Above- and below-ground biomass production in *Pinus roxburghii* forests along altitudes in Garhwal Himalaya, India

Munesh Kumar[1,*], Rahul Kumar[1], Bobbymoore Konsam[1], Mehraj A. Sheikh[1] and Rajiv Pandey[2]

[1]Department of Forestry, HNB Garhwal University, Srinagar-Garhwal 249 161, India
[2]Department of Informatics, Forest Research Institute, Dehradun 248 003, India

Chir pine (*Pinus roxburghii* Sargent) stands were selected across their distributional range from Himalaya, i.e. from lower altitude to upper altitude to understand distribution of chir tree density, basal cover and biomass with altitudes. Tree density was highest >1800 m (405 ind ha^{-1}) and lowest (171.67 ind ha^{-1}) between 1401 and 1800 m. Tree height was highest (23.69 m) between 1001 and 1400 m and lowest (17.71 m) >1800 m. Basal area was highest (30.51 m^2 ha^{-1}) between 1001 and 1400 m and lowest (17.16 m^2 ha^{-1}) between 1401 and 1800 m. The highest volume was observed between 1001 and 1400 m altitude and lowest between 1401 and 1800 m. Bole biomass was highest (145.51 t ha^{-1}) between 1001 and 1400 m and lowest (80.78 t ha^{-1}) between 1401 and 1800 m. The mean leaf litter biomass production was highest in summer and showed decreasing trend in winter to rainy seasons, except in Rudraprayag where the highest biomass was observed in summer and regressed from rainy to winter seasons. The study concluded that, the density, height, basal area and volume of *Pinus roxburgii* trees varied with altitude in the Himalaya, but it is not directional. Density of trees plays an important role which changes biomass accordingly. Litter production had inverse relation with altitude, however increase in biomass of litter at >1801 m was observed due to new plantations.

Keywords: Carbon, conifers, greenhouse gas, pure forest, REDD$^+$.

HUMAN beings are responsible for increasing the atmospheric carbon dioxide concentration through various anthropogenic activities such as land-use, land-use change and forest burning leading to emission and resulting in climate change[1]. Carbon emissions have to be curbed by at least 49% of 2017 levels by 2030 through major reductions in greenhouse gas (GHG) emissions, to limit the global warming to 1.5°C above pre-industrial levels, according to the Intergovernmental Panel on Climate Change (IPCC)[2]. Enhancing plantation forest lands for increasing global carbon sequestration is an effective mitigation measure for elevated concentration of atmospheric carbon[3,4]. Forest trees, herbaceous tissues and woody forest products are natural storehouses of carbon[5] and act as an agent for carbon removal from the atmosphere[6].

The earth's carbon balance includes the critical role of world's forests, which are spread around 30.6% of global land area, and store 296 Gt carbon in both above- and below-ground biomass, about three-quarters as much carbon as in the whole atmosphere[7]. Large amount of organic matter of trees in the form of tree litter mixes with soil on earth and after decomposition by microbes releases nutrients and forms stable soil organic matter[8]. Moreover, forest growth and development capture the atmospheric carbon and store it in wood, leaves and soil. Young growing forests sequester relatively higher carbon due to the plant growth that compared to old forests capture less carbon but sequester over time; on the contrary, old forests continue to hold large carbon with conserving biomass[9,10]. The carbon in the different components of forests remains stored in the forest ecosystem till forests are burned[11].

Carbon stock stored in the forests of India is a net sink of CO_2 and is capable of removing of GHGs[6]. The contribution of forests of Indian Himalayan region is significant as the region contains major forest type groups of India's forests. Forests of the Himalayan region are dominated by *Pinus roxburghii* and *Quercus leucotrichophora*, with many associated species. Both *Q. leucotrichophora* and *P. roxburghii* are evergreen[12]. In India, chir pine covers 869,000 ha area and spreads in Jammu and Kashmir, Haryana, Himachal Pradesh, Uttar Pradesh, Sikkim, West Bengal and Arunachal Pradesh state ranging from 450 to 2300 m amsl (ref. 13). Lower Himalayan region of Himalaya consists of chir pine forest[14] which provides various ecosystem services to the millions of people of the Himalayan basin[13]. Chir pine is distributed in large scale but common in the north-south oriented outer valleys of the Himalaya and its foothills and forms pure patches on dry and fire-prone slopes[15], and shows positive increment of carbon capturing between 1995 and 2005 (ref. 16). Chir pine is extensively used for afforestation programmes

*For correspondence. (e-mail: muneshmzu@yahoo.com)

Table 1. Study sites in *Pinus roxburghii* forests of Garhwal Himalaya, India

Altitude (m)	Location	Aspect	Latitude (N)	Longitude (E)	District
<1000	Khola	Southern	30°12′47.628″	78°48′2.088″	Pauri Garhwal
	Rudraprayag	Western	30°16′31.188″	78°59′4.812″	Rudraprayag
	Khedakhal	Southern	30°13′37.632″	78°53′3.372″	Pauri Garhwal
1001–1400	Kandikhal	Southern	30°20′50.316″	78°37′3.684″	Tehri Garhwal
	Mayali	Northern	30°22′23.7″	78°54′7.884″	Rudraprayag
	Badiyargarh	Northern	30°16′14.196″	78°50′52.188″	Tehri Garhwal
	Daddi	Northern	30°16′36.588″	78°50′23.1″	Tehri Garhwal
1401–1800	Pokhal	Southern	30°21′55.296″	78°36′51.588″	Tehri Garhwal
	Agrora	Western	30°40′.912″	78°47′26.124″	Pauri Garhwal
	Lansedown	Southern	29°50′43.584″	78°41′11.616″	Pauri Garhwal
	Gumkhal	Western	29°52′48.792″	78°40′9.696″	Pauri Garhwal
>1801	Ranichauri	Southern	30°18′56.268″	78°24′24.192″	Tehri Garhwal
	Dandachilli	Southern	30°18′0.972″	30°18′0.972″	Tehri Garhwal
	New Tehri	Southern	30°21′56.196″	78°25′47.316″	Tehri Garhwal

