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# Live tree biomass and carbon variation along an altitudinal gradient in moist temperate valley slopes of the Garhwal Himalaya (India)

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**The carbon (C) stored in the living biomass of trees is typically the largest C pool of the forest ecosystem which is directly impacted by deforestation and degradation. The relationships between diversity, biomass and C stocks at varied altitudes can have crucial implications for the management and conservation of C sinks. The study was undertaken in moist temperate Mandal-Chopta forest of Chamoli District, Garhwal Himalaya, Uttarakhand, India with the following objectives: (1) to assess live tree biomass and C stocks along an altitudinal gradient; (2) to assess relationship of live tree C density (TCD) with altitude, species richness, diversity and density, and (3) to compare values of live tree biomass and C density of the present study with the earlier reported values in forests of other parts of Garhwal Himalaya, Uttarakhand and India. The total live tree biomass density (TBD) varied from 215.5 to 468.2 Mg ha$^{-1}$ and TCD varied from 107.8 to 234.1 Mg C ha$^{-1}$. The average values of TBD and TCD for the study area were 356.8 ± 83.0 Mg ha$^{-1}$ and 178.4 ± 41.5 Mg C ha$^{-1}$ respectively. Comparative assessment of the data suggests that these values are similar to the earlier recorded values of C and biomass density for other forests of Garhwal Himalaya and Uttarakhand, but are higher than those reported from most of the other parts of the country. The stem density showed positive correlation with species richness (0.852) and diversity (0.749). No correlation between TCD and diversity was observed. However, statistically significant positive correlation of TCD with altitude (0.579) was observed, which could be attributed to dominance of large conifers and hardwoods at higher altitudes compared to lower altitudes.**

**Keywords:** Altitude, carbon stocks, live tree biomass, tree density and diversity.

FORESTS are natural storehouses of biomass and carbon (C). They sequester and store more C than any other terrestrial ecosystem and are an important natural ‘brake’ on climate change[1]. Forests fix, store and emit C by photosynthesis, respiration, decomposition and disturbances through a series of stages in the life cycle from regeneration to harvest[2]. Forest vegetation represents a major pool in the global C cycle and alone contains over

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350,000 Tg C (ref. 3). In the last few years in particular, there has been increasing interest in the quantification of the biomass of forest ecosystems and its potential C fixation[4]. Live tree biomass pool is an important source of uncertainty in C balance from the tropical regions in part due to scarcity of reliable estimates of tree biomass and its variation across landscapes and forest types[5]. It plays an important role in the global C cycle, accounting for a significant fraction of the total C pool and nutrient stocks.

Many environmental factors (e.g. temperature, precipitation, atmospheric pressure, solar and UV-B radiation, and wind velocity) change systematically with altitude. Therefore, altitudinal gradients are among the most powerful 'natural experiments' for testing ecological and evolutionary responses of biota to environmental changes[6]. As mountain regions cover about 27.2% of the total global land area[7] and there have been rapid climate changes in mountain regions during the past few decades[8], understanding the shifts in forest C storage and allocation along altitudinal gradients in mountain regions will help us better predict the response of regional and global C 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[9–12], the altitudinal patterns of C storage in forest ecosystems remain poorly studied[13].

Knowledge of biomass C densities for different forest types is one of the important components for assessing the contribution of forest lands to the global C cycle. A functional relationship between diversity and C storage and sequestration could have important implications for the management of C-sink, not only for reforestation and afforestation-type projects, which are currently supported under international agreements such as the clean development mechanism (CDM) under the Kyoto Protocol, but also for emission reduction projects that focus on forest conservation and management[14]. Recently, Sharma *et al.*[15] have studied tree diversity and C stocks of major forest types of the Pauri Garhwal region. But information about variation in biomass and C stocks along the altitudinal gradient in forests of the temperate region is still lacking. Keeping the aforesaid facts in view, the study was undertaken in moist temperate Mandal-Chopta forest, Chamoli District in the Garhwal region of Uttarakhand Himalaya with the following broad objectives: (1) to assess live tree biomass and C stocks along an altitudinal gradient; (2) to assess relationship of live tree C density (TCD) with altitude, species richness, diversity and density, and (3) to compare values of live tree biomass density (TBD) and TCD of the present study with the earlier reported values of forests of other parts of Garhwal Himalaya, Uttarakhand and other parts of India.

The study was conducted in the Mandal-Chopta forest area, which forms a large (nearly 1100 ha), prestigious and botanically valuable reserve complex (Trishula Reserve Forest of Kedarnath Forest Division) in the Garhwal region (Western Himalaya) (Figure 1). It lies at 30°27.560′N lat. and 79°15.234′E long. along an altitudinal gradient of 1500–2850 m asl. This rich moist temperate forest is situated 12 km away from the district headquarter, Gopeshwar. Recently, Gairola *et al.*[16] have recorded 338 species of higher plants (334 angiosperms and 4 gymnosperms) belonging to 93 families (91 angiosperms and 2 gymnosperms) and 249 genera (246 angiosperms and 3 gymnosperms) from the study area. The study area is characterized by undulating topography with gentle slopes on the northern, northeastern and northwestern faces and somewhat steep slopes in the southern and southwestern directions. Soil texture in the study area is predominantly sandy loam and sandy clay loam, whereas soil colour varies from yellowish-brown to dark brown[17]. Soils are generally gravelly and large boulders are common in the area. Geologically, the rocks in the study sites are a complex mixture of mainly sedimentary, low-grade metamorphosed with sequence capped by crystalline nappe[18].

