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RESEARCH ARTICLE

Biomass Production and Carbon Storage Potential of Selected Old-Growth Temperate Forests in Garhwal Himalaya, India

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Abstract Fifteen old-growth temperate forest types were assessed for biomass productivity and carbon (C) storage potential by laying out sample plots randomly in each forest type along with an altitudinal transect in Garhwal Himalaya. The average total carbon density values ranged between 96.53 ± 4.92 Mg C ha^{-1} (moist mixed-deciduous forest) to 307.11 ± 11.28 Mg C ha^{-1} (*Cedrus deodara* forest). It was observed that conifer-dominated forest types had higher average biomass and C stocks as 479.01 Mg ha^{-1} and 220.34 Mg C ha^{-1} respectively. In broadleaf dominated forest types, these values were 394.08 Mg ha^{-1} and 177 Mg C ha^{-1} respectively. The study suggests that owing to their long rotation periods the growth of conifers should be encouraged particularly in the inaccessible areas of higher Himalaya and old-growth forests should be protected as they continue to sequester C.

Keywords Growing stock · Biomass density · Old-growth forests · Total carbon density · Elevation

Introduction

Atmospheric CO_2 is an environmental paradox which is an essential component in photosynthesis and thus essential for life, yet its increasing concentration in the atmosphere threatens to alter earth's climate [1]. The global atmospheric CO_2 concentration is nearly 400 ppm, which is well above preindustrial levels of 278 ppm [2]. Hence, there is an urgent need to focus on some feasible solutions by managing ecosystems to sequester and store more carbon (C), to mitigate the potential effect of global climate change [3]. Scientific forest management is a decisive step towards controlling global warming and climate change, considering that forests are natural storehouses of C and play a key role in the global carbon cycle. They contain approximately 80 % of the aboveground C stocks in the form of standing timber, branches and foliage and 40 % of the world's belowground C stocks as roots [4] apart from necromass including litter, woody debris, soil organic matter and forest products [5]. However, it is recorded that as much as 50 % forest biomass is carbon [6]. Forest ecosystems fix more C and possess more C density than croplands or grasslands [7]. A detailed analysis by Pan et al. [8] has demonstrated that forests strongly influence CO_2 emission and can act as a net sink of carbon capturing 1.1 ± 0.8 pentagrams C/year. Measuring biomass and its other related parameters in forest ecosystems is a primary and fundamental exercise towards forest management [9]. Biomass is actually the carbon pool of the forest ecosystem, which is a useful measure for assessing the changes in forest structure and a parameter for comparing structural and functional attributes of forest ecosystems across a wide range of environmental conditions. The quantification of biomass is also required as the primary inventory data to understand carbon pool changes and productivity of the forests. The biomass and carbon densities of different forest types are important for assessing the contribution of forests to the global carbon cycle. Several authors have conducted such studies in different forest types of Brazilian Amazon [10] and boreal forests [11] to assist policy makers in forest management.

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Temperate forests play a major role in the global carbon budget because they dominate the dynamics of the terrestrial carbon cycle [12]. Geographically, 471 T 93 Pg C (55 %) is stored in tropical forests, 272 T 23 Pg C (32 %) in boreal forests and 119 T 6 Pg C (14 %) in temperate forests [8]. The Himalayan forests are one of the most fascinating and characteristic entities among the forests of the world, because of their peculiar ecological feature of possessing a temperate climate within a tropical zone. The temperate forest cover of Uttarakhand (one of the Himalayan states of India) is 38.52 % [13]; hence, the understanding of biomass production and carbon storage potential of different temperate forest cover types of Garhwal Himalaya (a part of Uttarakhand Himalaya) is imperative. As mountain regions cover about 24 % of total global land area [14] and there are reports on rapid climate change in mountain regions during the past few decades [15], understanding the shifts in forest carbon storage and allocation along altitudinal gradients in mountain regions will help to better predict the response of regional and global carbon balance to future climate change. Although changes in species composition and distribution, biodiversity and community structure along altitudinal gradients have been well documented in the past few decades [16], the altitudinal patterns of carbon storage and partition among components (vegetation, detritus and soil) of forest ecosystems remain poorly studied.