in sub-tropical Himalayan and Shiwalik regions[17], even in Nepal, chir pine is a major commercial species for plantation[17,18]. It is also most appropriate for GHG emission reduction and livelihood promotion projects for maximum utilization of carbon market[17].

Uttarakhand is among the most forested states of India with more than 45% forest cover[19], with chir pine forests as the major forest type. Chir pine is a principal species of Himalayan sub-tropical forests, having the 3rd highest contribution in growing stock after sal and teak forests and ranks 6th for trees outside forest growing stocks[19]. Chir pine forests have huge potential for storing carbon in both biomass and forest soils[20]. Earlier studies had confronting views about the biomass accumulation and carbon sequestration by chir trees under the changing environment with changing altitude. Chir pine provides many ecosystem services to the local people and their wide distribution in Garhwal Himalaya, could be suitable for carbon projects, specially REDD$^+$. However, a comprehensive account of the patterns on accumulation of biomass by chir has not been reported succinctly across altitudes in Garhwal Himalaya, therefore restricting the boarder understanding of the role of chir for climate mitigative options. This void has been attempted in this article by undertaking the hypothesis that biomass and litter production of chir pine differ across altitudes. The hypothesis has been evaluated by estimating the above-ground biomass (AGB) and below-ground biomass (BGB) and litter biomass of chir pine forests along different altitudes in Garhwal Himalaya.

Material and methods

Location and study area

Uttarakhand is situated in the northern part of India spread across an area of 53,483 km^2 with 46% of forested area[19] and lies between 28°43′N and 31°28′N and 77°34′E and 81°03′E. Uttarakhand has a temperate climate in the hills and tropical climate in the plain areas[21].

The present study was carried out in chir pine forests of Garhwal Himalaya. The chir pine stands were selected at random across the altitudinal range, i.e. from the lower altitude to upper altitude to cover all growing regions of chir pine forests in the state. In the preliminary survey, it was observed that the chir pine generally grows between 800 and 2200 m. Based on species growth pattern, four different altitudinal ranges, i.e. <1000 m, 1001–1400 m, 1401–1800 m and >1801 m amsl with a total of fourteen stands in three districts (viz. Pauri, Rudraprayag and Tehri) of Uttarakhand were considered for the study to understand the dynamic changes in the biomass production and carbon stock in the chir forests. Table 1 and Figure 1 provide details of the study sites. Mostly, study areas are part of the reserve forest; chir pine is generally not harvested without prior permission of the Forest Department but sometimes anthropogenic disturbances were observed in the stands. However, small branches at lower parts of the chir trees are lopped illegally by the villagers of the area for various uses.

Sampling

Sampling for estimation of AGB and BGB of trees and litter was done following the methods of Hairiah *et al.*[22]. Three plots were laid in each stand for sampling; a sample plot of size (20 m × 100 m = 2000 m^2) was laid for trees (>30 cm diameter), and sub-plots (5 m × 40 m = 200 m^2) for smaller trees (stem diameter 5–30 cm) and within these six smaller sub-plots of 0.5 m^2 size were laid randomly for collecting litter. Thus from each stand 18 samples of litter were collected for further analysis.

Estimation of standing biomass

Above-ground biomass: Tree diameter at breast height (dbh) was measured using a caliper and height with