The mean annual maximum and minimum temperatures recorded were 16.4 ± 3.6°C and 6.1 ± 2.0°C respectively (Figure 2). Mean annual rainfall was 2044.5 ± 476.0 mm and mean relative humidity round the year ranged from 15% to 86%.

A general survey of the study area was carried out to determine the nature of the terrain, tree composition, distribution and accessibility of different forest types of the forest area. After the reconnaissance survey, 12 forest types according to altitude, slope aspect and species composition were selected for the study (Table 1) and named according to the composition of the dominant tree species according to Prakash[19]. Physiographic factors, i.e. altitude and aspect across different forest types were measured by GPS (Garmin, Rino-130).

The composition of forest types along the altitudinal gradient was analysed using nested quadrat method according to Kent and Coker[20]. Trees were considered to be individuals ≥ 10 cm dbh (diameter at breast height, i.e. 1.37 m) according to Knight[21]. Tree vegetation was analysed by 10 m × 10 m sized quadrats as proposed by Curtis and McIntosh[22], and Phillips[23]. For each species, values of frequency, density and abundance were calculated following Curtis and McIntosh[22]. The importance value index (IVI) was calculated by summing up the three relative values, viz. relative density, relative frequency and relative dominance, following Phillips[23]. Species richness was simply taken as a count of the total number of species in that particular forest cover type. Shannon–Wiener diversity index was calculated according to Shannon and Weaver[24] as:

$$\bar{H} = -\sum_{i=1}^{s}\left(\frac{N_i}{N}\right)\log_2\left(\frac{N_i}{N}\right),$$

