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Carbon stock potential in *Pinus roxburghii* forests of Indian Himalayan regions

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Abstract

Chir pine (*Pinus roxburghii*) is the most important tree species used for afforestation programs in the Himalayan regions. In the present study, fourteen forest stands were selected in four different altitudes, i.e., < 1000, 1001–1400, 1401–1800, and > 1801 masl in Garhwal Himalayan of Uttarakhand, India, to assess carbon stock potential of the forest. The study was conducted during 2013–2015. Among the study sites, the maximum tree density (575 ± 90.14 ind. ha^{-1}) was reported in New Tehri (altitude: > 1801 masl) and minimum (135 ± 5.00 ind. ha^{-1}) in Daddi (altitude: 1001–1400 masl). The highest (96 ± 18.36 t ha^{-1}) above-ground carbon stock was estimated in Kandikhal where bole, branch, and foliage contribute 89.93 ± 19.47, 5.17 ± 1.04 and 0.90 ± 0.14 t ha^{-1}, respectively, while lowest (26.68 ± 9.48 t ha^{-1}) was in Gumkhal, and contribution from the same component was found as 20.72 ± 7.84, 4.50 ± 1.58, and 1.47 ± 0.11 t ha^{-1}, respectively. Further, highest value of below-ground carbon was in Kandikhal (28.58 ± 4.81 t ha^{-1}) with an altitude range between 1001 and 1400 masl and the lowest in Gumkhal (9.19 ± 2.87 t ha^{-1}) between 1401 and 1800 masl. Besides, litter production was found higher in the summer season followed by winter and rainy seasons. The study concluded that the density, height, basal area, and volume of *Pinus roxburgii* varied with altitude, but it was not directional. However, growth patterns and tree density were the key factors in estimating total carbon stocks and further to know the behavior of carbon dynamics (source/sink). Litter production had an inverse relation with altitude; however, increase in litter biomass at > 1801 masl was observed due to new plantations of pine. This study will be highly helpful to the forester and policy-makers in planning carbon mitigation strategies (e.g., catchment area treatment, afforestation activities) at regional and global scales.

Keywords Carbon · Chir pine · Altitudes · Himalaya · Climate change

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1 Introduction

The Indian Himalayan forests are considered large reservoirs of carbon due to thick forest vegetation and high forest cover. This Himalayan zone covers nearly 19% area and contributes 33% of soil organic carbon (SOC) reserves of the country (Bhattacharyya et al. 2008). However, the Himalayan forest eco-region is most vulnerable to climate change (Ravindranath et al. 2006 and Chaturvedi et al. 2010). Even over short periods, degradation increases the susceptibility of these areas to climate alteration. As forest degradation plays a significant role in climate change in the Himalayan region, it is essential to obtain information about this change at the outset (Pant and Tiwari 2014).

This study focuses on Chir pine (*Pinus roxburghii* Sarg.) forest. Chir pine dominates in lower Himalaya (Ghildiyal et al. 2009) and provides various ecosystem services to the people of the Himalayan catchment (Gupta et al. 2009). Chir pine covers 869,000 ha and spreads in Jammu and Kashmir, Haryana, Himachal Pradesh, Uttar Pradesh, Sikkim, West Bengal, and Arunachal Pradesh states ranging from 450 to 2300 m above sea level (masl; Gupta et al. 2009). Chir pine is a principal species of Himalayan subtropical forests and reported to be 3rd (3.97%) highest contributors in growing stock after sal (*Shorea robusta,* 11.36%) and teak (*Tectona grandis*, 5.57%) forests and further holding ranks 7th (3.04%) for trees outside forest growing stocks (FSI, 2017). Although both *Shorea robusta* and *Tectona grandis* range up to 1220 masl–1300 masl, respectively, *Pinus roxburghii* has been reported to be growing up to 2300 masl (Luna, 2005). Chir pine forests have huge potential for storing carbon in both biomass and forest soils (Jianmin and Zhing 2007; Kumar and Kumar 2020).

Uttarakhand forests can accumulate carbon ranges from 1.5 to 3.0 t C ha^{-1} yr^{-1} in poor-quality forests and to 5.0–9.0 t C ha^{-1} yr^{-1} in the good forests (Singh et al. 1985). However, because of forest degradation, the regional averages are falling between 2.5 and 3.5 t C ha^{-1} yr^{-1} (Rajeev et al. 2011). Uttarakhand is among the most forested states of India with more than 45% forest cover (FSI 2017), with Chir pine forests as the major forest type. Recently, anthropogenic activity (e.g., hydropower construction, extension of road, installation of transmission lines) resulting in extensive deforestation and fragmentation of the forests in the Garhwal Himalaya caused serious environmental degradation (Roy and Tomar 2000; Sharma and Roy 2007; Kumar and Sharma 2016, 2018; Kumar and Pandey 2017; Batar et al. 2017). According to Ministry of Environment, Forests and Climate Change (MoEFCC), in Uttarakhand, 44,868 ha of forest land has been changed into non-forest use since 1980 and around 9500 ha has been felled for construction of roads, followed by 5500 ha for hydro-projects and 3100 ha for installation of transmission lines (Batar et al. 2017).