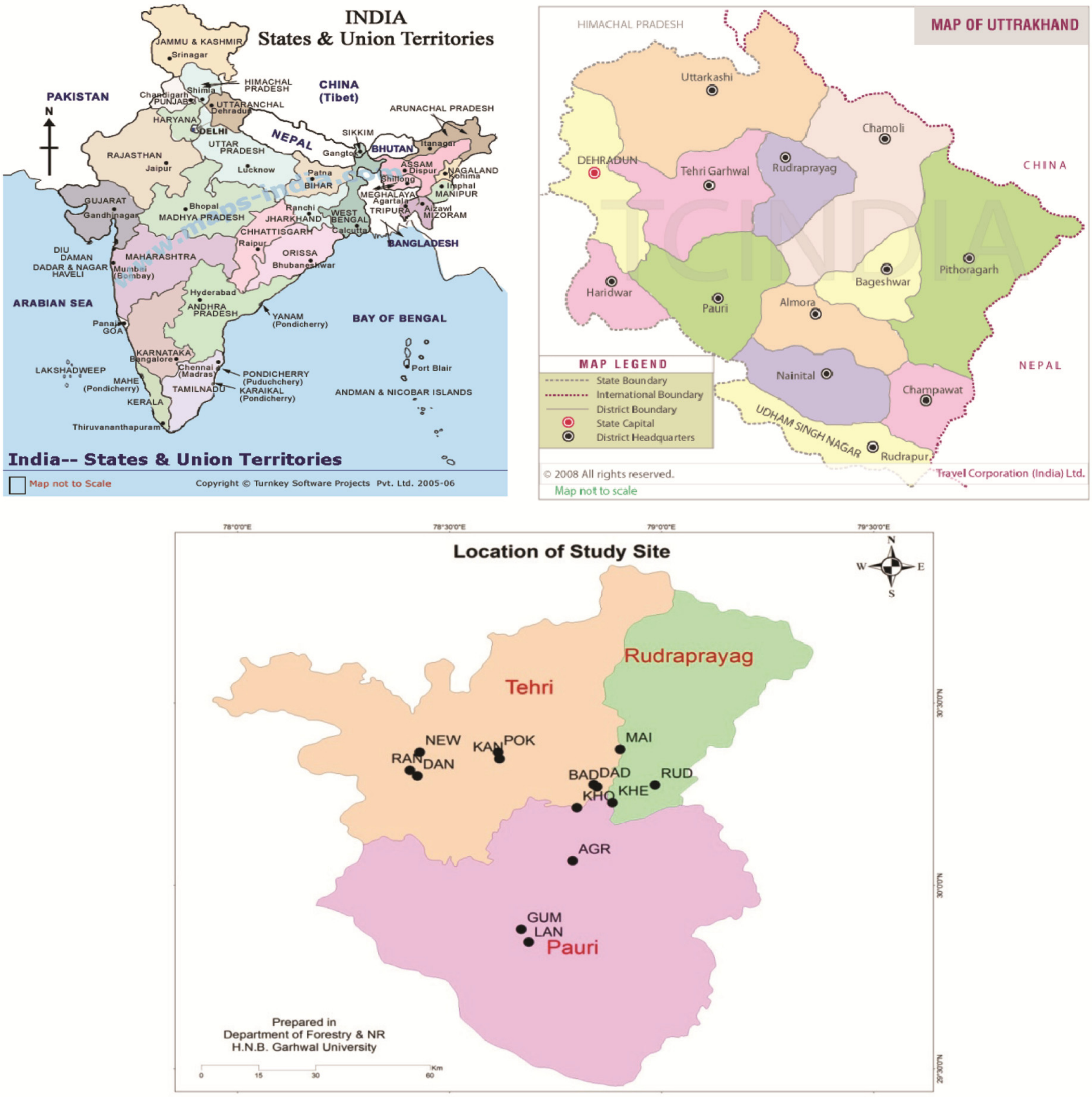

Figure 1. Location map of the study sites. AGR, Agrora; BAD, Badiyargarh; DAD, Daddi; DAN, Dandichilli; GUM, Gumkhal; KAN, Kandikhal; KHE, Kherakhal; KHO, Khola; LAN, Lansedown; MAI, Mayali; NEW, New Tehri; POK, Pokhal; RAN, Ranichauri.

Ravi's multimeter. Form factor was calculated using Spiegel relaskope to measure tree volume[23,24]. $F = 2h_1/3h$, where F is the form factor, h_1 the height at which diameter is half of dbh and h is the total height. Tree volume (V) was calculated using the Pressler[23] formula according to Koul and Panwar[25] as: $V = F \times h \times g$, where g is the basal area calculated, i.e. πr^2, where r is the radius. Biomass of wood was estimated by Biomass = specific gravity × volume. Specific gravity was estimated by taking the stem cores using the maximum moisture method[25].

Branch biomass: The total number of branches (irrespective of size) of each tree was counted, and categorized based on basal diameter, i.e. viz. <6, 6–10 and >10 cm. Fresh weight of two branches from each size category was recorded separately. Dry weight of branches was estimated using the following equation[26]: $B_{\mathrm{dwi}} = B_{\mathrm{fwi}}/(1 + M_{\mathrm{edbi}})$, where B_{dwi} is the dry weight of branches, B_{fwi} the fresh/green weight of branches and M_{edbi} is the moisture content of branches on dry weight. Total branch biomass (fresh/dry) per sample basis was determined as follows

$$B_{\mathrm{bt}} = n_1 bw_1 + n_2 bw_2 + n_3 bw_3 = \sum_{i=1}^{n} n_i bw_i,$$

Table 2. Mean of density, diameter, height and basal area of *P. roxburghii* forests in Garhwal Himalaya

Elevation (m)	Site	Density (individual ha^{-1})	Mean diameter (cm)	Mean height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
<1000	Khola	211.67 ± 32.53	31.25 ± 4.04	22.33 ± 2.06	18.82 ± 1.28	214.41 ± 20.99
	Rudraprayag	191.67 ± 68.07	33.32 ± 5.16	20.61 ± 1.33	24.66 ± 14.96	228.30 ± 145.36
	Khedakhal	190.00 ± 26.46	36.31 ± 9.25	20.31 ± 6.65	20.36 ± 9.64	202.93 ± 167.50
1001–1400	Kandikhal	148.33 ± 20.82	56.16 ± 5.45	24.99 ± 1.33	41.36 ± 7.94	407.07 ± 88.15
	Mayali	270.00 ± 61.44	38.04 ± 9.42	24.21 ± 4.72	32.68 ± 8.56	299.88 ± 104.17
	Badiyargarh	258.33 ± 59.65	37.13 ± 0.59	23.32 ± 0.58	29.66 ± 7.88	291.18 ± 93.80
	Daddi	135.00 ± 5.00	38.34 ± 10.59	22.25 ± 2.35	18.33 ± 8.87	187.37 ± 86.11
1401–1800	Pokhal	168.33 ± 27.54	38.52 ± 6.17	23.96 ± 0.38	21.90 ± 7.78	215.89 ± 73.49
	Agrora	195.00 ± 26.46	31.33 ± 3.45	25.29 ± 3.41	16.24 ± 4.95	150.41 ± 45.78
	Lansedown	138.33 ± 33.29	39.02 ± 2.08	23.81 ± 0.95	19.36 ± 6.08	198.07 ± 62.13
	Gumkhal	185.00 ± 15.00	26.19 ± 5.58	20.23 ± 5.00	11.12 ± 3.13	93.98 ± 35.43
>1801	Ranichauri	441.67 ± 40.10	31.60 ± 2.76	19.86 ± 2.79	29.23 ± 5.26	238.51 ± 64.44
	Dandachilli	198.33 ± 52.04	37.23 ± 8.34	20.60 ± 4.78	24.29 ± 1.06	215.57 ± 28.38
	New Tehri	575.00 ± 90.14	19.00 ± 1.63	12.67 ± 2.29	17.72 ± 3.58	96.36 ± 37.65