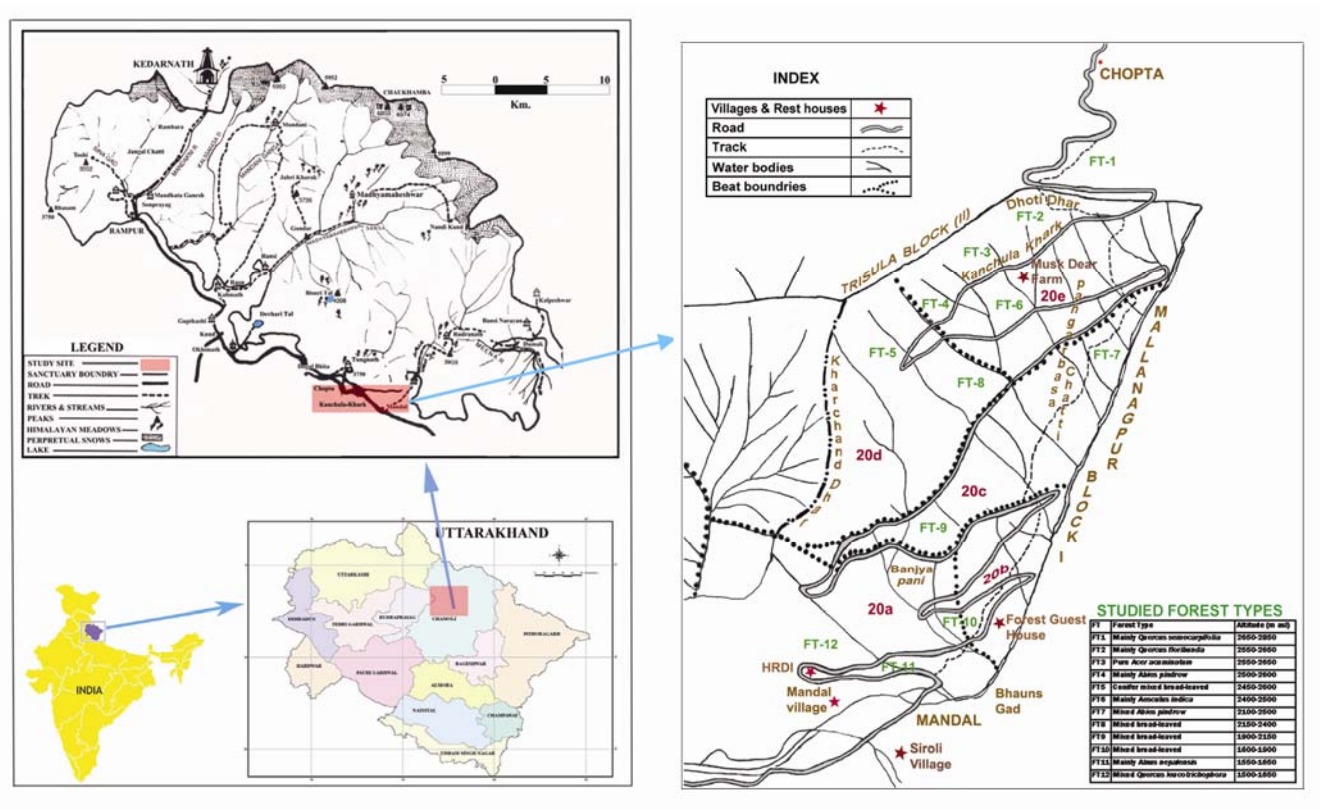


**Figure 1.** Map of the study area.

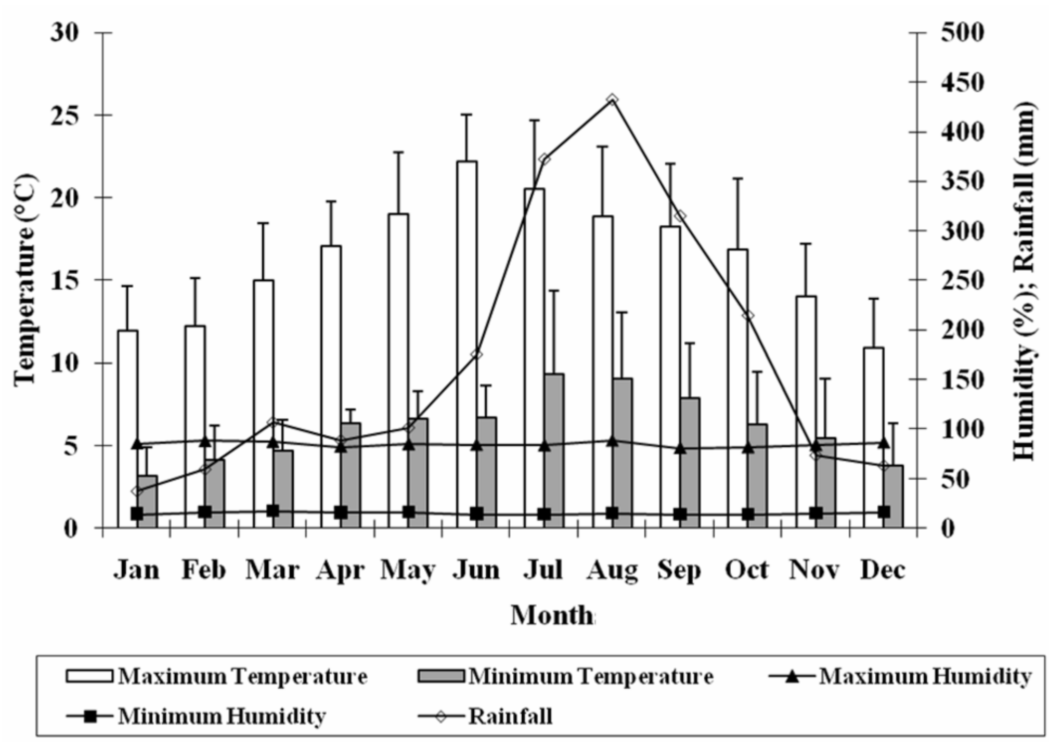


**Figure 2.** Meteorological data of the study area (1998–2007). (Source: Uttarakhand Forest Department.)

**Table 1.** Details of forest type and density, diversity, biomass and carbon stock values in different forest types

| Forest type | Forest type | SA | Altitude (m asl) | SD | SR | $\bar{H}$ | AGBD (Mg ha$^{-1}$) | BGBD (Mg ha$^{-1}$) | TBD (Mg C ha$^{-1}$) | TCD (Mg C ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| FT1 | Mainly *Quercus semecarpifolia* | E | 2650–2850 | 600 | 5 | 1.60 | 315.0 | 74.5 | 389.5 | 194.7 |
| FT2 | Mainly *Quercus floribunda* | NE | 2550–2650 | 493 | 5 | 1.95 | 348.3 | 81.4 | 429.7 | 214.8 |
| FT3 | Pure *Acer acuminatum* | S | 2550–2650 | 1180 | 9 | 1.74 | 346.3 | 80.9 | 427.3 | 213.6 |
