sub-plots, two plots of size 1×1m^2 were laid out for measurement of herbs biomass. The plot sizes used for estimation of trees (0.1ha), shrubs (5 × 5 m^2) and herbs/grasses (1×1 m^2) biomass is standard one (Devi, 2010). 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. Volume of *Ulmus villosa* was determined following the procedure of Kaul and Panwar (2008).

Specific gravity of wood: Specific gravity was calculated from stem core measurement of wood. The biomass of the stem was measured using maximum moisture method as presented in equation 1 (Smith, 1954).

$$G_f = \frac{1}{\frac{M_m - M_0}{M_0} + \frac{1}{GS_0}} \quad \text{............... (Equation 1)}$$

Where, Gf is specific gravity of wood, M_m is constant weight of sample having maximum moisture content, M_o is oven dried constant weight of sample and GS_o is average density of wood, a constant having value of 1.53.

Biomass of wood: Stem biomass = Average specific gravity of stem wood x 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 1.3m from the larger end of the tree along with its length and was categorized in decay class 1-5 as assumed by Yan *et al.* (2006).

Branch biomass of forest trees: Total number of branches were counted on each of the sample tree and categorised into three groups, *viz.,* <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).

$$B_{dwi} = B_{twi} / 1 + M_{cbdi} \quad \text{............... (Equation 2)}$$

where, B_{dwi} is oven dry weight of branch, B_{twi} is fresh weight of branches and M_{cbdi} is Moisture content of branch on dry weight basis. The Total branch biomass (Fresh/dry) per sample tree was determined by equation 3 is shown below.

$$B_{bt} = n_1bw_1 + n_2bw_2 + n_3bw_3 - n_ibw_i = \sum_{i-l}^{n} n_ibw_i \quad \text{........ (Equation 3)}$$

where, Bbt is branch biomass (fresh/dry) per tree, n_i is number of branches in the i^{th} branch group, bw is average weight of branch of i^{th} group and i = 1, 2, 3…

Leaf biomass of forest trees: Leaves from the sampled branches were removed, weighed and oven dried separately to a constant weight at 80±5^0 C. Leaf biomass was derived by equation 4 (Chidumaya, 1990).

$$L_{bt} = n_1 l_{w1} + n_2 l_{w2} + n_3 l_{w3} - n_i l_{wi} = \sum_{i-l}^{n} n_i l_{wi} \quad \text{...... (Equation 4)}$$

where, Lbt is Leaf biomass dry per tree, n_i is number of branches in the i^{th} branch group, lw is average weight of leaf in i^{th} group and i = 1, 2, 3... 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 5x5m quadrates were enumerated. 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 1m x 1m quadrate. Collected samples were weighed, sub sampled and oven dried at 65±5^0 C to a constant weight, ground and ashed. Ash corrected dry weight was assumed to contain 45% carbon.

Detritus carbon sequestration: Detritus carbon content = Dry biomass x 0.5 ... (Equation 5), (assumed carbon concentration of 50%, as per IPCC). 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 *et al.* (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).

Below ground biomass = Above ground biomass x Root: shoot ratio.... (Equation 6).

Collection, preparation and analysis of soil samples: Soil samples in three replicates were collected from 0-20, 20-40 and 40-100 cm depths. Soil organic carbon was determined by wet digestion method (Walkley and Black, 1934); available nitrogen by alkaline permanganate method (Subbiah and Asija, 1956); bulk density by specific gravity method (Singh, 1980). Soil carbon (t ha^{-1}) was estimated following equation 7.

Soil Carbon = [Soil bulk density (g cm^{-3}) x Soil depth (cm) x Carbon (%)] x 100.... (Equation 7), (Nelson and Sommers, 1996).

Statistical analysis: One way ANOVA (LSD test) was performed for detecting significant differences of carbon density of plantation ecosystem and vegetation type. In plantation, each species was selected as treatment. Similarly in vegetation different ecosystems- ban oak forest, chirpine forest, oak and pine forest *etc.* were considered as separate treatment. Statistical analyses were conducted using the SAS System software.