The age of the forest is a significant factor that determines its carbon storage potential. A substantial portion of the Garhwal Himalaya is covered by old-growth forests. The net primary production and net ecosystem production in many old forest stands have been found to be increased; the carbon fluxes were definitely lower in young stands as compared to old stands [17]. There are mounting evidences that forest ecosystems do not necessarily reach an equilibrium between assimilation and respiration, but can continue to accrue carbon in living biomass, coarse woody debris and soils and may act as net carbon sinks for longer periods [18]. However, to the best of the knowledge, an in-depth biomass assessment of old-growth forests of the Garhwal Himalaya has not been conducted so far. A critical assessment of available information on Himalayan forests is essentially required and the outcome should be used to create a globally acceptable Himalayan forest database. The present study is, therefore, an attempt to fill this gap and was conducted to establish the baseline information for the biomass production and carbon storage potential of fifteen old-growth temperate forest types of the Garhwal Himalaya. The present study examines C storage at various sites within the old-growth temperate forests of Garhwal Himalaya and addresses the following questions: (1). What are the above ground and below ground carbon densities in old-growth temperate forests of Garhwal Himalaya? (2). Which forest type sequesters more carbon and act as major carbon sink? (3). Is carbon storage potential related to altitude in the forests of Garhwal Himalaya?

Material and Methods

Study Area

Uttarakhand, a northern state of India, is the easternmost part of the Western Himalaya. The state is divided into three physiographic regions, viz., (1) the higher Himalayas (2) the Shivaliks, and (3) the plains. Uttarakhand has a geographical area of 53,483 km^2 out of which recorded forest area is 34,651 km^2 (64.79 % of total geographical area) in which 71.12 % is reserved, 28.52 % is protected and 0.35 % is un-classed forest [13]. The study area is located between the latitudes 30°00′993″–30°03′764″N and longitudes 79°9′724″–79°12′040″E, in the altitudinal gradient of 1500–3100 m asl, encompassing biodiversity rich moist temperate forests of Garhwal Himalaya. The mean annual rainfall and snowfall in the study area ranges between 2731 mm and 23 inches (at 1500 m asl) to 1745 mm and 170 inches (at 3100 m) asl. The rainy season accounts for about three-quarters of the annual rainfall. Mean minimum monthly temperature ranges between 8 °C (Jan)–20.65 °C (June) at 1500 m asl and 2.68 °C (Jan)–9.30 °C (June) at 3100 m asl, whereas, maximum monthly temperature ranges between 20.0 and 30.15 °C at 1500 m asl and 7.45–18.73 °C at 3100 m asl. The soil type is basically brown-black forest soils and podozolic soils. Soils are generally gravelly with large boulders in the area [18].

Sampling and Analysis

A general survey of the study area was carried out to identify and earmark different temperate forest types. For quantitative analysis of forest vegetation, five sample plots of 0.1 ha each were randomly laid out in each forest type (05 sample plots × 15 forest types = 75 plots) in different locations of temperate zone. The physiographic features of the selected locations were ascertained using a GPS (Gramin Rino130) and the slope correction of sample plots was done with the help of specified formula [19]. The dbh of the trees was measured by tree calliper and height by Ravi multimeter. The Growing Stock Volume Density (GSVD) per hectare was calculated using standard volume tables or volume equations (as the case may be), which were provided by the Forest Survey of India (FSI) [20] for the respective species. In a few cases, where the volume tables or volume equations for the desired species were not available, calculations were made as per convention using volume tables/equations of species possessing similar height, form, taper, and growth rate.

