Variation in carbon stocks on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya, India

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Recto running title: *Variation in carbon on different slope aspects*
Verso running title: *CM Sharma et al.*

The present study was undertaken in seven major forest types of temperate zone (1500 m a.s.l. to 3100 m a.s.l.) of Garhwal Himalaya to understand the effect of slope aspects on carbon (C) density and make recommendations for forest management based on priorities for C conservation/sequestration. We assessed soil organic carbon (SOC) density, tree density, biomass and soil organic carbon (SOC) on four aspects, viz. north-east (NE), north-west (NW), south-east (SE) and south-west (SW), in forest stands dominated by *Abies pindrow*, *Cedrus deodara*, *Pinus roxburghii*, *Cupressus torulosa*, *Quercus floribunda*, *Quercus semecarpifolia* and *Quercus leucotrichophora*. TCD ranged between 77.3 CMg ha^{-1} on SE aspect (*Quercus leucotrichophora* forest) and 291.6 CMg ha^{-1} on NE aspect (moist *Cedrus deodara* forest). SOC varied between 40.3 CMg ha^{-1} on SW aspect (Himalayan *Pinus roxburghii* forest) and 177.5 CMg ha^{-1} on NE aspect (moist *Cedrus deodara* forest). Total C density (SOC+TCD) ranged between 118.1 CMg ha^{-1} on SW aspect (Himalayan *Pinus roxburghii* forest) and 469.1 CMg ha^{-1} on NE aspect (moist *Cedrus deodara* forest). SOC and TCD were significantly higher on northern aspects as compared with southern aspects. It is recommended that for C sequestration, the plantation silviculture be exercised on northern aspects, and for C conservation purposes, mature forest stands growing on northern aspects be given priority.

[Sharma CM, Gairola S, Baduni NP, Ghildiyal SK and Suyal S 2011 Variation in carbon stocks on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya, India. *J. Biosci.* **36** XXX–XXX] **DOI**

Keywords. Carbon sequestration; carbon storage; Himalayan forests; soil organic carbon; stem density; tree biomass

Abbreviations used: AGBD, aboveground biomass density; BEF, biomass expansion factor; BGBD, belowground biomass density; FRI, Forest Research Institute; FSI, Forest Survey of India; GSVD, growing stock volume density; IPCC, International Panel on Climate Change; NE, north-east; NW, north-west; SE, south-east; SOC, soil organic carbon; SW, south-west; TBD, total biomass density; TCD, tree C density

1. Introduction

Human beings are accelerating the rate of increase in atmospheric CO_2 concentration through fossil fuels burning, land use, land-use changes and forestry activities, resulting in global warming and climate change during the recent times (Upadhyay *et al.* 2005). The average atmospheric CO_2 concentration has increased from pre-industrial concentration of 280 μmol mol^{-1} to 364 μmol mol^{-1} in 1994, and is currently increasing at a rate of about 1.5 μmol mol^{-1} year^{-1} (Kelling and Whorf 1998). The International Panel on Climate Change (IPCC) in its fourth assessment report has strongly recommended to limit the increase in global temperature below 2°C as compared with pre-industrial level (i.e. measured from 1750) to avoid serious ecological and economic threats. A rise in global mean temperature by 0.74°C has already been recorded, and hence climate scientists are focusing on an urgent action to curb global warming (IPCC 2007; Kerr 2007). Forests play an important role in regional and global carbon (C) cycles because they store large quantities of C in vegetation and soil, exchange C with the atmosphere through photosynthesis and respiration, are sources of atmospheric C when they are disturbed by human or natural causes, become atmospheric C sinks during re-growth after disturbance, and can be managed to sequester or conserve significant quantities of C on the land (Brown *et al.* 1996). Forest ecosystems merit consideration in this context of climate change because they can act as sources as well as sinks of CO_2, the most abundant greenhouse gas (Haripriya 2002). About two-thirds of terrestrial C, exclusive of that sequestered in rocks and sediments, is sequestered in the standing forests, forest understorey plants, leaf and forest debris, and in forest soils (Sedjo *et al.* 1998).