| FT4 | Mainly *Abies pindrow* | NE | 2500–2600 | 380 | 5 | 1.45 | 237.9 | 58.1 | 296.0 | 148.0 |
| FT5 | Conifer mixed broadleaved | NE | 2450–2600 | 627 | 8 | 2.70 | 240.1 | 58.6 | 298.6 | 149.3 |
| FT6 | Mainly *Aesculus indica* | NE | 2400–2500 | 580 | 5 | 1.72 | 380.3 | 87.9 | 468.2 | 234.1 |
| FT7 | Mixed *Abies pindrow* | S | 2100–2500 | 1390 | 12 | 3.19 | 354.6 | 82.7 | 437.3 | 218.6 |
| FT8 | Mixed broadleaved | NE | 2150–2400 | 1200 | 16 | 3.33 | 325.2 | 76.6 | 401.8 | 200.9 |
| FT9 | Mixed broadleaved | NE | 1900–2150 | 1007 | 13 | 3.14 | 211.8 | 52.4 | 264.2 | 132.1 |
| FT10 | Mixed broadleaved | N | 1600–1900 | 1470 | 13 | 3.09 | 308.9 | 73.2 | 382.1 | 191.1 |
| FT11 | Mainly *Alnus nepalensis* | NE | 1550–1650 | 520 | 7 | 1.69 | 217.6 | 53.7 | 271.3 | 135.7 |
| FT12 | Mixed *Quercus leucotrichophora* | NE | 1500–1650 | 990 | 10 | 2.43 | 171.9 | 43.6 | 215.5 | 107.8 |