Total Biomass Density (TBD)

The AGBD was calculated by using Biomass Expansion Factors (BEFs) proposed by Brown and Schroeder [21] as under:

$$\text{AGBD}\,(\text{Mg ha}^{-1}) = \text{GSVD}\ (\text{m}^3\ \text{ha}^{-1}) \times \text{BEF}(\text{Mg m}^{-3})$$

where, AGBD = Above Ground Biomass of the tree components (stem, branches, twigs and leaves); GSVD = growing-stock volume density; BEF = [total above ground biomass of all living trees to minimum diameter at breast height (DBH ≥ 2.5 cm)] ÷ [growing stock volume (DBH ≥ 12.7 cm].

The BEFs were calculated using the following equations [21]:

Forest types	GSVD (m^3 ha^{-1})	BEF (mg m^{-3})
Hardwood forest	≤200	exp{1.912 − (0.344 × ln GSVD)}
	>200	1.0
Spruce/Fir/other conifer-dominated forest	≤160	exp{1.771 − (0.339 × ln GSVD)}
	>160	1.0
Pine forest	<10	1.68
	10–100	0.95
	>100	0.81

The below ground biomass (coarse and fine roots) for temperate forest cover types was quantified using the regression model given by Cairns et al. [22] as under:

$$\text{BGBD} = \exp\{-1.059 + 0.884 \times In(\text{AGBD}) + 0.284\}$$

AGBD and BGBD were then added to get the total biomass density (TBD).

Total Carbon Density (TCD)

The Total C density (TCD) was computed by using the following formula:

$$\begin{aligned}\text{TCD} = {} & \text{Above Ground Biomass Carbon (AGBC)} \\ & + \text{Below Ground Biomass Carbon(BGBC)} \\ & \text{Carbon (Mg C ha}^{-1}) = \text{Biomass (Mg ha}^{-1}) \\ & \times \text{Carbon fraction.}\end{aligned}$$

The 46 % C value was used for coniferous forest types (where all conifers together constituted more than 50 % of the forest composition) and in case of broad leaved species a carbon value of 45 % was used [23]. Relationships between mean elevation and GSVD, TBD and TCD were also calculated by regression analysis, which was performed using MS-Excel 2007.

Results and Discussion

The biomass production and carbon storage potential of all fifteen temperate forest types have been described in Table 1. In the present findings, the total biomass production ranged between 214.52 ± 10.93 and 667.62 ± 24.51 Mg ha^{-1} mean being 441.83 Mg ha^{-1}. In the broad leaved forests, the highest TBD value was recorded for the *Aesculus indica* forest (527.63 ± 17.52 Mg ha^{-1}), followed by *Quercus glauca* forest (512.99 ± 32.40 Mg ha^{-1}). Among the coniferous forests, maximum biomass production was recorded for *Cedrus deodara* forest (667.62 ± 24.51 Mg ha^{-1}), followed by *Abies pindrow* forest (626.31 ± 25.04 Mg ha^{-1}). These values are greater than those reported by Gairola et al. [24], Sharma et al. [19] and Tiwari et al. [25]. This may be because of the fact that the mature old-growth forests were considered. However, in a previous study, biomass in the range of 500–600 Mg ha^{-1} has been reported for the forests of Kumaun [26], Central Himalaya. The Indian temperate coniferous forests generally sustain high level of biomass, because they receive higher precipitation [27]. Carbon storage in forest ecosystems is strongly affected by climate, forest type, stand age, disturbance regimes, and edaphic conditions [28]. The amount of biomass in different forest types may also vary due to species composition. The total standing biomass in forest types of India was estimated to be 8375 Mt [29]. Total AGBD and BGBD values for Indian forests have been estimated as 6865.10 and 1818.70 Mt, contributing 79 and 21 % of TBD, respectively [30]. In the present study, the AGBD was found to be greater than BGBD. Haripriya [31] explained that average biomass of forest ecosystems in India is 46 Mg C ha^{-1}, of which 76 % is aboveground and the rest is belowground. However, the authors observed that the AGBD values in the temperate forests were always 81 % of the total carbon density [19, 24].