Chir pine is planted in many areas as monoculture where Chir pine forests and plantations cover about 4018 km^2 in the western Himalaya (Seth, 1980). Chir pine in Himalaya plays a major role in carbon sequestration (Kumar and Pandey 2017; Kumar and Sharma 2017a). Out of total of 24,414.80 km^2 area under forests, Chir pine occupies 3,943.83 km^2 which is 16.15% of total forest area of the state (Kumar 2015). Chir pine is a major commercial species used for afforestation in subtropical Himalayan regions in India and Nepal (Amatya, 2002; Sharam and Verma 2011). It has also great potential for GHG emission reduction and livelihood promotion projects for maximum utilization of carbon market (Sharam and Verma 2011; Kumar et al. 2017b, 2019a).

Chir pine occupies a broader range of habitats such as sandy and loamy soils. Moreover, it needs poor nutrition to an unfertile area usually not suitable for agriculture practices and even other species occupying area. Generally, it has characteristics to grow in all categories of soil, i.e., acidic, neutral, and basic (Singh et al. 2017) and thus potential for wide adaptability in the areas and therefore large forest cover. In Uttarakhand, Chir pine has been utilized for several raw materials both commercial and traditional purposes in national and international demand. It has been reported that the tree is used for construction, fencing post, ornamental purposes, and many societal needs (Silori et al., 2013).

Chir pine grows well in the tough terrain in the Garhwal Himalaya and helps in reducing soil erosion and landslide on a steep gradient. If the Chir pine is removed, it will expose the area to different environmental dimensions, and frequent landslide may occur which will lead to devastating effect of the study area. The inflammable capacity of its litter is also promoting fire especially during the hot summer season which may further cause devastating effects in the entire forest area. It affects biodiversity and new growing seedling and creates problems for the regeneration of forest. These Chir pine forests provide favorable habitat for several medicinally important species having high value in market. Further, it has also been noticed that the smoke produced through fire has also negative impact on forest, wildlife, and many other issues of forests. However, trees have huge potential to sustain life support in these forests, providing many valuable products (small timber from lopping, big timber through harvesting, producing resin) including medicine and other purposes. Thus, instead of harmful impact, it has a beneficial impact on human as well as environmental. The clean and huge bole system of the tree compared to other trees in this location has huge carbon storing potential and provides further regional and global carbon mitigation potential. Chir pine forests have biomass ranging of 150 t ha^{-1} to 200 t ha^{-1} (Singh and Singh 1992). Much of this carbon (60% – 90%) is stored in the vegetation while the upper 30 cm of soil accounts for 10% – 40% of sequestered carbon in Chir pine forests (Pant and Tiwari, 2014). Soil organic carbon (SOC), soil organic matter (SOM), and their correlations with bulk density are frequently used to estimate carbon pools (Post et al. 1982). Therefore, keeping in view the importance of Chir pine trees and its extensive distribution along altitudes in Garhwal Himalaya, the hypothesis is developed that carbon storage potential of Chir pine forest affects with altitudes with the research questions that what is the carbon storing potential of Chir pine forest with altitudes in Garhwal Himalaya. Therefore, to understand the questions and proof the hypothesis, the following objectives have been selected for the study that; (i) to understand the carbon storing potential of Chir pine forest in Garhwal Himalaya and (ii) to understand the effect of altitudes on carbon storing potential of Chir pine forest.

2 Materials and methods

2.1 Study area

The present study was carried out in Chir pine forests of Garhwal Himalaya, Uttarakhand, and lies between 28°43′N and 31°28′N and 77°34′E and 81°03′E. In the preliminary survey, range of Chir pine was recorded between 800 and 2200 masl in Garhwal Himalaya. A total of fourteen stands were selected randomly across four different altitudinal ranges, i.e., < 1000, 1001–1400, 1401–1800, and > 1801 masl covering three districts (viz. Pauri, Rudraprayag, and Tehri) for this study to understand the dynamics in the production of carbon stocks in the Chir pine forests (Fig. 1). The study was conducted during 2013–2015,