SA, Slope aspect (facing); E, East; NE, Northeast; S, South; N, North; SD, Stem density (N ha$^{-1}$); SR, Species richness; $\bar{H}$, Shannon–Wiener diversity index; AGBD, Aboveground biomass density; BGBD, Belowground biomass density; TBD, Total biomass density, and TCD, Total carbon density.

where $\bar{H}$ is the Shannon–Wiener diversity index; $N_i$ the IVI of a species and $N$ the total IVI of all the species. Based on the qualitative, quantitative and synthetic characters of the vegetation (especially stem density, species richness and diversity), the detailed community structure and composition along with secondary estimates (like aboveground and belowground C stocks) can be ascertained using proper correlations[17,25].

Ten sample plots of 0.1 ha each (total of $12 \times 10 = 120$) were laid out in each forest type (Table 1). The 0.1 ha square plots were laid down by determining the plot centre. After laying out the plot, measurements were made on individual tree basis. The height and dbh of all the trees falling within the sample plot were measured. For sample plots located on a slope of >10%, the slope was quantified so that an adjustment can be made to the plot area at the time of analysis. The slope angle was measured using a clinometer. Tree height was measured using a Ravi multimeter. The growing stock density (GSVD) was estimated using volume tables or volume equations based on the Forest Research Institute and Forest Survey of India publications for the respective species[26]. In a few cases, where the volume tables or volume equations for the desired species were not available, the volumes of those species were calculated according to convention using volume tables/equations of similar species having similar height, form, taper and growth rate. The estimated GSVD (m$^3$ ha$^{-1}$) was then converted into aboveground biomass density (AGBD) of tree components (stem, branches, twigs and leaves), which was calculated by multiplying GSVD of the forest with appropriate biomass expansion factor (BEF)[27]. BEF (Mg m$^{-3}$) is defined as the ratio of AGBD of all living trees at DBH $\geq$ 2.54 cm to GSVD for all trees of DBH $\geq$ 12.7 cm. BEF for hardwood, spruce–fir and pine was calculated using the following equations:

Hardwood: $\text{BEF} = \exp\{1.91 - 0.34 \times \ln(\text{GSVD})\}$ (for GSVD $\leq 200$ m$^3$ ha$^{-1}$),
BEF = 1.0 (for GSVD > 200 m$^3$ ha$^{-1}$).

Spruce–fir: $\text{BEF} = \exp\{1.77 - 0.34 \times \ln(\text{GSVD})\}$ (for GSVD $\leq 160$ m$^3$ ha$^{-1}$),
BEF = 1.0 (for GSVD > 160 m$^3$ ha$^{-1}$).

Pine: BEF = 1.68 (for GSVD < 10 m$^3$ ha$^{-1}$),
BEF = 0.95 (for GSVD = 10–100 m$^3$ ha$^{-1}$);
BEF = 0.81 (for GSVD > 100 m$^3$ ha$^{-1}$).

The equation of spruce–fir was applied for other conifer-dominated strata. Using the regression equation of Cairns *et al.*[28], the belowground biomass density (BGBD; fine and coarse roots) was estimated for each forest type as follows:

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

AGBD and BGBD were added to get the TBD. TCD was computed using the following formula:

$$\text{TCD (Mg C ha}^{-1}) = \text{TBD (Mg ha}^{-1}) \times \text{carbon\%}.$$

The C percentage of 46 was used for forest types where all conifers together constituted more than 50% of the forest composition. For forest types (i) where conifers and broadleaved species occurred in similar proportion, (ii) where broadleaved species constituted more than 50% and (iii) where deciduous species were dominant, the C percentage was taken as 45 (refs 29 and 30). A one-tailed Pearson correlation coefficient was calculated between mean altitude, stem density, species richness, $\bar{H}$ and TCD using a SPSS-16 package. The literature was widely surveyed and values of biomass and C stocks in living tree biomass were collected to compare with the present results. In many studies only values of AGBD and TBD were present; in such cases we have converted the biomass values to C stocks using the IPCC default 0.47 C fraction[31] for easy comparison.