The present study revealed that the carbon density in the temperate forests oscillated between 96.53 ± 4.92 Mg C ha^{-1} (moist mixed temperate deciduous forest) to 307.11 ± 11.28 Mg C ha^{-1} (*Cedrus deodara* forest), which is greater than the earlier reported values [32–40] for temperate forests of Garhwal Himalaya and the world (Table 2) [41–48].

The present results are comparable with those of old-growth temperate forests on the Changbai mountains of northeast China [7, 33] with reported carbon densities in

Table 1 Mean values ± SE of AGBD, BGBD, AGBC, BGBC, TBD and TCD of the selected temperate forests

Forest types	Forests	AGBD (Mg ha^{-1})	BGBD (Mg ha^{-1})	AGBC (Mg C ha^{-1})	BGBC (Mg C ha^{-1})	TBD (Mg ha^{-1})	TCD (Mg C ha^{-1})
FT1	*Acer acuminatum*	410.2 ± 17.8	93.8 ± 3.6	184.6 ± 8.0	42.2 ± 1.6	504.0 ± 21.5	226.8 ± 9.7
FT2	*Alnus nepalensis*	215.7 ± 9.3	53.2 ± 2.0	97.0 ± 4.2	23.9 ± 0.9	268.9 ± 11.3	120.9 ± 5.1
FT3	*Aesculus indica*	429.8 ± 14.6	97.8 ± 2.9	193.4 ± 6.6	44.0 ± 1.3	527.6 ± 17.5	237.4 ± 7.8
FT4	*Quercus semecarpifolia*	413.4 ± 26.6	94.4 ± 5.4	186.0 ± 11.9	42.5 ± 2.4	507.8 ± 31.9	228.5 ± 14.4
FT5	*Q. leucotrichophora*	218.7 ± 11.9	53.8 ± 2.6	98.4 ± 5.4	24.2 ± 1.2	272.5 ± 14.6	122.6 ± 6.6
FT6	*Q. floribunda*	416.2 ± 20.0	95.0 ± 4.1	187.3 ± 9.0	42.7 ± 1.8	511.2 ± 24.1	230.0 ± 10.8
FT7	*Q. glauca*	417.7 ± 26.9	95.3 ± 5.4	187.9 ± 12.1	42.8 ± 2.4	512.9 ± 32.4	230.8 ± 14.6
FT8	Mixed Broad Leaf	266.7 ± 9.5	64.1 ± 2.0	120.0 ± 4.3	28.8 ± 0.9	330.8 ± 11.5	148.8 ± 5.2
FT9	Moist Mixed Deciduous	171.2 ± 8.9	43.3 ± 2.0	77.0 ± 4.0	19.5 ± 0.9	214.5 ± 10.9	96.5 ± 4.9
FT10	*Abies pindrow*	512.2 ± 20.9	114.1 ± 4.1	235.6 ± 9.6	52.5 ± 1.9	626.3 ± 25.0	288.1 ± 11.5
FT11	*Cedrus deodara*	546.7 ± 20.5	120.9 ± 4.0	251.5 ± 9.4	55.6 ± 1.8	667.6 ± 24.5	307.1 ± 11.3
FT12	*Cupressus torulosa*	402.1 ± 18.6	92.1 ± 3.8	184.9 ± 8.6	42.4 ± 1.7	494.3 ± 22.4	227.4 ± 10.3
FT13	*Picea smithiana*	307.4 ± 10.8	72.7 ± 2.3	141.4 ± 4.9	33.4 ± 1.0	380.2 ± 13.0	174.9 ± 6.0
FT14	Conifer Mixed	291.6 ± 16.2	69.4 ± 3.4	134.1 ± 7.5	31.9 ± 1.5	361.0 ± 19.6	166.1 ± 9.0
FT15	*Pinus roxburghii*	363.4 ± 9.9	84.3 ± 2.0	167.2 ± 4.6	38.8 ± 0.9	447.7 ± 12.0	205.9 ± 5.5