Results and Discussion

Biomass production of forest ecosystems: Above ground biomass in natural forest of *P. roxburghii* (168.13 t ha^{-1}) was statistically at par, with oak and pine (134.05 t ha^{-1}) and minimum biomass was recorded in grassland (0.56 t ha^{-1}) ecosystem. Maximum below ground biomass was found in *P. roxburghii* (38.79 t ha^{-1}) and minimum in grassland (0.19 t ha^{-1}) ecosystem. Total biomass of tree also followed the similar trend being maximum in *P. roxburghii* (206.92 t ha^{-1}) and minimum in grassland (0.75 t ha^{-1}) ecosystem (Table 2). Maximum shrub biomass was observed under mixed broad leaved forest (11.94 t ha^{-1}), which was statistically at par with the *A. catechu* forest (11.83 t ha^{-1}), and least in grassland (0.86 t ha^{-1}) ecosystem. Minimum grass biomass was in ban oak forest (2.14 t ha^{-1}). The comparison of natural forest systems with eight plantation system of 26 years age in the similar region (Devi *et al*., 2013) , revealed that maximum total biomass production of plantation systems ranged from 72.46 to 236.75 t ha^{-1} signifying almost same production potential (Table 6).

The above ground biomass in our study falls well within the average range of above ground biomass reported by the various workers for Himalayan region (Sharma *et al.,* 2010). In general, biomass of shrubs and grasses was maximum under the forest having higher humus content under both natural and manmade forests. Variation in the shrub and grass biomass under different forests have also been reported by Zhu *et al.,* (2010) for temperate forest ecosystem of Indian Himalayas and Chinese temperate region, respectively.

Soil carbon sequestration of forest ecosystems: In humus layer, maximum carbon sequestration was recorded in *A. catechu* (28.21 t ha^{-1}), followed by mixed broad leaved forest (25.07 t ha^{-1}), ban oak forest (19.56 t ha^{-1}), scrub land (16.68 t ha^{-1}) and minimum in natural grassland (3.16 t ha^{-1}) (Table 3). In 0-100 cm layer, carbon sequestration was maximum in *A. catechu* (210 t ha^{-1}), and minimum (153.48 t ha^{-1}) in grassland. The soil carbon sequestration in eight tree based planted forest system in the same region ranged from 170.83 to 219.86 t ha^{-1}. This signifies a similar potential of soil carbon sequestration of both natural and plantation system (Table 6). Removal of trees from the forest displaces a large amount of sequestered carbon and consequently reduces the SOC held in soil profiles (Glaser *et al.*, 2000). Under natural as well as plantation forest, the soil carbon density declined with increase in soil depth. Addition of root and leaf litter to the soil play a key role in regulating organic carbon in forest soil. The upper layer is generally richer in carbon as it is in direct dynamic equilibrium with biological and anthropological activities. Similar results have been reported by Shrestha *et al.*, (2004) in mountain watershed of Nepal.