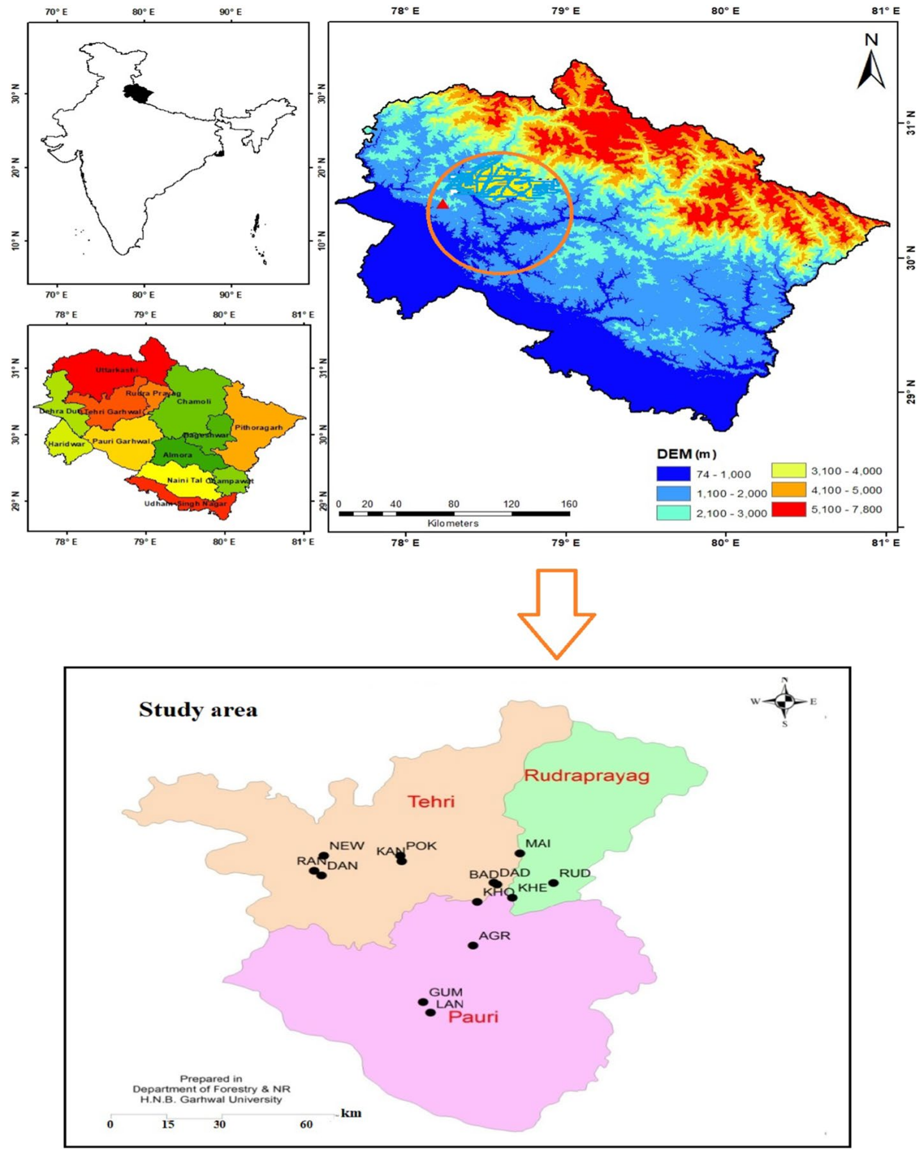

Fig. 1 Location map of the study sites (AGR Agrora, BAD Badiyargarh, DAD Daddi, DAN Dandichilli, GUM Gumkhal, KAN Kandikhal, KHE Khedakhal, KHO Khola, LAN Lansedown, MAI Mayali, NEW New Tehri, POK Pokhal and RAN Ranichauri)

where the parameter of tree density, biomass, carbon, and other related parameter was collected once from the study sites; however, the data on litter production and their biomass and further carbon were assessed seasonally to observe the impact of season on litter.

2.2 Methodology adopted

The details of stands sites in each altitude are given in Table 1. The climate of study sites was mainly dry-subtropical in low and mid-low altitudes and gradually changing into temperate type in higher altitudinal ranges. Estimation of above- and below-ground carbon stock was done following method proposed by Hairiah et al. (2001). Three plots ($20 \times 100 = 2000$ m^2) were randomly laid in each stand for sampling trees (> 30 cm diameter), smaller trees (stem diameter 5–30 cm) were sampled in nested subplot of 5×40 m, and within each subplot 6 random quadrats of 0.5 m^2 size were laid for litter collection.

Tree diameter at breast height (dbh) was measured using tree caliper, while half dbh was measured via. Spiegel Relaskope and the height by using Ravi's multimeter. The form factor was calculated following Pressler (1895) and Bitlerlich (1984) as $F = 2\ h_1\ /3\ h$, where F is the form factor, h_1 is the height at which diameter is half dbh, and h denotes the total height of tree. Volume (V) was estimated using Pressler (1895) formula (Koul and Panwar (2008): $V = F \times h \times g$, where F is the form factor, h denotes the total height, and g is the basal area. Basal area was estimated using the formula: $g = \pi r^2$ or (dbh /2)^2 where r is the radius. Biomass was estimated using the following equation: Biomass = Specific gravity × Volume. Specific gravity was estimated by evaluating the stem cores, which was again used to determine biomass of stem using the maximum moisture method (Koul and Panwar 2008). The branch biomass and leaf biomass was estimated according to Chidumaya (1990) and Koul and Panwar (2008). The below-ground carbon (BGC) was estimated from biomass of *Pinus roxburghii* (i.e., BGB multiplied with a factor of 0.45) following Woomer (1999). Litter carbon was estimated by following Hairiah et al. (2001) as total dry weight (kg m^{-2}) = total fresh weight (kg) × subsample dry weight (g)/sub sample fresh weight (g) × Sample area (m^2). The detailed methodology for the estimation of biomass (AGB, BGB) and its carbon (AGC, BGC) is given in our earlier study (Kumar et al. 2019a, b).

3 Results and discussion

3.1 Tree structure

In all the fourteen studied sites, the mean values of density, diameter, height, basal area, and volume of Chir pine forests were estimated as given in Table 1. The tree density ranged from 135.00 ± 5.00 to 575.00 ± 90.14 ind.ha^{-1} (individual per hectare). The tree height ranged between 12.67 ± 2.29 and 25.29 ± 3.41 m, whereas maximum (56.16 ± 5.45 cm) and minimum (19.00 ± 1.63 cm) values of diameter breast height were observed in Kandikhal and New Tehri, respectively. The values of basal area were maximum (41.36 ± 7.94 m^2 ha^{-1}) and minimum (11.12 ± 3.13 m^2 ha^{-1}) in the altitude ranges between 1001 and 1400 m and between 1401 and 1800 m, respectively. Similarly, minimum and maximum for tree volume was estimated as 93.98 ± 35.43 and 407.07 ± 88.15 m^3 ha^{-1} within the same altitudinal ranges (Table 1).