where B_{bt} is the branch biomass (fresh/green) per tree, n_i the no. of branches in the ith branch group and $i = 1, 2, 3…$ is the branch group[25].

Leaf biomass: Leaves of five branches from each tree were collected randomly. The collected leaves were weighed and oven-dried separately to a constant weight at 80 ± 5°C. The average leaf biomass was estimated by multiplying the average biomass of the leaves per branch with the number of branches in a single tree and then the number of trees in a quadrate[25,26].

Estimation of BGB

The root biomass was calculated using non-destructive method to find root–shoot ratio according to IPCC guidelines. To arrive at the amount of carbon stock stored in stands, biomass of *P. roxburghii* was multiplied with a factor of 0.45 (ref. 27).

Litter biomass: Litter was collected seasonally, i.e. summer (March–June), rainy (July–October) and winter (November–February) and total dry weight was estimated using the equation[22]

$$\text{Total dry weight (kg m}^{-2}) = \frac{\text{(Total fresh weight (kg)} \times \text{Sub-sample dry weight (g))}}{\text{(Sub-sample fresh weight (g)} \times \text{Sample area (m}^2))}.$$

Results

Stand structure

Density, diameter, height, basal area and volume of chir pine forests were observed and estimated across the study stands. The maximum tree density (575.00 ± 90.14 ind ha^{-1}) was recorded in New Tehri (>1801 m) and minimum density (135.00 ± 5.00 ind ha^{-1}) in Daddi (1001–1400 m) (Table 2). The maximum (25.29 ± 3.41 m) and minimum (12.67 ± 2.29 m) tree height was recorded in Agrora and New Tehri respectively (Table 2). The maximum and minimum mean diameter of trees was recorded in Kandikhal (56.16 ± 5.45 cm) and New Tehri (19.00 ± 1.63 cm). The basal area and volume of bole was observed with a maximum of 41.36 ± 7.94 m^2 ha^{-1} and 407.07 ± 88.15 m^3 ha^{-1} respectively, and minimum of 11.12 ± 3.13 m^2 ha^{-1} and 93.98 ± 35.43 m^3 ha^{-1} respectively in Kandikhal and Gumkhal (Table 2).

Above-ground biomass (bole, branch and foliage)

Table 3 gives the total AGB and its allocation to different tree components, i.e. bole, branch and foliage of all the studied sites. Total AGB was highest (213.33 ± 40.79 t ha^{-1}) in Kandikhal with biomass of 199.85 ± 43.26, 11.48 ± 2.32 and 1.99 ± 0.30 t ha^{-1} for bole, branch and foliage respectively, followed by Mayali (185.79 ± 51.82 t ha^{-1}) with 147.22 ± 51.15, 32.95 ± 1.65 and 5.63 ± 0.75 t ha^{-1} for bole, branch and foliage respectively, with both at the altitude between 1001 and 1400 m. The lowest AGB was observed in Gumkhal (59.30 ± 21.07 t ha^{-1}) with biomass of 46.03 ± 17.41, 10.00 ± 3.50 and 3.26 ± 0.25 t ha^{-1} for bole, branch and foliage respectively, between altitudes of 1401 and 1800 m (Table 3). Significance analysis results show that bole, branch foliage and total AGB allocation between different altitudes were not significant at $P < 0.05$ level. Thus there is no significant effect of altitude on all described parameters of AGB. AGB allocation in different components such as bole between 1001 and 1400 m (Table 3) was significant ($P < 0.05$) from the stored biomass at other altitudes whereas branch and foliage were significant ($P < 0.05$) at other altitudes >1801 m.

Table 3. Above-ground biomass allocation in different components (bole, branch and foliage) of *P. roxburghii* forests in Garhwal Himalaya