Fig. 1: Soil properties under natural forests

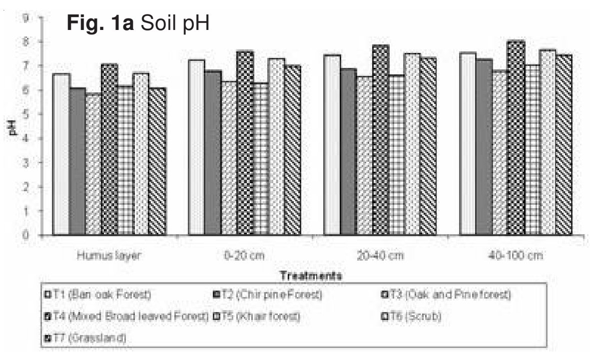

Fig. 1a Soil pH

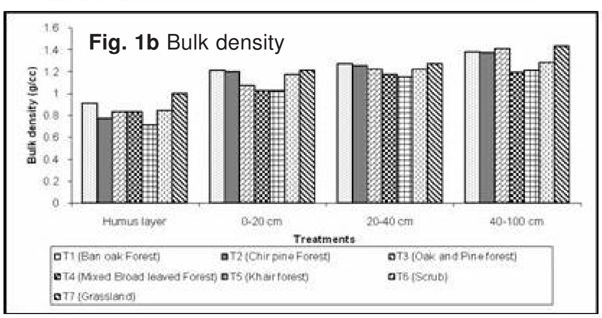

Fig. 1b Bulk density

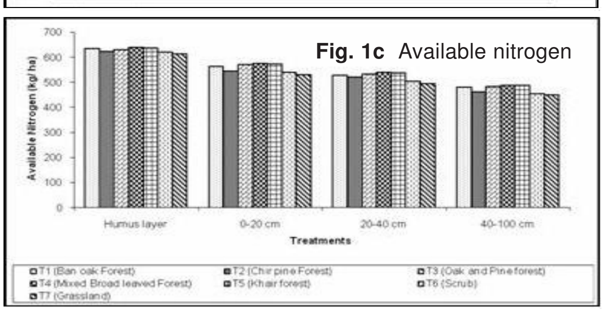

Fig. 1c Available nitrogen

Detritus carbon sequestration of forest ecosystems: Standing dead tree carbon sequestration was found to be maximum under mixed broad leaved forest (4.95 t ha^{-1}) and minimum in grassland (0.04 ha^{-1}) (Table 4). The minimum quantity of detritus material added to the soil was comparable in both the systems, but the maximum amount of detritus that was added was almost double in natural system as compared to plantation (Table 6). In the natural ecosystems, high light demanding nature of the trees like ban oak, *P. roxburghii*, *A. catechu*, *Bombax*, *Pistacia etc*. leading to more natural pruning and thinning resulting into more carbon sequestration in the dead pool. On the contrary, in plantation ecosystem, the trees are equally spaced and hence, competition is less among the trees which leads to less buildup of carbon in the detritus pools of their ecosystems.