When the values of tree density were assessed altitudinally, the highest (405 ind.ha^{-1}) was at > 1801 m and lowest (171.67 ind.ha^{-1}) between 1401 and 1800 m (Table 1) with mean density was 244.34 (ind.ha^{-1}). The values of carbon reported tree density-dependent and observed that the density of Chir pine forest between 1001–1400 and 1401–1800 altitudes can be considered an actual growth range of this forest, whereas density of middle

Table 1 Details of the study area of *Pinus roxburghii* forest in Garhwal Himalaya

Altitude (masl)	Name of study area	Latitude	Longitude	Mean density (ind. ha^{-1})	Mean diameter (cm)	Mean height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
< 1000	Khola	30° 12′ 47.628″ N	78° 48′ 2.088″ E	197.78 ± 12.05	33.63 ± 2.54	21.08 ± 1.09	21.28 ± 3.02	215.21 ± 12.70
	Rudraprayag	30° 16′ 31.188″ N	78° 59′ 4.812″ E					
	Khedakhal	30° 13′ 37.632″ N	78° 53′ 3.372″ E					
1001–1400	Kandikhal	30° 20′ 50.316″ N	78° 37′ 3.684″ E	202.92 ± 71.09	42.42 ± 9.18	23.69 ± 1.18	30.51 ± 9.51	296.38 ± 89.77
	Mayali	30° 22′ 23.7″ N	78° 54′ 7.884″ E					
	Badiyargarh	30° 16′ 14.196″ N	78° 50′ 52.188″ E					
	Daddi	30° 16′ 36.588″ N	78° 50′ 23.1″ E					
1401–1800	Pokhal	30° 21′ 55.296″ N	78° 36′ 51.588″ E	171.67 ± 24.80	33.77 ± 6.15	23.32 ± 2.17	17.16 ± 4.64	164.59 ± 54.59
	Agrora	30° 4′ 0.912″ N	78° 47′ 26.124″ E					
	Lansedown	29° 50′ 43.584″ N	78° 41′ 11.616″ E					
	Gumkhal	29° 52′ 48.792″ N	78° 40′ 9.696″ E					
> 1801	Ranichauri	30° 18′ 56.268″ N	78° 24′ 24.192″ E	405.00 ± 190.99	29.28 ± 9.33	17.71 ± 4.38	23.75 ± 5.77	183.48 ± 76.32
	Dandachilli	30° 18′ 0.972″ N	30° 18′ 0.972″ N					
	New Tehri	30° 21′ 56.196″ N	78° 25′ 47.316″ E					

altitudes (i.e., average density of 1001–1400 and 1400–1800 m altitudes) was 187.27 ind. ha^{-1} (Table 1).

Across the altitudes, the mean diameter, height, basal area, and volume were estimated as 34.77 cm, 21.45 m, 23.17 m^2 ha^{-1}, and 214.91 m^3 ha^{-1}, respectively (Table 1). According to Gairola et al. (2009), tree density and its basal area decrease with increasing altitude, 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 this is because of the variation in growing pattern with different altitudinal ranges with inherent climatic conditions (such as precipitation and rainfall). However, reported biomass was tree density-dependent.

Mishra (2017) carried out a study in the Chir pine forest in Rudraprayag district of Uttarakhand at altitudinal ranges between 1500 and 1700 masl in five different permanent plots and reported density values of 366, 438, 366, 414, and 350 ind.ha^{-1} and basal area values of 31.64, 35.7, 27.3, 31.56, 24.75 m^2 ha^{-1}. These reported values of tree density are within the range of present study, and however, the values of basal area are close to the present study. Rana et al. (2020) conducted a comprehensive study on *Pinus roxburghii* forest in tropical regions of Makawanpur district, Nepal, and reported density, diameter, and height as 107 tree ha^{-1}, 30.84 cm, and 17.85 m, respectively. Further, Ghimire (2019) studied the Okhe community forest of Kailash Rural Municipality Makawanpur district south of Kathmandu at an elevation between 900 and 1600 masl in the natural *Pinus roxburghii* under management practices and reported density, diameter, and height values are 95 tree ha^{-1}, 31.90 cm and 19.0 m, respectively.

3.2 Estimation of AGC and BGC stock

Among the study sites, Kandikhal showed the highest AGC stock (96.00 ± 18.36 t ha^{-1}) which comprise of 89.93 ± 19.47, 5.17 ± 1.04, and 0.90 ± 0.14 t ha^{-1} for bole, branch, and foliage, respectively, followed by Mayali (83.61 ± 23.32 t ha^{-1}) where carbon contributed for bole, branch, and foliage were reported 66.25 ± 23.02, 14.83 ± 0.74, and 2.53 ± 0.34 t ha^{-1}, respectively, with both at the altitude between 1001 and 1400 m. Similarly, the lowest AGC stock was in Gumkhal (26.68 ± 9.48 t ha^{-1}) with the values of 20.72 ± 7.84, 4.50 ± 1.58, and 1.47 ± 0.11 t ha^{-1} for bole, branch, and foliage, respectively, between altitudes of 1401 and 1800 masl (Table 2). Among the AGC estimated under different components (i.e., bole, branch, and foliage), bole contributed to maximum carbon followed by branch and foliage in each study site (Table 2). The total biomass carbon allocation among different altitudes was found non-significant at $p < 0.05$. Thus there is no significant effect of altitude on all the parameters of AGC. AGC allocation in different components such as bole between 1001 and 1400 masl (Table 2) was significant ($P < 0.05$) from the stored biomass at other altitudes (< 1000, 1001–1400, and 1401–1800 masl), whereas branch and foliage were significant ($P < 0.05$) at altitudes > 1801 masl (Table 2). Similarly, the BGC (i.e., root carbon) was estimated highest in Kandikhal (28.58 ± 4.81 t ha^{-1}) followed by Mayali (25.25 ± 6.28 t ha^{-1}) at an altitude between 1001 and 1400 masl and in Ranichauri (24.86 ± 4.51 t ha^{-1}) at an altitude > 1800 masl (Table 3). However, the lowest BGC was observed in Gumkhal (9.19 ± 2.87 t ha^{-1}) at an altitude between 1401 and 1800 masl (Table 3). The TC stock (BGC and AGC) under different altitudes was not significant (p < 0.05). However, AGC, BGC, and TC at altitudes between 1001–1400 masl and > 1800 masl altitudes were significantly different ($p < 0.05$) from the stored carbon at other altitudinal ranges (Table 3).