		Biomass allocation (t ha^{-1})			
Elevation (m)	Site	Bole	Branch	Foliage	Total
<1000	Khola	105.27 ± 10.30	15.08 ± 3.93	4.98 ± 0.96	125.33 ± 11.56
	Rudraprayag	112.07 ± 71.36	17.23 ± 8.79	8.83 ± 3.53	138.13 ± 83.42
	Khedakhal	99.60 ± 82.23	18.07 ± 2.92	3.97 ± 0.32	121.64 ± 85.08
	Mean	105.65	16.79	5.93	128.37
1001–1400	Kandikhal	199.85 ± 43.26	11.48 ± 2.32	1.99 ± 0.30	213.33 ± 40.79
	Mayali	147.22 ± 51.15	32.95 ± 1.65	5.63 ± 0.75	185.79 ± 51.82
	Badiyargarh	142.90 ± 46.07	20.33 ± 6.33	9.60 ± 2.28	172.83 ± 54.68
	Daddi	92.05 ± 42.32	10.22 ± 3.53	3.32 ± 0.71	105.58 ± 45.15
	Mean	145.51	18.75	5.14	169.38
1401–1800	Pokhal	106.00 ± 36.04	13.62 ± 1.41	10.55 ± 0.84	130.16 ± 38.26
	Agrora	73.83 ± 22.47	6.87 ± 2.43	4.33 ± 0.67	85.03 ± 24.85
	Lansedown	97.27 ± 30.47	14.67 ± 3.21	4.47 ± 0.65	116.40 ± 34.25
	Gumkhal	46.03 ± 17.41	10.00 ± 3.50	3.26 ± 0.25	59.30 ± 21.07
	Mean	80.78	11.29	5.65	97.72
>1801	Ranichauri	117.10 ± 31.64	50.53 ± 5.40	14.61 ± 0.61	182.24 ± 37.30
	Dandachilli	105.87 ± 13.99	23.33 ± 12.21	3.39 ± 0.46	132.59 ± 9.33
	New Tehri	47.31 ± 18.49	10.38 ± 2.97	30.90 ± 3.19	88.59 ± 23.69
	Mean	90.09	28.08	16.30	134.47
Mean		106.60 ± 39.63	18.20 ± 11.45	7.85 ± 7.53	132.64 ± 43.15
F (3,10)		2.925	1.35	1.977	2.487
$P < 0.05$		0.086 (NS)	0.313 (NS)	0.181 (NS)	0.120 (NS)

Below-ground biomass

The BGB values for all the altitude are reported in Table 4. The BGB showed similar trend as that of AGB. The BGB was highest in Kandikhal (63.51 ± 10.69 t ha^{-1}), followed by Mayali (56.12 ± 13.95 t ha^{-1}) both between the altitudes 1001 and 1400 m (Table 4). The third highest BGB was observed in Ranichauri (55.24 ± 10.01 t ha^{-1}) of altitude >1801 m (Table 4). However, the lowest BGB was observed in Gumkhal (9.19 ± 2.87 t ha^{-1}) between altitudes 1401 and 1800 m (Table 4). Results of one-way ANOVA indicate that total AGB and BGB under different altitudes were not significant ($P < 0.05$). Total biomass between 1001 and 1400 m and >1801 m altitudes (Table 4) was significant ($P < 0.05$) from the stored biomass at other altitudes.

Seasonal litter biomass

Annual average litter production (t ha^{-1}) was estimated based on the observations of different seasons, i.e. summer, rainy and winter. The highest litter production was observed in summer for all the studied sites (Table 5). The litter production further decreased in the rainy season and again increased in the winter, except in Rudraprayag where it decreased with change in season. In summer the highest (0.0018 ± 0.0026 t ha^{-1}) litter production was in Ranichauri (>1801 m); in the rainy season in Khola (0.0035 ± 0.0009 t ha^{-1}; <1000 m) and in winter season in Khairakhal (0.0059 ± 0.0030 t ha^{-1}; <1000 m). However, the lowest values of litter production in summer, rainy and winter seasons were reported in Gumkhal (0.0018 ± 0.0026 t ha^{-1}) between 1401 and 1800 m, Dandichilli (0.0009 ± 0.0002 t ha^{-1}; >1801) and Gumkhal (0.0017 ± 0.0012 t ha^{-1}) between 1401 and 1800 m respectively. Average seasonal (summer, rainy and winter) pattern of litter production (biomass) of *P. roxburghii* forests in Garhwal Himalaya was not significantly ($P < 0.05$) different under various altitudes (Table 5).

Discussion

Various components of forest ecosystems need to be better parameterized, quantified and interrelated for precise estimation of forest carbon pools[28]. The aim of this study was to estimate standing biomass (AGB and BGB) and seasonal litter production biomass of *P. roxburghii* forests in Garhwal Himalaya to test the change dynamics of these parameters across the habitational range focusing on altitude of the chir trees. In the preliminary survey, it was observed that majority of the *P. roxburghii* forests occurs between 1000 and 2000 m, therefore, four different altitudinal ranges, i.e. <1000, 1001–1400, 1401–1800 and >1801 m were classified to understand actual differences in results with altitudes.

Chir pine forests in the present study were located at different aspects in the Garhwal Himalaya. Generally, forests of the southern aspects face harsher conditions than the forests of the northern aspects. They are more prone to natural disturbances such as windfall, wild fire,

Table 4. Aboveground biomass (AGB), belowground biomass (BGB) and total biomass (TB) (t ha^{-1}) of *P. roxburghii* forests in Garhwal Himalaya