AGBD Above Ground Biomass Density, *BGBD* Below Ground Biomass Density, *TBD* total biomass density, *TCD* total carbon density, *AGBC* Above Ground Biomass Carbon, *BGBC* Below Ground Biomass Carbon

the range of 233–317 and 112–338 Mg C ha^{-1}, respectively. In the present study, conifer forests were found to have maximum carbon storage potential, followed by deciduous and evergreen forests. The *Cedrus deodara* forest (307.11 ± 11.28 Mg C ha^{-1}) was most efficient in carbon sequestering capacity, followed by *Abies pindrow* forest (288.10 ± 11.52 Mg C ha^{-1}). Further, it was observed that the *Cedrus deodara* forest was the most productive in terms of biomass production and carbon storage. The overall highest AGBC and BGBC values (251.48 ± 9.43 and 55.623 ± 1.84 Mg C ha^{-1}, respectively) were recorded for *Cedrus deodara* forest. Conifers have also been reported as more efficient in carbon sequestration by Negi et al. [42]. Sharma et al. [19] have pointed out that conservation of conifer-dominated forests in higher Himalaya will have considerable impact on reducing global C emissions from deforestation.

Elevation was found to be significantly and positively related to TBD and TCD. It is interesting to point out that the highest live tree biomass was recorded in the forest types growing between 2250 and 2750 m asl elevation (Fig. 1). Regression analysis revealed a positive correlation between altitude v/s growing stock ($R^2 = 0.4817$; $F = 12.07$, $P < 0.004$), biomass production ($R^2 = 0.5508$; $F = 15.93$, $P < 0.001$) and carbon storage potential ($R^2 = 0.5524$; $F = 16.04$, $P < 0.001$). Similar results for forests growing between 2400 and 2650 m asl have been reported in the Garhwal Himalaya [24, 26]. However, these results are at variance with reports from other parts of the world with researchers across the globe, describing reduced live tree biomass and carbon stocks with increasing altitude [43]. There was dominance of dense undisturbed old-growth coniferous and hardwood forests with DBH sometimes more than 200 cm at higher altitude in the moist temperate forests of Garhwal Himalaya. These undisturbed stands, rich in biomass and carbon density may explain the peculiar feature of increasing biomass productivity and carbon storage potential at higher elevation. However, beyond 3100 m asl in western Himalaya the timberline ecotone marks a gradual recession from closed canopy forests to stunted forests or krummholtz and exhibits a sharp ecological gradient of biotic and abiotic components. This zone experiences the climate of temperate as well as alpine regions and creates a large number of microhabitats manifested by the action of snow, wind, topography, anthropogenic pressures [44] and environmental factors such as temperature, precipitation, atmospheric pressure, solar and UV-B radiations, and considerable wind velocity change with altitude. Therefore, altitudinal gradients are among the most powerful ''natural triggers'' for testing ecological and evolutionary responses of biota to environmental changes [45].

Since forests act as net carbon sinks, the most obvious option to prevent release of carbon in the atmosphere is by fixing it in trees. Forests often store carbon at rates well below their natural potential and, thus, likely to respond

Table 2 Comparison between estimates of biomass and carbon stocks per unit area in temperate and other forest types of India and the world