Values of stem density, $\bar{H}$, biomass and C stocks in different forest types are given in Table 1. Amount of biomass in different forest types varied due to differences in species composition. The mean biomass density in Indian forests in 1993 was estimated at 135.6 Mg $ha^{-1}$ and amongst the states it varied from 27.4 Mg $ha^{-1}$ in Punjab to 251.8 Mg $ha^{-1}$ in Jammu and Kashmir[32]. Whereas in the present study, TBD ranged between 215.5 and 468.2 Mg $ha^{-1}$ (Table 1). Values of AGBD ranged between 171.9 and 380.3 Mg $ha^{-1}$, whereas BGBD varied between 43.6 and 87.9 Mg $ha^{-1}$. Total aboveground and belowground biomass in Indian forests has been estimated as 6865.1 and 1818.7 Mt respectively, contributing 79% and 21% respectively of the total biomass[32]. Average TBD in the study area was recorded as 356.8 ± 83.0 Mg $ha^{-1}$, out of which average AGBD accounted for 80.8% (288.2 ± 68.5 Mg $ha^{-1}$) of the TBD and average BGBD accounted for 19.2% (68.6 ± 14.6 Mg $ha^{-1}$) of the TBD. The estimated total BGBD was 23.8% of the total AGBD. Brown and Lugo[33] also found that belowground biomass can vary from 10% to 50% (with an average of 17%) of the aboveground biomass in many tropical forests, most likely as a function of soil type, soil fertility and moisture regime.

In the Mandal-Chopta forest area, TCD ranged between 107.8 Mg C $ha^{-1}$ in mixed *Quercus leucotrichophora* forest (FT12) and 234.1 Mg C $ha^{-1}$ in mainly *Aesculus indica* forest (FT6). Greater biomass in forest types (mainly *Abies pindrow*, mainly *Quercus semecarpifolia*, mainly *Quercus floribunda*, pure *Acer acuminatum* and mainly *Aesculus indica*) was mainly due to the presence of canopy-dominant trees of large girth classes, viz. *Q. semecarpifolia*, *Q. floribunda*, *A. acuminatum*, *A. pindrow* and *A. indica*. Forest types with relatively lower biomass, viz. mixed *Q. leucotrichophora* (FT12), mainly *A. pindrow* (FT4), conifer mixed broadleaved (FT5) and mixed broadleaved (FT8, FT9 and FT10) forests were dominated by sub-canopy tree species of lower diameters. Compared to mainly *A. pindrow* forest type (FT4) growing between 2100 and 2500 m asl, the mainly *A. pindrow* forest type (FT7) growing between 2500 and 2600 m asl had higher TBD. In mainly *A. pindrow* (FT4) forest type, the Forest Department had practised clear felling of large, mature *A. pindrow* trees some years ago, which caused loss of large amount of biomass from this forest type. Such felling is generally done to remove mature and dead trees. This caused loss of large amount of biomass in the form of removal of mature *A. pindrow* trees, which is the main reason for the difference between the biomass of FT4 and FT7. The average value of TCD for the study area was recorded as 178.4 ± 41.5 Mg C $ha^{-1}$. A total of 196.2 Gg C was estimated as the amount of C present in the living tree biomass of the study area, which was calculated by multiplying the average value of TCD with the size of the study area (1100 ha). Although this is an approximate estimation of the amount of C stored in the study area, it gives an idea of the amount of C stored in this rich forest area.

The physiographic factors are widely known to show a major impact on plant microhabitats, especially in hill-slope form[17]. Average temperature lapse rate varies from 4.52 to 6.56°C $km^{-1}$. The minimum value is approximately 4.52°C $km^{-1}$ on the south side of mountains. The maximal values occur at the opposite side of sunshine, which is 6.56°C $km^{-1}$ on the north side of the mountains[34]. This variation in temperature also affects diversity, biomass and C stock in the forest ecosystems, which has been observed in many earlier studies. Although it has been reported by many workers in other parts of the world that live tree biomass and C decline with increasing altitude[35,36], inversely, in our study area we observed that live tree C had positive correlation (at the 0.05 level of significance) with increasing altitude (0.579). Similar results were also reported by Alves *et al.*[5] in tropical Atlantic moist forest of Brazil, and Zhu *et al.*[13] in temperate forests of Mount Changbai, Northeast China. In our study area dominance of mature large conifers and hardwoods at higher altitudes compared to lower altitudes can be assigned as a possible reason for this relationship. In a study by Singh *et al.*[37] on different forest types of the Kumaun region in Uttarakhand Himalaya, it was observed that live tree biomass remained high up to 2600 m asl and declined sharply above 3100 m asl. Similarly, in our study area we also observed that above 2650 m asl in mainly *Q. semecarpifolia* forest type, live tree biomass was lower than forest types (FT2 and FT3) growing between 2550 and 2650 m asl.

Ecologists are interested in potential functional relationships between diversity, and C sequestration and storage[38]. Research dedicated towards understanding this relationship has increased over the past several decades as human activities have begun to alter diversity and productivity at unprecedented rates[39]. The relationship between diversity and C stocks is still debatable, and the link always depends on other factors and features, viz. altitude, physiographic factors, etc. In an earlier study on major forest types of Pauri District, Garhwal region, Sharma *et al.*[15] observed negative correlation between $\bar{H}$ and total C density. However, no correlation of C density with species richness and $\bar{H}$ was observed in the present study, which suggests that there is not direct relationship between the C stocks and diversity in forest communities growing in varying environmental conditions like the Mandal-Chopta forest area. Similarly, Kirby and Potvin[38] also found no correlation between tree biomass and species richness in Tierra Colectiva of Ipetí-Emberá in the eastern Panama Province, Panama. Stem density was positively correlated (at the 0.01 level of significance) with species richness (0.852) and $\bar{H}$ (0.749).