Elevation (m)	Site	AGB (t ha^{-1})	BGB (t ha^{-1})	TB (t ha^{-1})
<1000	Khola	125.33 ± 11.56	39.73 ± 3.23	165.06 ± 14.79
	Rudraprayag	138.13 ± 83.42	42.74 ± 23.19	180.87 ± 106.61
	Khedakhal	121.64 ± 85.08	38.10 ± 23.56	159.74 ± 108.64
	Mean	128.37	40.19	168.56
1001–1400	Kandikhal	213.33 ± 40.79	63.51 ± 10.69	276.84 ± 51.48
	Mayali	185.79 ± 51.82	56.12 ± 13.95	241.91 ± 65.77
	Badiyargarh	172.83 ± 54.68	52.62 ± 14.65	225.45 ± 69.33
	Daddi	105.58 ± 45.15	33.90 ± 13.15	139.49 ± 58.30
	Mean	169.38	51.54	220.92
1401–1800	Pokhal	130.16 ± 38.26	40.96 ± 10.71	171.13 ± 48.97
	Agrora	85.03 ± 24.85	28.11 ± 7.35	113.15 ± 32.20
	Lansedown	116.40 ± 34.25	37.10 ± 9.79	153.51 ± 44.04
	Gumkhal	59.30 ± 21.07	20.42 ± 6.38	79.72 ± 27.45
	Mean	97.72	31.65	129.38
>1801	Ranichauri	182.24 ± 37.30	55.24 ± 10.01	237.48 ± 47.31
	Dandachilli	132.59 ± 9.33	41.76 ± 2.60	174.35 ± 11.94
	New Tehri	88.59 ± 23.69	29.17 ± 6.87	117.77 ± 30.56
	Mean	134.47	42.06	176.53
Mean		132.64 ± 43.15	41.39 ± 12.03	174.03 ± 55.17
F (3,10)		2.487	2.454	2.480
$P < 0.05$		0.120 (NS)	0.123 (NS)	0.121 (NS)

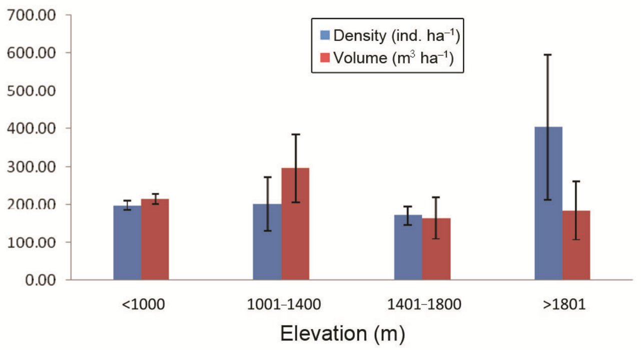

Figure 2. Altitudinal variation in density (ind ha^{-1}) and volume (m^3 ha^{-1}) of *Pinus roxburghii* forests in Garhwal Himalaya, India.

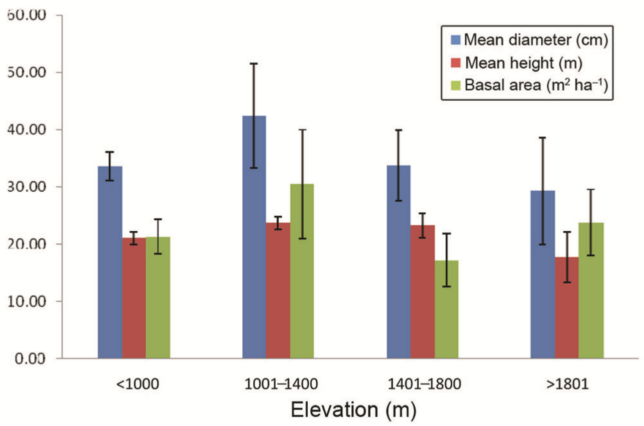

Figure 3. Altitudinal variation in mean diameter (cm), mean height (m) and basal area (m^2 ha^{-1}) of *P. roxburghii* forests in Garhwal Himalaya.

because of high inflammability of pine wood, higher temperature of the area and low amount of moisture content. Higher temperature facilitates faster rate of leaf and wood litter production on forest floor[29]. In summer season, fire causes rapid degradation of forest soil fertility; it further reduces survival and invasion of new species. After a fire, in some soils, it has been observed that there is a sharp decrease in organic matter content due to the change in soil physico-chemical properties, e.g. water repellency[30]. However, soil organic matter content also increases due to deposition of dry leaves and charred plant materials[31]. It has also been suggested that moderate level of fire increases carbon in the soil by incorporation of forest necromass[32]. However, sharp reduction in organic carbon in forest has also been observed after a wildfire[31].

Forest structure

Tree density was highest (405 ind ha^{-1}) at >1801 m and lowest (171.67 ind ha^{-1}) between 1401 and 1800 m (Figure 2). However, mean tree density was 244.34 (ind ha^{-1}), which is less than that reported for similar forests (i.e. 275 ind ha^{-1})[33]. According to Gairola *et al.*[34], tree density and its basal area decreased with increase in elevation but no such trend was found in the present study. This study observed the disagreement with the hypothesis that the trend of biomass and litter production of trees decreases with altitude, as per empirical data. However, reported biomass was tree density-dependent. As density changes (increase or decrease), biomass also

Table 5. Average seasonal (summer, rainy and winter) pattern of litter production (biomass) (t ha^{-1}) of *P. roxburghii* forests in Garhwal Himalaya, India