Fig. 2: Soil properties under plantation forests

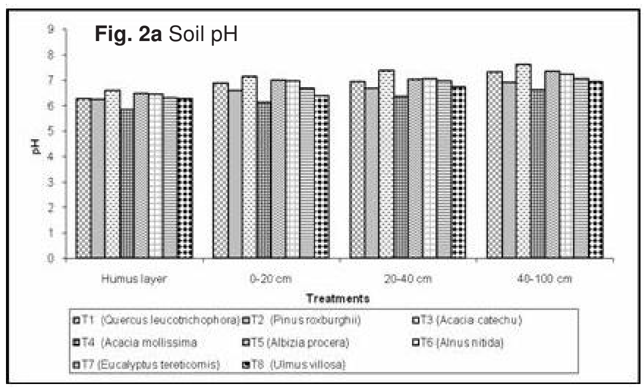

Fig. 2a Soil pH

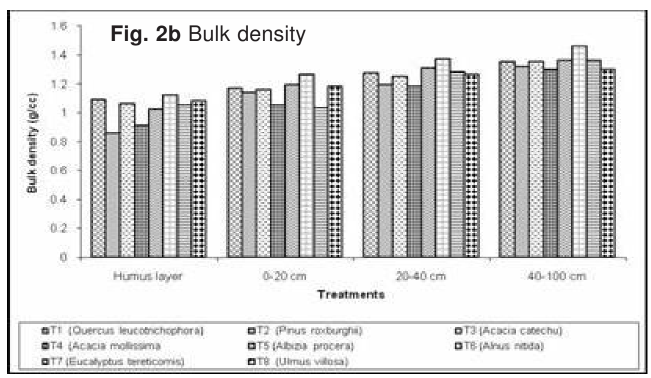

Fig. 2b Bulk density

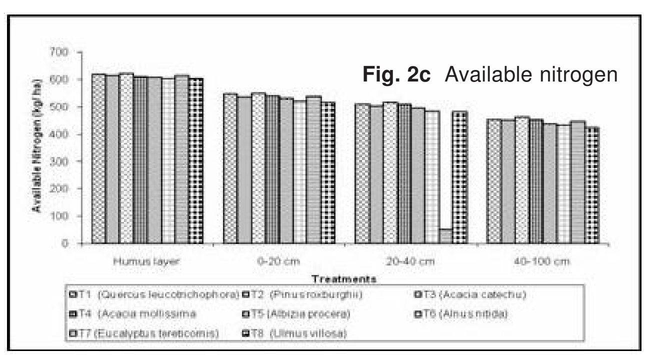

Fig. 2c Available nitrogen

Table 2. Biomass production of natural forest ecosystems

Treatments	Tree biomass (t ha^{-1})			Vegetation biomass (t ha^{-1})		
	Above ground (A)	Below ground (B)	Total (C= A+B)	Shrub (D)	Grass (E)	Total (F=C+D+E)
T_1	98.34±2.51^{b}	23.61±0.55^{b}	122.11±3.05^{b}	0.99±0.11^{d}	2.14±0.16^{e}	125.25±2.78^{bc}
T_2	168.13±5.69^{a}	38.79±1.24^{a}	206.92±6.92^{a}	1.41±0.04^{cd}	6.55±3.04^{bc}	214.90±4.77^{a}
T_3	134.05±61.41^{ab}	31.3±13.46^{ab}	165.36±74.87^{ab}	2.11±1.17^{c}	3.39±1.59^{ed}	170.85±76.93^{ab}
T_4	121.89±4.92^{b}	28.82±1.09^{b}	150.71±6.01^{b}	11.94±0.22^{a}	8.27±1.56^{ab}	170.91±7.38^{ab}
T_5	53.82±2.05^{c}	13.51±0.49^{c}	67.33±2.55^{c}	11.83±0.09^{a}	8.46±1.49^{ab}	87.62±2.7^{c}
T_6	4.27±3.99^{d}	1.26±1.15^{d}	5.52±5.14^{d}	7.15±0.69^{b}	4.85±0.29^{dc}	17.53±5.6^{d}
T_7	0.56±0.14^{d}	0.19±0.05^{d}	0.75±0.19^{d}	0.86±0.15^{d}	9.26±0.30^{a}	10.87±0.34^{d}
P-value	<0.0001	<0.0001	<0.0001	<0.0001	0.0003	<0.0001

Table 3. Soil carbon sequestration (t ha^{-1}) of natural forest ecosystems

Treatments	Humus layer (A)	0-20 cm depth (B)	20-40 cm depth (C)	40-100 cm depth (D)	Total (F= A+B+C+D)
T_1	19.56±2.70^{c}	52.68±6.84^{a}	49.15±10.10^{ab}	105.98±39.37^{a}	227.37±52.31^{a}
T_2	9.69±0.71^{e}	56.26±7.49^{a}	47.5±8.83^{abc}	99.46±10.38^{ab}	212.91±21.29^{ab}
T_3	16.79±0.54^{cd}	63.57±10.18^{a}	47.9±10.09^{abc}	92.06±23.64^{abc}	220.32±43.39^{ab}
T_4	25.07±0.61^{b}	55.89±6.28^{a}	46.09±6.01^{bcd}	81.18±12.74^{c}	208.23±23.97^{b}
T_5	28.21±2.21^{a}	55.01±5.03^{a}	54.14±6.96^{a}	101.16±14.98^{ab}	238.52±5.09^{a}
T_6	16.68±0.56^{cd}	53.6±16.41^{a}	39.07±8.72^{bcd}	105.07±19.51^{ab}	214.42±37.36^{ab}
T_7	3.16±0.10^{f}	50.53±24.76^{a}	31.14±4.01 ^{cd}	71.81±25.33^{c}	156.64±49.78^{b}
P-value	<0.0001	0.67	0.0287	0.0989	0.1038

Values in the columns followed by same letter (s) are not significantly different (P < 0.05) according to LSD test.
Values suffixing ± denote standard error.