**Table 2.** Biomass and carbon stocks in different forest types of Garhwal Himalaya, Uttarakhand and other parts of India

| (Source)Forest type and location | Altitude (m asl) | AGBD (Mg ha$^{-1}$) | TBD (Mg ha$^{-1}$) | AGBC (Mg C ha$^{-1}$) | TBC (Mg C ha$^{-1}$) |
|---|---|---|---|---|---|
| Uttarakhand | | | | | |
| (42)*Abies pindrow*, Kumaun | 2500 | 454.6 | 565.0 | 213.7* | 265.6* |
| (15)*Abies pindrow*, Pauri Garhwal | 2600–3100 | 305.3 | 377.7 | na | 173.7 |
| **(P)Mainly *Abies pindrow*, Chamoli Garhwal** | **2600–2500** | **237.9** | **296.0** | **na** | **148.0** |
| **(P)Mixed *Abies pindrow*, Chamoli Garhwal** | **2500–2100** | **354.6** | **437.3** | **na** | **218.6** |
| (43)*Acer cappadocicum*, Kumaun | 2750 | 241.0 | 308.3 | 113.3* | 144.9* |
| **(P)Pure *Acer acuminatum*, Chamoli Garhwal** | **2650–2550** | **346.3** | **427.3** | **na** | **213.6** |
| (42)*Aesculus indica*, Kumaun | 2300 | 397.2 | 501.8 | 186.7* | 235.8* |
| **(P)Mainly *Aesculus indica*, Chamoli Garhwal** | **2500–2400** | **380.3** | **468.2** | **na** | **234.1** |
| **(P)Mainly *Alnus nepalensis*, Chamoli Garhwal** | **1650–1550** | **217.6** | **271.3** | **na** | **135.7** |
| (15)*Anogeissus latifolia–Spondias pinnata*, Pauri Garhwal | 560–630 | 138.8 | 174.9 | na | 80.4 |
| (15)*Cedrus deodara*, Pauri Garhwal | 2200–2500 | 434.4 | 533.3 | na | 245.3 |
| **(P)Conifer mixed broadleaved, Chamoli Garhwal** | **2600–2450** | **240.1** | **298.6** | **na** | **149.3** |
| (15)*Cupressus torulosa*, Pauri Garhwal | 2100–2500 | 271.6 | 336.6 | na | 154.8 |
| (44)*Dalbergia sissoo*, Kumaun | 300 | 35.1–89.7 | 43.9–109.6 | 16.5–42.1* | 20.6–51.5* |
| (15)*Holoptelea integrifolia*, Pauri Garhwal | 480–1000 | 191.6 | 239.6 | na | 110.2 |
| **(P)Mixed broadleaved, Chamoli Garhwal** | **2400–2150** | **325.2** | **401.8** | **na** | **200.9** |
| **(P)Mixed broadleaved, Chamoli Garhwal** | **2150–1900** | **211.8** | **264.2** | **na** | **132.1** |
| **(P)Mixed broadleaved, Chamoli Garhwal** | **1900–1600** | **308.9** | **382.1** | **na** | **191.1** |
| (15)Moist deciduous miscellaneous, Pauri Garhwal | 380–510 | 152.8 | 192.0 | na | 88.3 |
| (15)Moist temperate deciduous, Pauri Garhwal | 1700–2200 | 114.3 | 144.7 | na | 66.5 |
| (45)Mixed oak, Kumaun | 2200 | 263.2 | 344.0 | 123.7* | 161.7* |
| (46)Mixed oak-pine, Kumaun | na | 325.8 | na | 153.1* | na |
| (15)Dry Siwalik *Shorea robusta*, Pauri Garhwal | 800–1200 | 143.6 | 180.8 | na | 83.2 |
| (15)Dry sub-deciduous *Shorea robusta*, Pauri Garhwal | 800–1100 | 128.5 | 162.0 | na | 74.5 |
| (15)Moist Bhabhar *Shorea robusta*, Pauri Garhwal | 450–600 | 279.6 | 346.5 | na | 159.4 |
| (15)Riverian *Shorea robusta*, Pauri Garhwal | 450–610 | 186.4 | 233.2 | na | 107.3 |
| (46)*Shorea robusta*, Kumaun | 300 | 562.0 | 710.0 | 264.1* | 333.7* |
| (46)*Shorea robusta*, Kumaun | 350 | 357.0 | 455.0 | 167.8* | 213.9* |
| (15)Moist *Shorea robusta* Savannah, Pauri Garhwal | 350–460 | 207.6 | 259.0 | na | 119.2 |
| (46)*Pinus roxburghii*, Kumaun | 1750 | 163.0 | 199.0 | 76.6* | 93.5* |
| (47)*Pinus roxburghii*, Kumaun | na | 91.5–232.3 | na | 43.2–109.2* | na |
| (15)*Pinus roxburghii*, Pauri Garhwal | 1500–1800 | 239.9 | 298.0 | na | 137.1 |
| (15)*Pinus roxburghii*, Pauri Garhwal | 750–1250 | 126.2 | 159.4 | na | 73.3 |
| **(P)Mainly *Quercus floribunda*, Chamoli Garhwal** | **2650–2550** | **348.3** | **429.7** | **na** | **214.8** |
| (46)*Quercus floribunda*, Kumaun | 2200 | 640.0 | 782.0 | 300.8* | 367.5* |
| (48)*Quercus floribunda*, Kumaun | 2194 | 375.5 | 458.5 | 176.5* | 215.5* |
| (15)*Quercus floribunda*, Pauri Garhwal | 2300–2600 | 235.2 | 292.4 | na | 134.5 |
| (46)*Quercus lanata*, Kumaun | 2150 | 464.0 | 557.0 | 218.1* | 261.8* |
| (48)*Quercus lanata*, Kumaun | 2240 | 237.7 | 285.3 | 111.7* | 134.1* |
| **(P)Mixed *Quercus leucotrichophora*, Chamoli Garhwal** | **1650–1500** | **171.9** | **215.5** | **na** | **107.8** |
| (48)*Quercus leucotrichophora*, Kumaun | 1950 | 291.4 | 387.3 | 137.0* | 182.0* |
| (15)*Quercus leucotrichophora*, Pauri Garhwal | 1600–2100 | 159.4 | 200.1 | na | 92.1 |
| **(P)Mainly *Quercus semecarpifolia*, Chamoli Garhwal** | **2850–2650** | **315.0** | **389.5** | **na** | **194.7** |
| (42)*Quercus semecarpifolia*, Kumaun | 2650 | 459.7 | 590.2 | 216.1* | 277.4* |
| (15)*Quercus semecarpifolia*, Pauri Garhwal | 2500–3000 | 224.3 | 279.3 | na | 128.5 |
| (15)*Quercus* spp. Scrub, Pauri Garhwal | 1600–1800 | 115.2 | 145.8 | na | 67.1 |
| (43)*Rhododendron campanulatum*, Kumaun | 3300 | 27.0 | 40.5 | 12.7* | 19.0* |
| (15)Riverian *Acacia catechu–Dalbergia sissoo*, Pauri Garhwal | 350–565 | 101.4 | 128.7 | na | 59.2 |
| (49)*Tectona grandis* plantation, Dehradun Garhwal | na | 129.6 | na | 60.9* | na |
| (15)Western Gangetic moist-mixed deciduous, Pauri Garhwal | 474–750 | 168.7 | 211.6 | na | 97.3 |
| Other parts of India | | | | | |
| (50)Reserved and protected forests, Himachal Pradesh | na | 728.0–1158.0 | na | 342.2–544.3* | na |
| (51)Dry deciduous forest, Varanasi, UP | na | 205.5 | 239.8 | 96.6* | 112.7* |
| (52)Dry deciduous forest, Varanasi, UP | na | 64.3 | 73.8 | 30.2* | 34.7* |
| (53)Mixed forest, Raipur, Chhattisgarh | na | 78.3 | na | 39.1 | na |
| (53)*Tectona grandis* mixed forest, Raipur, Chhattisgarh | na | 66.3 | na | 33.2 | na |
| (53)Degraded forest, Raipur, Chhattisgarh | na | 45.9 | na | 22.9 | na |
| (53)*Shorea robusta* mixed forest, Raipur, Chhattisgarh | na | 66.5 | na | 33.3 | na |