		Season			
Elevation (m)	Site	Summer (t ha^{-1})	Rainy (t ha^{-1})	Winter (t ha^{-1})	Total (t ha^{-1})
<1000	Khola	0.0103 ± 0.0046	0.0035 ± 0.0009	0.0054 ± 0.0022	0.0193 ± 0.0035
	Rudraprayag	0.0040 ± 0.0027	0.0034 ± 0.0031	0.0031 ± 0.0009	0.0105 ± 0.0004
	Khairakhal	0.0069 ± 0.0062	0.0018 ± 0.0004	0.0059 ± 0.0030	0.0146 ± 0.0027
	Mean	0.0071	0.0029	0.0048	0.0148
1001–1400	Kandikhal	0.0064 ± 0.0022	0.0012 ± 0.0002	0.0028 ± 0.0017	0.0104 ± 0.0026
	Mayali	0.0043 ± 0.0031	0.0021 ± 0.0008	0.0040 ± 0.0015	0.0104 ± 0.0012
	Badiyargarh	0.0065 ± 0.0021	0.0021 ± 0.0011	0.0052 ± 0.0024	0.0138 ± 0.0022
	Daddi	0.0061 ± 0.0037	0.0019 ± 0.0010	0.0051 ± 0.0029	0.0131 ± 0.0022
	Mean	0.0058	0.0018	0.0043	0.0119
1401–1800	Pokhal	0.0065 ± 0.0053	0.0016 ± 0.0007	0.0044 ± 0.0024	0.0125 ± 0.0024
	Agrora	0.0037 ± 0.0013	0.0028 ± 0.0014	0.0033 ± 0.0021	0.0097 ± 0.0005
	Lansedown	0.0028 ± 0.0019	0.0011 ± 0.0009	0.0024 ± 0.0012	0.0064 ± 0.009
	Gumkhal	0.0018 ± 0.0026	0.0010 ± 0.0003	0.0017 ± 0.0012	0.0044 ± 0.0004
	Mean	0.0037	0.0016	0.0030	0.0083
>1801	Ranichauri	0.0135 ± 0.0118	0.0020 ± 0.0007	0.0060 ± 0.0040	0.0215 ± 0.0058
	Dandichilli	0.0047 ± 0.0022	0.0009 ± 0.0002	0.0040 ± 0.0042	0.0096 ± 0.0020
	New Tehri	0.0059 ± 0.0026	0.0011 ± 0.0004	0.0045 ± 0.0012	0.0114 ± 0.0025
	Mean	0.0080	0.0013	0.0048	0.0142
Mean		0.0060 ± 0.0030	0.0019 ± 0.0009	0.0041 ± 0.0013	0.0120 ± 0.0045
F (3,10)		1.528	2.801	1.950	1.851
P < 0.05		0.267 (NS)	0.095 (NS)	0.186 (NS)	0.202 (NS)

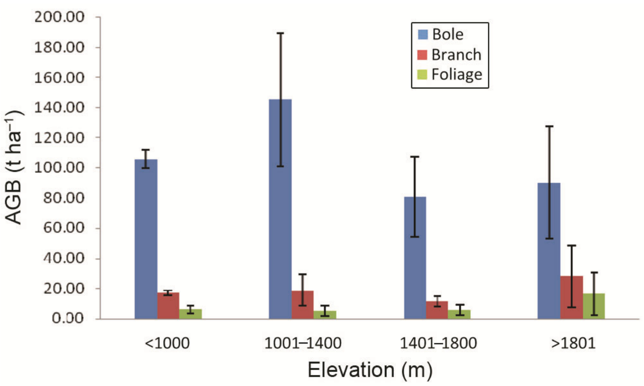

Figure 4. Altitudinal variation in aboveground biomass (bole, branch and foliage) in t ha^{-1} of *P. roxburghii* forests in Garhwal Himalaya.

changes accordingly and subsequently changes in litter production also occurred. In a general trend in our study, tree density reported <1000 (197.78 ind ha^{-1}) which reduced with increasing altitude; it reported 187.27 ind ha^{-1} (1001–1400, 1401–1800 average density of both altitude) and suddenly increased above >1800 m (405 ind ha^{-1}). The main reason of higher tree density at >1801 m is due to the chir pine plantations in the altitudinal sites. Thus the hypothesis of addressing biomass reduction with altitude was not supported. This may be due to the presence of scattered and old pine trees in lower altitudes and new plantation of chir pine at >1801 m, which was instrumental for increased density at the site. The volume was highest at altitude between 1001 and 1400 m and lowest between 1401 and 1800 m, with mean values of 296.38 and 164.59 m^3 ha^{-1} and average mean value of 214.88 m^3 ha^{-1} for all the sites (Figure 2). Mean diameter was highest (42.42 cm) between 1001 and 1400 m and lowest (29.28 cm) at >1801 m, with average mean diameter of 34.77 cm for all the sites (Figure 3). Similarly, tree height was highest (23.69 m) between 1001 and 1400 m and lowest (17.71 m) at >1801 m, with average mean height of 21.45 m for all the sites (Figure 3). Comparing findings[33], the mean diameter observed in the study was less, whereas mean tree height was more. The highest and lowest values of basal area were at altitudes between 1001 and 1400 m and 1401 and 1800 m with the values of 30.51 and 17.16 m^2 ha^{-1} respectively, with average mean value of 23.17 m^2 ha^{-1} for all the sites (Figure 3).

Standing biomass

Bole biomass was highest between 1001 and 1400 m and lowest between 1401 and 1800 m with mean values of 145.51 and 80.78 t ha^{-1} respectively, with average mean value of 105.51 t ha^{-1} (Figure 4). Branch biomass was highest at >1801 m with 28.08 t ha^{-1} and lowest between 1401 and 1800 m with 11.29 t ha^{-1} and average mean value of all the sites was 18.73 t ha^{-1} (Figure 4). Thus, results of component-wise biomass accumulation of living trees were in accordance with the fact that the largest portion of AGB was in the bole (79.64%) followed by branch (14.13%) and foliage (6.22%) (Figure 4).