Table 2 Carbon stock allocation in different components (bole, branch, and foliage) of *Pinus roxburghii* forest in Garhwal Himalaya

Altitude (masl)	Name of study area	Biomass carbon allocation (t ha^{-1})			Total
		Bole	Branch	Foliage	
< 1000	Khola	47.37 ± 4.64	6.79 ± 1.77	2.24 ± 0.43	56.40 ± 5.20
	Rudraprayag	50.43 ± 32.11	7.76 ± 3.95	3.97 ± 1.59	62.16 ± 37.54
	Khedakhal	44.82 ± 37.00	8.13 ± 1.31	1.79 ± 0.14	54.74 ± 38.29
1001–1400	Kandikhal	89.93 ± 19.47	5.17 ± 1.04	0.90 ± 0.14	96.00 ± 18.36
	Mayali	66.25 ± 23.02	14.83 ± 0.74	2.53 ± 0.34	83.61 ± 23.32
	Badiyargarh	64.31 ± 20.73	9.15 ± 2.85	4.32 ± 1.03	77.77 ± 24.61
	Daddi	41.42 ± 19.04	4.60 ± 1.59	1.49 ± 0.32	47.51 ± 20.32
1401–1800	Pokhal	47.70 ± 16.22	6.13 ± 0.64	4.75 ± 0.38	58.57 ± 17.22
	Agrora	33.23 ± 10.11	3.09 ± 1.09	1.95 ± 0.30	38.27 ± 11.18
	Lansedown	43.77 ± 13.71	6.60 ± 1.45	2.01 ± 0.29	52.38 ± 15.41
	Gumkhal	20.72 ± 7.84	4.50 ± 1.58	1.47 ± 0.11	26.68 ± 9.48
> 1801	Ranichauri	52.70 ± 14.24	22.74 ± 2.43	6.57 ± 0.27	82.01 ± 16.78
	Dandachilli	47.64 ± 6.30	10.50 ± 5.49	1.53 ± 0.21	59.67 ± 4.20
	New Tehri	21.29 ± 8.32	4.67 ± 1.34	13.90 ± 1.43	39.87 ± 10.66
	Mean	47.97	8.19	3.53	59.69
	F(3,10)	2.93	1.35	1.98	2.49
	p	NS	NS	NS	NS

Results of one-way ANOVA indicate that bole, branch foliage, and total AGC (t ha^{-1}) allocation between different altitudes were not significantly different at 0.05 level. Thus there is no significant effect of altitude on all described variables

A study carried out by Mishra (2017) reported AGC, BGC, and TC values of 55.44 ± 4.49, 12.54 ± 0.96 and 67.98 ± 5.44, respectively. Ghimire (2019) also reported total carbon stock (AGC, BGC, and SOC) in *Pinus roxburghii* forest was 213.05 t ha^{-1} with AGC stock of 140.56 t ha^{-1} and BGC stock of 27.14 t ha^{-1}. Ghimire et al. (2018), in their study, revealed that the total carbon stock density (AGC, BGC, and SOC) in a *Pinus roxburghii* reported 188.90 t ha^{-1} in mid-hills of Makawanpur district of Nepal. Similarly, the total carbon stock density in natural *Pinus roxburghii* in Kumaun Central Himalaya India was also reported (Pant and Tewari 2014). The average value of carbon allocation from all altitudes was reported as 47.48 t ha^{-1}, 8.43 t ha^{-1}, and 3.72 t ha^{-1} for bole, branch, and foliage, respectively (Fig. 2). The mean AGC and BGC for present study were 59.62 t ha^{-1} and 18.61 t ha^{-1}, respectively (Fig. 3), but it was not directional. Tree density played an important role which changes the carbon stock accordingly. Moreover, litter production decreased with increasing altitude but due to new plantations at an altitudinal range > 1800 m as the tendency was different, i.e., carbon stock of litter was found more.