Table 4. Detritus carbon sequestration (t ha^{-1}) of natural ecosystems

Treatments	Detritus carbon sequestration (t ha^{-1})			
	Standing dead tree (above+ below) (A)	Fallen tree (above+ below) (B)	Floor material (C)	Total detritus (D= A+B+C)
T_1	0.96±0.52^{c}	0.12±0.04^{c}	3.35±0.05^{dc}	4.44±0.09^{bc}
T_2	1.42±0.01^{b}	0.69±0.03^{b}	3.56±1.81^{bc}	5.66±1.81^{b}
T_3	1.34±0.03^{b}	0.67±0.02^{b}	2.02±0.84^{d}e	4.01±0.83^{c}
T_4	4.95±0.37^{a}	2.07±0.11^{a}	5.22±0.49^{a}	12.24±0.22^{a}
T_5	0.25±0.19^{c}	0.08±0.03^{dc}	4.78±0.26^{ab}	5.11±0.42^{b}
T_6	0.14±0.06^{d}	0.003±0.00^{d}	0.69±0.14ef	0.83±0.11^{d}
T_7	0.04±0.00^{d}	0.001±0.00^{d}	0.45±0.04f	0.49±0.04^{d}
P-value	<0.0001	<0.0001	<0.0001	<0.0001

Values in the columns followed by same letter (s) are not significantly different (P < 0.05) according to LSD test.
Values suffixing ± denote standard error.

Carbon sequestration of forest ecosystems: Carbon sequestration (t ha^{-1}) varied significantly (P < 0.0001) among the different natural forests (Table 5). Maximum biomass carbon density was found in *P. roxburghii* (107.50 t ha^{-1}) , followed by mixed broad leaved forest (85.47 t ha^{-1}) and oak and pine forest (85.44 t ha^{-1}). Vegetation carbon sequestration of trees plantation systems in the same region was found to vary from 72.46 - 236.75 t ha^{-1}, which is higher than natural forest ecosystems. Similar results were also reported by Baishya *et al.*, (2009) in the natural semi-evergreen forest and *Shorea robusta* plantation forest in the humid tropical region of north east India. Maximum soil: vegetation ratio (28.79) was in grassland, which was statistically at par with scrub ecosystem and minimum in *P. roxburghii* (1.98), while in planted forest ecosystems in the same region it was in a similar range (1.44 to 5.28) (Table 6).

Table 5. Soil vegetation ratio of natural forest ecosystem

Treatments	Vegetation (A)	Soil (B)	Detritus (C)	Ecosystem (D= A+B+C)	Soil: vegetation ratio
T_1	62.58±1.45^{bc}	227.32±52.31^{a}	4.44±0.09^{bc}	294.3±53.66^{a}	3.63^{b}
T_2	107.5±2.43^{a}	212.9±21.29^{ab}	5.66±1.81^{b}	325.56±17.52^{a}	1.98^{c}
T_3	85.44±38.49^{ab}	220.3±43.39^{ab}	4.01±0.83^{c}	309.89±72.34^{a}	2.59^{b}
T_4	85.47±3.73^{ab}	208.24±23.97^{ab}	12.24±0.22^{a}	305.95±25.65^{a}	2.43^{bc}
T_5	43.79±1.35^{c}	238.53±5.09^{a}	5.11±0.42^{b}	287.43±4.69^{a}	5.44^{b}
T_6	8.75±2.81^{d}	214.4±37.36^{ab}	0.83±0.11^{d}	224.08±43.03^{bc}	24.50^{a}
T_7	5.44±0.17^{d}	156.64±49.78^{b}	0.49±0.04^{d}	162.57±11.74^{c}	28.79^{a}
P-value	<0.0001	0.1038	<0.0001	0.0091	0.0132

Values in the columns followed by same letter (s) are not significantly different ($P < 0.05$) according to LSD test.
Values suffixing ± denote standard error.

Table 6. Biomass and carbon sequestration potential of Plantation forest ecosystems.