The mean AGB was highest between 1001 and 1400 m and lowest between 1401 and 1800 m with values of

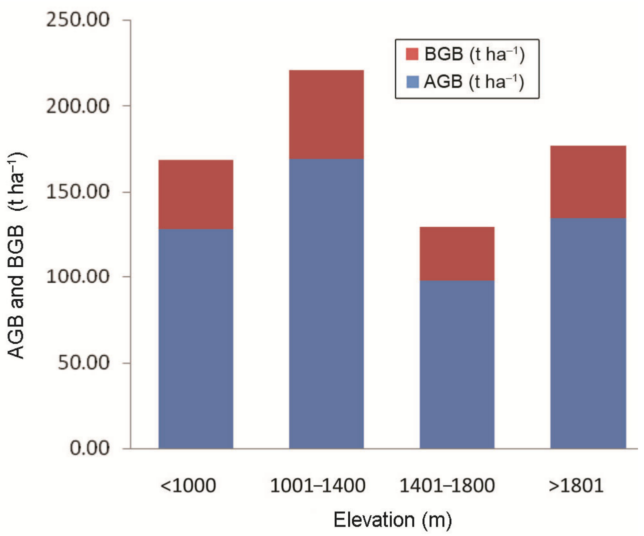

Figure 5. Altitudinal variation in aboveground biomass (AGB) and belowground biomass (BGB) in t ha^{-1} of *P. roxburghii* forests in Garhwal Himalaya.

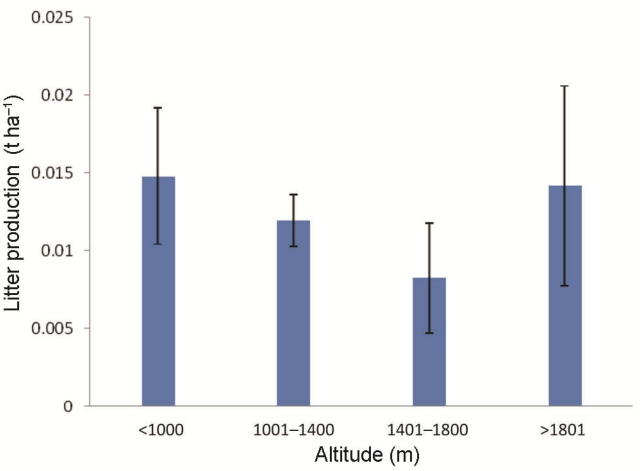

Figure 6. Annual altitudinal variation in leaf litter biomass production (t ha^{-1}) of *P. roxburghii* forests in Garhwal Himalaya.

169.38 and 97.72 t ha^{-1} respectively, with average mean value of 132.48 t ha^{-1} for all the studied sites (Figure 5). Similarly, BGB was highest between 1001 and 1400 m and lowest between 1401 and 1800 m with values of 51.54 and 31.65 t ha^{-1} respectively, with average mean value of 41.36 t ha^{-1} for all the studied sites (Figure 5). The mean AGB value was much higher than the value (69.50 t ha^{-1}) reported by Haripriya[35] for *P. roxburghii* forests of India but much lower than the values of 173.39 t ha^{-1} reported by Sheikh *et al.*[33], and 183.05 t ha^{-1} by Gairola *et al.*[36] for Pauri Garhwal. The difference in mean values may be attributed to differences in methodological approaches and in the number of sites used for data collection. The estimated mean value of BGB was 41.36 t ha^{-1} (23.79%) which was almost similar to 43.91 t ha^{-1} reported by Haripriya[35]. The mean TBD was around 173.84 t ha^{-1} which was much less than that reported[37] for Siwalik *P. roxburghii* forests. The variation with earlier studies was probably due to methodological issues such as small sampling areas, a few altitudes, and only one aspect besides the estimation protocol. Moreover, production of leaf litter in a single season can also not provide actual information for all seasons and the full year. However, in the present study, representative sites of *P. roxburghii* were considered from lowest to highest altitude, for different aspects and for large area, and therefore the present study provides more precise information of chir pine forests.

Litter biomass (needles)

Among the seasons, litter production reduced from summer to rainy and winter. In *P. roxburghii* forest, the leaf litter to total annual litter production was reported highest during summer months[38]. The total annual leaf litter production does not follow any increasing or decreasing trend along altitude. The maximum (0.0148 t ha^{-1}) total annual leaf litter production was <1000 m and minimum (0.0083 t ha^{-1}) between 1401 and 1800 m (Figure 6). The *P. roxburghii* forests seem to deposit between 7 and 8 t ha^{-1} litter each year[38]. The total leaf litter production in the present study compared to that of Kumar and Tewari[38] was low due to consideration of the leaf litter (needles) only, whereas they included all components of litter. However, total annual leaf litter production in summer, rainy and winter seasons was 0.0246, 0.0076 and 0.0169 t ha^{-1} respectively.

Conclusion

The present study is based on the hypothesis that both the biomass and litter production are influenced by altitude. The present study does not support the hypothesis for tree biomass which decreased with increasing altitude; however, litter production supports the hypothesis, i.e. litter decreased with increasing altitude. This finding clearly signifies that in the natural habitat, the natural growth of chir trees remains similar irrespective of the altitudinal variation.

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ACKNOWLEDGEMENT. We thank the Science and Engineering Research Board-Department of Science and Technology for financial assistance for the study.

Received 30 April 2016; revised accepted 19 February 2018

doi: 10.18520/cs/v116/i9/1506-1514