In numerous studies in the past, it was reported that carbon stock reduced with increasing altitude and subsequent litter production. In the present study, the trend of both carbon stock of trees and litter production was not accordingly to the altitude but reported tree density-dependent (as density increased and decreased carbon stock also changed and subsequently changes in litter production). The possible reason for higher density of trees > 1800 masl was because of new plantations of Chir pine in New Tehri. In order to scale-up plot estimates to the landscape, regional or global scale, additional

Table 3 Above-ground carbon (AGC), below-ground carbon (BGC) and total carbon (TC) of *Pinus roxburghii* forest in Garhwal Himalaya

Altitude (masl)	Name of study area	AGC (t ha^{-1})	BGC (t ha^{-1})	TC (t ha^{-1})
< 1000	Khola	56.40 ± 5.20	17.88 ± 1.45	74.28 ± 6.65
	Rudraprayag	62.16 ± 37.54	19.23 ± 10.44	81.39 ± 47.98
	Khedakhal	54.74 ± 38.29	17.15 ± 10.60	71.88 ± 48.89
1001–1400	Kandikhal	96.00 ± 18.36	28.58 ± 4.81	124.58 ± 23.17
	Mayali	83.61 ± 23.32	25.25 ± 6.28	108.86 ± 29.60
	Badiyargarh	77.77 ± 24.61	23.68 ± 6.59	101.45 ± 31.20
	Daddi	47.51 ± 20.32	15.26 ± 5.92	62.77 ± 26.24
1401–1800	Pokhal	58.57 ± 17.22	18.43 ± 4.82	77.01 ± 22.04
	Agrora	38.27 ± 11.18	12.65 ± 3.31	50.92 ± 14.49
	Lansedown	52.38 ± 15.41	16.70 ± 4.41	69.08 ± 19.82
	Gumkhal	26.68 ± 9.48	9.19 ± 2.87	35.87 ± 12.35
> 1801	Ranichauri	82.01 ± 16.78	24.86 ± 4.51	106.87 ± 21.29
	Dandachilli	59.67 ± 4.20	18.79 ± 1.17	78.46 ± 5.37
	New Tehri	39.87 ± 10.66	13.13 ± 3.09	52.99 ± 13.75
	Mean	59.69	18.63	78.32
	F(3,10)	2.49	2.46	2.48
	p	NS	NS	NS

Results of one-way ANOVA indicate that total carbon both below and above ground level under different altitudes were not significantly different at 0.05 level

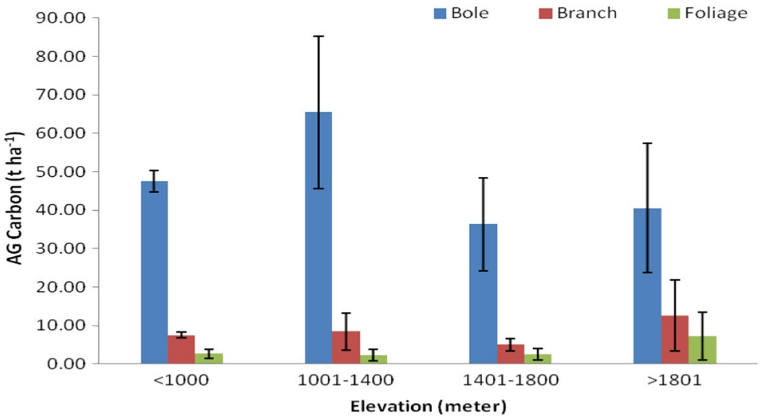

Fig. 2 Altitudinal variation (masl) in above-ground carbon (bole, branch, and foliage) in of *Pinus roxburghii* forest in Garhwal Himalaya

information about the spatial arrangement of vegetation types and land use and land cover (LULC) needs to be taken into the account, which reduces the uncertainties and increase précised results (Petrokofsky et al. 2012). Moreover, issues pertaining to suitability of standardized methodology, data collection, and estimation of forest carbon stock and its underlaid soil and creditable monitoring systems to deal with uncertainty need to be addressed precisely.

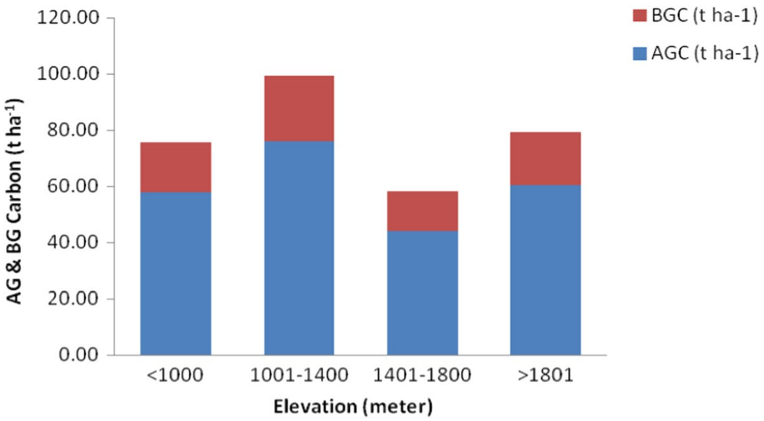

Fig. 3 Altitudinal variation (masl) in above-ground (AG) and below-ground (BG) carbon of *Pinus roxburghii* forest in Garhwal Himalaya

3.3 Seasonal input of carbon stock in forest floor through litter

The litter production was estimated for different seasons, i.e., summer, rainy, and winter. Results found that litter production estimated highest in summer season followed by winter and rainy seasons (Table 4). However, the trend was different for Rudraprayag, where highest was reported in summer followed by rainy season and winter season. Among the seasons, summer was found to be more productive (0.0060 ± 0.0053t ha^{-1}) in Ranichauri (> 1801 masl) and less productive (0.0008 ± 0.0011 t ha^{-1}) in Gumkhal (1401 masl–1800 masl), while in winter litter carbon was estimated as 0.0027 ± 0.0018 t ha^{-1} in Ranichauri and 0.0007 ± 0.0005 t ha^{-1} in Gumkhal. Moreover, In rainy season, the highest carbon (0.00157 ± 0.0003 t ha^{-1}) in Khola (< 1000 m) and lowest (0.0008 ± 0.0003 t ha^{-1}) observed in Ranichauri (> 1801 masl). The difference in litter productivity might be due to difference in temperature and evaporative fraction at different altitudes and plays an important role in the seasonal carbon dynamics (Singh et al. 2019). The trend of litter carbon with altitudes was reported in the present study as 1000 > 1001–1400 > 1401–1800 > 1801masl, which reduced gradually up to three different altitudes and then increased further with higher altitude (altitude > 1800 and beyond). However, seasonal litter production under different altitudes was found statistically non-significant ($p < 0.05$) (Table 4).