Treatments	Vegetation biomass (t ha^{-1})	Total soil carbon sequestration (t ha^{-1})	Total detritus carbon sequestration (t ha^{-1})	Soil: vegetation ratio
T_1	187.84 ± 7.08^{abc}	170.87 ± 29.30^{a}	3.098 ± 0.02^{c}	1.8^{bc}
T_2	174.59 ± 18.34^{bc}	170.83 ± 20.60^{a}	6.79 ± 2.0^{a}	1.96^{bc}
T_3	72.46 ± 20.62^{d}	193.08 ± 19.09^{a}	4.52 ± 0.10^{b}	5.28^{a}
T_4	143.88 ± 29.83^{c}	200.60 ± 40.01^{a}	3.33 ± 0.47^{bc}	2.79^{b}
T_5	236.75 ± 2.91^{a}	171.04 ± 26.01^{a}	2.99 ± 0.04^{c}	1.44^{c}
T_6	193.05 ± 2.00^{abc}	219.86 ± 10.34^{a}	2.88 ± 0.101^{c}	2.27^{b}
T_7	196.21 ± 51.37^{ab}	171.50 ± 21.7^{a}	3.60 ± 0.38^{bc}	1.75^{c}
T_8	232 ± 59.96^{a}	209.56 ± 2.61^{a}	4.03 ± 0.03^{bc}	1.80^{bc}
P-value	0.0002	0.1907	0.0393	0.0523

Values in the columns followed by same letter (s) are not significantly different ($P < 0.05$) according to LSD test.
Values suffixing ± denote standard error.

Soil quality of forest ecosystems: Highest pH was observed in mixed broad leaved forest at 40-100 cm soil depth (8.02) and minimum in oak-pine forest (5.84) in humus layer of natural forest (Fig. 1a). In general, the values of the soil pH increased with increasing soil depth in both natural and plantation forest ecosystems (Fig. 2a). In natural forest, maximum bulk density was found in humus layer of grassland (1.00 g cm^{-3}), and minimum (0.71 g cm^{-3}) in *A. catechu* forest (Fig. 1b). However, in humus layer of plantation, bulk density was maximum in *A. nitida* (1.12 gcm^{-3}) and minimum in *P. roxburghii* (0.86 g cm^{-3}) (Fig. 2b). In natural forest, maximum available nitrogen was in mixed broad leaved forest (638.6 Kg ha^{-1}) and minimum (611.7 Kg ha^{-1}) in grassland (Fig. 1c). In plantation, *A. catechu* had maximum available nitrogen (621.28 ± 36.03 Kg ha^{-1}) in humus layer and minimum in *A. nitida* (602.92 Kg ha^{-1}) (Fig. 2c). In soil, maximum available N (575.28 Kg ha $^{-1}$) was found in mixed broad leaved forest and minimum in surface soil of grassland (528.26 Kg ha $^{-1}$).

Trees being perennial in nature, a large quantity of litterfalls and fine - roots are likely to influence physico-chemical properties of soils in long-term as they enrich the soil with organic matter and nutrients by rapid turnover, intercept blocked nutrients and recycle them in the surface. The different trends of soil enrichment may be due to differences in species-site interaction, quantum of litter produced, its decomposition and mineralization. Bulk density was slightly higher in plantations as compared to natural forest because of lower soil organic carbon in plantation than that of natural forest. Soil organic carbon decreased with increase in soil depth in various forest types. Higher organic carbon accumulation in surface soil could be attributed to higher amount of litter accumulation on surface.

Conclusion

In natural forest maximum and minimum biomass and carbon sequestration was recorded in *P. roxburghii* and grasslands, respectively. In natural forest, detritus carbon sequestration was minimum in grassland and maximum in mixed broad leaved forest. Soil carbon sequestration was minimum in grassland and maximum in natural forest of *A. catechu* in natural forest, whereas in plantation it was minimum in *P. roxburghii* and maximum in *A. nitida* plantation. Thus, large scale plantations of *P. roxburghii* is recommended for sequestering carbon in both long term and short term in Indian sub-Himalayas. Such assessment of vegetation and soil carbon inventory in natural and planted forest ecosystem can play a key role in mitigating the atmospheric CO_2 and can also be used by researchers, policy makers and planners for getting carbon credit under Clean Development Mechanism (CDM).

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