S. no.	Forest type	Location	TBD (Mg ha^{-1})	AGBD (Mg ha^{-1})	AGBC (Mg C ha^{-1})	TCD (Mg C ha^{-1})
1	Temperate forests	Garhwal Himalaya, India [P]	214.5–667.6	171.2–546.7	77.0–251.4	96.5–307.1
2	Temperate forests	Mandal-Chopta Area, Garhwal Himalaya [18]	215.5–468.2	171.9–380.3	53.2–190.1	107.7–234.1
3	Temperate forests	Garhwal NW Himalaya [19]	128.7–533.3	101.4–434.4	46.6–199.8	59.2–245.3
4	India (1994)	India [23]			17.1	
5	Temperate forests	India (1984) [23]			48.0	
6	Temperate forests	India (1994) [23]			47.4	
7	Hardwood and conifers forests	India [23]			19.8	
8	Hardwood and conifers forests	India [23]			20.8	
9	UP-lands hardwood forests	India [23]			21.6	
10	UP-lands hardwood forests	India [23]		49.1	24.5	
11	Temperate forests	Pauri, Garhwal Himalaya, India [32]	169.2–633.8	134.1–518.2		77.3–291.6
12	Temperate forests	North East China [33]				52.0–245.0
13	Non-degraded pine oak forests	Kumaun Central Himalaya [34]				173.7–262.6
14	Temperate forests	USA [35]				57.0
15	India (1993)	India [36]		67.4	33.7	
16	Good forests	Central Himalayan [37]			131.5–225.6	
17	Asian forest	India [38]			40.0–135.0	
18	Hardwood forests	USA [39]		36.0–344.0		
19	Temperate forests	World [40]				125.0
20	Temperate forests	India [41]	516.12 ± 106.03			258.05 ± 53.01

P present study

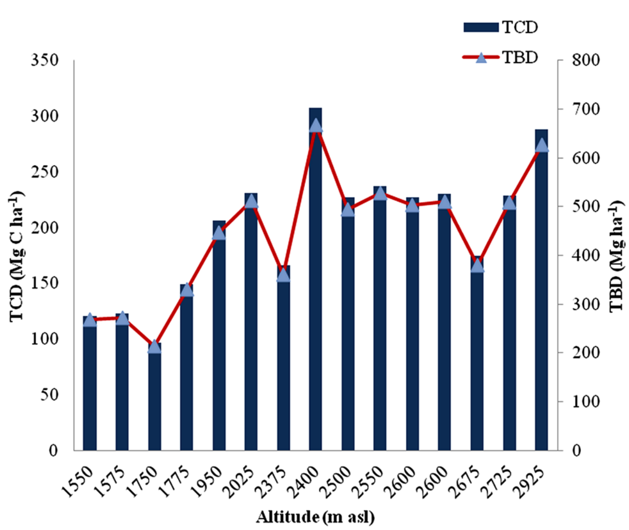

Fig. 1 Relationship of TBD (Mg ha^{-1}) and TCD (Mg C ha^{-1}) with elevation (m asl)

positively to scientific management for improved carbon sequestration. Contrary to earlier reports, in which it was reported that old-growth forests cease to accumulate carbon [46] because of the apprehension that carbon exchange would be at its equilibrium after maturity [47], a recent meta analysis of 519 stands of up to 800 years old forests around the globe has also shown that old-growth forests continue to accumulate significant amounts of carbon [17]. Therefore, old-growth forests should be protected as new plantations will take a long period of time to sequester an equivalent amounts of carbon [48].

Conclusion

The present findings add to the growing literature which suggests that the forests of Garhwal Himalaya have tremendous potential to act as carbon sink if proper attention is given through scientific management. The results corroborate previous findings that old-growth forest continues to sequester carbon. Clearly the study is important for suggesting the effect of elevation on biomass productivity. There is a significant abundance of mature conifer and hardwood forests at higher altitudes (2300–3100 m asl) of the Himalaya, which sustain higher live tree biomass. In addition, it unravels the differential carbon sequestering potential of conifers as well as broad leaved forest types in such a way that forest types with higher carbon sequestering potential and long rotation periods may be recommended for conservation and eventual global C emission reduction.

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Compliance with Ethical Standards

Conflict of interest The authors also declare that there is no conflict of interest.

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