Litter production on forest floor plays a significant role in determining the moisture, runoff, and release of mineral elements of the vegetation; therefore, it represents an essential link in organic production–decomposition cycle and fundamental ecosystem process (Kumar and Tiwari 2015). In all the 14 forest sites, the mean leaf litter carbon was highest in summer season followed by winter and rainy seasons. The lowest leaf litter carbon in rainy season is due to the outbreak of forest fire during the pre-monsoon season in all the sites except in Rudraprayag, where no fire outbreak took place during the sampling period or before the present study. Being an evergreen species, *P. roxburghii* had litter fall throughout the year; however, this was concentrated during April–May (summer) perhaps due to warm, drier conditions prevailing during this period as reported (Kumar and Tiwari 2015). In this study, the peak leaf litter fall was observed in summer season. In *Pinus roxburghii* forest, the contribution of leaf litter to total annual litter production was highest during summer months (Kumar and Tiwari 2015). The total annual leaf litter carbon

Table 4 Average seasonal (summer, rainy, and winter) pattern of litter carbon production of *Pinus roxburghii* forest in Garhwal Himalaya

Altitude (masl)	Name of study area	*Sampling season			Total (t ha^{-1})
		Summer (t ha^{-1})	Rainy (t ha^{-1})	Winter (t ha^{-1})	
< 1000	Khola	0.0046 ± 0.0020	0.0015 ± 0.0003	0.0024 ± 0.0009	0.0086 ± 0.0015
	Rudraprayag	0.0017 ± 0.0012	0.0015 ± 0.0013	0.0013 ± 0.0004	0.0047 ± 0.0002
	Khedakhal	0.0030 ± 0.0028	0.0008 ± 0.0002	0.0026 ± 0.0013	0.0065 ± 0.0012
1001–1400	Kandikhal	0.0028 ± 0.0009	0.0005 ± 0.0001	0.0012 ± 0.0007	0.0046 ± 0.0011
	Mayali	0.0019 ± 0.0014	0.0009 ± 0.0003	0.0017 ± 0.0006	0.0046 ± 0.0005
	Badiyargarh	0.0029 ± 0.0009	0.0009 ± 0.0005	0.0023 ± 0.0010	0.0062 ± 0.0010
	Daddi	0.0027 ± 0.0016	0.0008 ± 0.0004	0.0023 ± 0.0013	0.0058 ± 0.0009
1401–1800	Pokhal	0.0029 ± 0.0023	0.0007 ± 0.0003	0.0019 ± 0.0010	0.0056 ± 0.0010
	Agrora	0.0016 ± 0.0005	0.0012 ± 0.0006	0.0014 ± 0.0009	0.0043 ± 0.0002
	Lansedown	0.0012 ± 0.0008	0.0004 ± 0.0004	0.0010 ± 0.0005	0.0028 ± 0.0004
	Gumkhal	0.0008 ± 0.0011	0.0004 ± 0.0001	0.0007 ± 0.0005	0.0019 ± 0.0002
> 1801	Ranichauri	0.0060 ± 0.0053	0.0008 ± 0.0003	0.0027 ± 0.0018	0.0096 ± 0.0026
	Dandichilli	0.0021 ± 0.0009	0.0004 ± 0.0001	0.0018 ± 0.0018	0.0043 ± 0.0009
	New Tehri	0.0026 ± 0.0011	0.0004 ± 0.0001	0.0020 ± 0.0005	0.0051 ± 0.0011
	Mean	0.0026	0.0008	0.0018	0.0053
	F(3,10)	1.50	3.21	2.06	1.88
	p	NS	NS	NS	NS

*Average seasonal (summer, rainy, and winter) pattern of litter carbon production of *Pinus roxburghii* forests in Garhwal Himalaya was not significantly different under various altitudes

does not follow any increasing or decreasing trend along with altitude (Fig. 4). Kumar and Tiwari (2015) reported an annual litter production falling within the ranges of 7–8 t ha^{-1}. However, the litter production was estimated very less because study is based on the leaf litter (needles), whereas Kumar and Tiwari (2015) include all components of litter, so