(*Contd*)

**Table 2.** (*Contd*)

| (Source)Forest type and location | Altitude (m asl) | AGBD (Mg $ha^{-1}$) | TBD (Mg $ha^{-1}$) | AGBC (Mg C $ha^{-1}$) | TBC (Mg C $ha^{-1}$) |
|---|---|---|---|---|---|
| (54)Tropical dry deciduous *Tectona grandis*, Chhindwara, MP | 410–457 | 28.1–85.3 | 37.1–100.9 | 13.2–40.1* | 17.4–47.4* |
| (55)Semievergreen, Western Ghats, Maharashtra | na | na | 114.9–202.6 | na | 54.0–95.2* |
| (55)Mixed moist deciduous, Western Ghats, Maharashtra | na | na | 115.5–209.3 | na | 54.3–98.3* |
| (55)Plantation, Radhanagari, Western Ghats, Maharashtra | na | na | 112.8 | na | 53.0* |
| (55)Degraded Scrub, Radhanagari, Western Ghats, Maharashtra | na | na | 92.5 | na | 43.5* |
| (56)Tropical forests, Kolli hills, Eastern Ghats, Tamil Nadu | 200–1415 | na | 57.5–307.3 | na | 27.0–144.4* |
| (57)Tropical dry evergreen, Pudukottai district, Tamil Nadu | na | 39.7–138.7 | na | 18.7–65.2* | na |
| (57)Tropical dry evergreen, Coromandel coast, Tamil Nadu | na | 61.2–173.1 | na | 28.8–81.4* | na |
| (58)Tropical rainforests, Karnataka | 200–800 | 210.0–324.5 | na | 98.7–152.5* | na |
| (59)Temperate natural, Mamlay watershed, Sikkim | 300–2650 | na | na | 80.9–182.1 | 85.5–190.9 |
| (59)Subtropical natural, Mamlay watershed, Sikkim | 300–2650 | na | na | 88.4 | 89.8 |
| (60)Tropical semi evergreen, NWLS, Meghalaya | 208–295 | 324.0 | na | 152.3* | na |
| Indian forests | | | | | |
| (61)Potential C Density, India (1980) | na | na | na | 173.0 | 201.0 |
| (61)Actual C Density, India (1980) | na | na | na | 66.0 | 77.0 |
| (30)India (1984) | na | na | na | 16.9 | na |
| (62)India (1985) | na | na | na | na | 31.1 |
| (63)India (1986) | na | na | na | na | 58.8 |
| (32)India (1988) | na | na | na | na | 54.5 |
| (64)India (1993) | na | 67.4 | na | 33.7 | na |
| (32)India (1993) | na | na | na | na | 61.1 |
| (30)India (1994) | na | na | na | 17.1 | na |
| (65)India (1995) | na | na | na | na | 31.7 |

*These values were not present in original source publications of the authors. We have converted the biomass values to C stocks using the IPCC default 0.47 carbon fraction[31].
(P)Values in bold are from the present study.
na, Not available; AGBC, Aboveground biomass carbon.

A completely opposite finding to the present results was observed by Sharma *et al.*[15], according to which negative correlation between stem density and $\bar{H}$ was recorded. Sharma *et al.*[15] conducted their studies on mature, fully stocked, old growth, high forests distributed at various localities of Pauri District, whereas our study was conducted on the continuous patch of the forest situated in the Chamoli District. The differences in the successional stages of the forests and the effects of other site factors may be the possible reasons for the variation in the results.

Comparisons of AGBD, TBD, aboveground biomass C (AGBC) and TCD values of the present study with earlier recorded values for Garhwal Himalaya, Uttarakhand and other parts of India are presented in Table 2. A comprehensive comparison of the biomass and C estimates of the present study with other works is difficult because of variation in the methods employed for estimation in different studies. In some studies biomass was directly estimated, whereas in others allometric and regression equations were used. Some other results of ground study were coupled with the remote sensing and GIS techniques to obtain estimates of larger regions. The fraction of C used to convert biomass to C stocks also varied in different studies (generally between 0.45 and 0.50). However, Table 2 provides the extent of information available in the scientific literature about the living tree biomass and C stocks in forests of Garhwal Himalaya, Uttarakhand and other parts of India, which can be used to chalk out effective C management and conservation policies in response to recent threats posed by climate change.

According to Houghton[40], the forest biomass has a large potential for temporary and long-term C storage. In the established forest ecosystems, greater storage of C in large, long-lived species and in species with dense wood was observed[41]. Similarly, the results of the present study highlight the disproportionate contribution of a small number of species (viz. *A. acuminatum*, *A. pindrow*, *A. indica*, *A. nepalensis*, *Q. semecarpifolia*, *Q. floribunda* and *Q. leucotrichophora*) to stand-level C stock. Most of these species were slow-growing and had adequate protection in this forest due to its reserved status. Because of this, they contain large amount of biomass and C in their stands. While comparing with other life-forms, conifers have been observed to have maximum C stored in them[29]. In mainly *A. pindrow* (148.0 Mg C $ha^{-1}$) and mixed *A. pindrow* (218.6 Mg C $ha^{-1}$) forest types, high amount of C was observed. Interestingly, among temperate forests *A. pindrow* stands have been considered to be the most productive forests. Sharma *et al.*[15] have suggested that preventing the deforestation of conifer-dominated stands (especially *A. pindrow* forests) would have the largest per-unit-area-impact on reducing C emissions from deforestation.

Our study provides relevant information on live tree biomass and live tree C stocks along an altitudinal gradient of a representative moist temperate forest. The results of the present study will be helpful for understanding the patterns of C storage in various forest types/species of temperate regions in other parts of the globe having similar species composition. The results of the present study will also help the policy-makers at both the national and international level to find the most effective solutions to problems that are threatening the similar ecologically fragile regions. Comparative assessment of the data suggests that these values are similar to those of C and biomass density recorded for other forests of the Garhwal region and Uttarakhand, but higher than the values reported for forests in most of the other parts of the country. This may be because this forest has the status of 'protected forest' and hence has higher density. It is necessary to obtain more accurate and precise biomass estimates for Himalayan forests in order to improve our understanding of the role of Himalayan forests in the global C cycle. Further, in future, estimates of total C stocks for this biome will require more extensive spatial sampling and the addition of important components of forest biomass, including coarse wood debris (necromass), litterfall stocks, saplings (1–10 cm dbh), seedlings, herbs and shrubs.


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