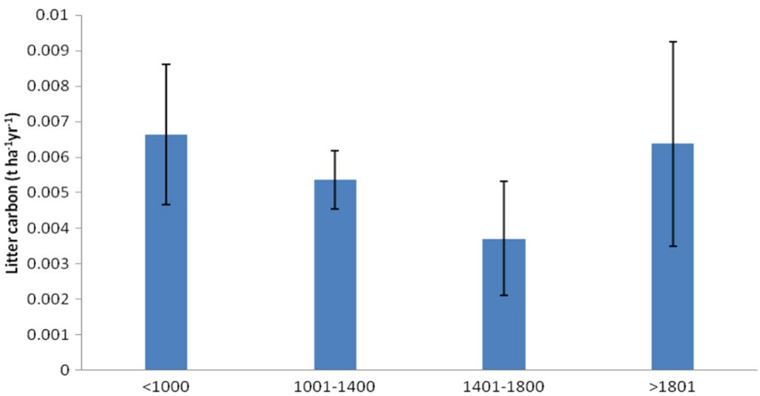

Fig. 4 Season-wise and altitudinal variation (masl) leaf litter carbon (t ha^{-1}) of *Pinus roxburghii* forest in Garhwal Himalaya

reported value was found higher. The litter carbon with altitudes reported as 0.0066 t ha^{-1} (< 1000 masl), 0.0054 t ha^{-1} (between 1001 and 1400 masl), 0.0037 t ha^{-1} (between 1401 and 1800 masl), and 0.0064 t ha^{-1} (> 1801 masl), which reduced from lower altitude up to 1401–1800 masl and again increased at > 1801 masl. The details of contribution of carbon of different components in Chir pine forest in present study shown in Fig. 5.

From the above discussion, it is found that the estimation of forest biomass carbon is essential for the better management of forests which provides information about forest productivity, nutrient flow, and carbon dynamics. The availability of higher number of seedlings in the forest followed pole and tree stages in natural regeneration is an indicator of well managed and healthy forest. However, loss of natural regeneration indicates loss of future biomass potential, which further affects carbon sequestration potential of the forest. Hence, conserving and protecting the pine species in efficient ways would help in achieve goal of reducing carbon sources and increasing the carbon sink in the Himalayas regions. However, future direction should focus on long-term monitoring of the above aspect to understand more on ecosystem carbon components and key climatic factors including anthropogenic disturbances on this forest to clear understand changes for further conservation strategies.

4 Conclusion

In this present study, an attempt has been made to quantify the carbon and other associated parameters for the Chir pine forests based on primary data collected from a representative number of samples with wide altitudes (800–2200 masl). Based on our hypothesis, both biomass and litter production are influenced by altitude. The findings do not prove the hypothesis of tree biomass which decreased with increasing altitude while as litter

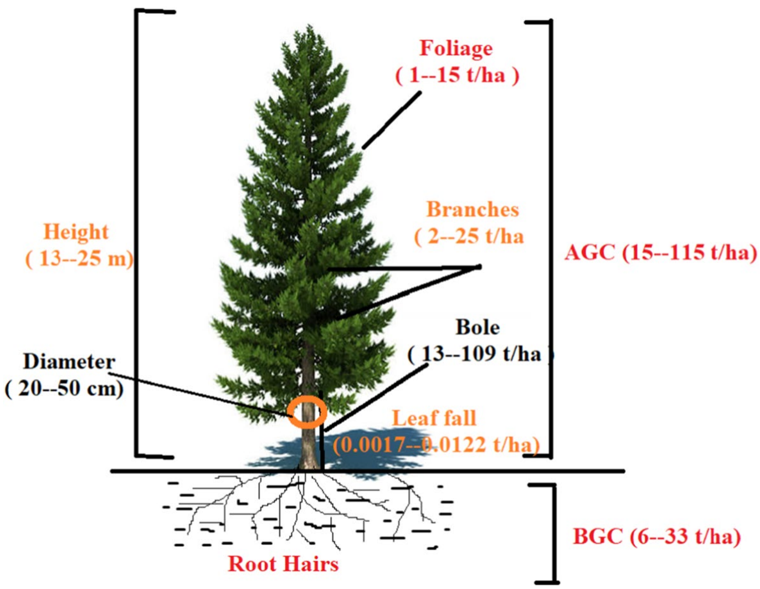

Fig. 5 Contribution of carbon of different components in Chir pine forest in Garhwal Himalaya

production decreased with increasing altitude, i.e., 0.0148 t ha^{-1} (> 1000 masl), 0.0119 t ha^{-1} (between 1000 and 1400 masl), 0.0082 t ha^{-1} (between 1400 and 1800 masl); however, litter production > 1800 masl (0.0141 t ha^{-1}) was reported with swift change due to plantation of new trees (approximate age > 10 years). Therefore, results deviated from the natural trend showing a reverse trend above 1800 masl altitudes. So, tree density and growth patterns playing an important role in biomass and litter biomass changes and further affect carbon dynamics in the forest. At this stage, a key limitation continues to be the patchy data collection at regional and/or national levels. However, there are significant limitations to published results, which we have demonstrated in this article by making distinctions based on methodological approaches with associated strengths and weaknesses.

The result of the study can be useful for future references besides assisting forest carbon at local, regional, national, and global scale. The precise estimation at different levels would add value to the removal capability of forests. The estimates in the present paper for Chir pine would also facilitate in future the improvement in the inventory of forests. The present study concludes that the present carbon stock of pine in Uttarakhand is of significant value and with many young stands present in the state, the rate of accumulation will be constant and these forests may play a significant role as carbon sink. Such precise estimation would assist in effective valuation of incentives through REDD + project activities for the regions with Chir pine forests. Moreover, involvement of local community is encouraged to develop a strategy for conservation and sustainable development of Chir pine forest for assisting forest carbon in this region.

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Author contributions MK designed the study, MK, RK, BK collected and analyzed the data and developed the manuscript, AK generated new concept, analyzed data, and finally edited manuscript; NAP and JAB read manuscript and provided suggestions to improve the quality of MS.

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Compliance with ethical standards

Consent to participate yes.

Consent for publication Yes.

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