The elevation and slope aspect play a key role in determining the temperature regime of any sites. Within one elevation, cofactors like topography, aspect, inclination of slope and soil type affect the forest composition (Shank and Noorie 1950). Differences in insolation period may occur according to site aspect, thereby forming a range of microclimates in multifaceted landscapes. Consequently, the microclimate is often linked to soil moisture and distribution of particular plant communities (Holland and Steyn 1975) on different slope forms. The micro-environment of different aspects of hill slopes is influenced by the intensity and duration of available sunlight (Yadav and Gupta 2006). With the intense focus on the increasing levels of atmospheric CO_2 and the potential for global climate change, there is an urgent need to assess the feasibility of managing ecosystems to sequester and store C (Johnson and Kern 2002). On the basis of review of large number of past studies, Upadhyay *et al.* (2005) suggested that there is high potential for enhancing the C sequestration in the vegetation and soils of the Himalayan region through improved management of degraded lands. The forest productivity parameters studied in mountains are overestimated in most of the studies as they do not take into consideration the slope aspects and are affected by the selective sampling in dense patches of the forest mainly growing on NW and NE aspects only. Brown and Lugo (1992) also argued that ecologists generally tend to adjust the placement of experimental plots in forests to include large trees. The effect of adjusting plot placement to include large-diameter trees overestimates forest biomass because biomass per tree increases geometrically with increasing diameter. In our earlier studies on forests of the Garhwal region, the role of physiographic factors (Sharma *et al.* 2010a), regeneration (Gairola *et al.* 2011a), physical properties of the soils (Sharma *et al.* 2010b), tree diversity and carbon stocks (Sharma *et al.* 2010c; Gairola *et al.* 2011b), structure and composition (Gairola *et al.* 2011c), and effects of slope aspects on tree diversity (Baduni and Sharma 1999; Sharma and Baduni 2000; Sharma *et al.* 2010d) on the dominant forest types were worked out. However, the studies on the effects of slope aspects on the C stocks in different forest types are still lacking. Under the backdrop of the aforesaid facts, the present study was undertaken in seven major forest types of temperate region of Garhwal Himalaya to assess the variation caused by slope aspects on the soil organic C and live tree C stocks.

2. Methods

2.1 *Study area*

The state of Uttarakhand is situated in the northern part of India and shares an international boundary with China in the north and Nepal in the east. It has an area of 53483 km^2 and lies between latitude 28° 43′ and 31° 28′ N and longitude 77° 34′ and 81° 03′ E. The state has a temperate climate except in the plain areas, where the climate is tropical. The average annual rainfall of the state is 1550 mm and temperatures range from sub-zero to 43°C (FSI 2009). Of the total geographical area of the state, about 19% is under permanent snow cover, glaciers and steep slopes where tree growth is not possible due to climatic and physical limitations (FSI 2009). The recorded forest area of the State is 34691 km^2, which constitutes 64.79% of its geographical area (FSI 2009).

The present study was conducted in temperate zone (1500 m a.s.l. to 3100 m a.s.l.) of district Pauri of Garhwal Himalaya in Uttarakhand state of India. Pauri Garhwal is situated in the central part of Garhwal Himalaya, between 29°20′–30°15′ N latitude and 78°10′–79° 20′ E longitude, covering about 5329 km^2, out of which 61.72% (3289 km^2) of the total geographical area is forested. The climate of study sites was typical moist temperate type. The region receives moderate to high snowfall from December to February on higher elevations. In the study area, the year is represented by three main seasons: the cool and relatively dry winter (December to March); the warm and dry summer (mid-April to June); and a warm and wet period (July to mid-September) called as the monsoon or rainy season. Meteorological data were taken from the state observatories of Gopeshwar and Pauri (table 1). Average annual rainfall in these areas ranged between 1125 mm and 2350 mm. The rainfall in rainy season accounts for about three-quarters of the annual rainfall. Apart from these main seasons, the transitional periods interconnecting rainy and winter, and winter and summer are referred to as autumn (October to November) and spring (February to March).

2.2 *Sampling and data analysis*

The general survey of the study area was carried out to determine the nature of terrain, tree composition, distribution and accessibility of different forest types in Pauri Garhwal. The working plans of Pauri, Lansdowne and Kaulagarh forest divisions were also consulted for the verification of details. After the reconnaissance survey, seven major forest types were selected for the study (table 1). The selected forest types were named according to the classification given by Champion and Seth (1968). This classification system is most widely accepted and used by forest managers in the region. These forest types are the major forest types of moist temperate region of northern Himalayan region and are also found throughout the Himalayan region from Nepal to Kashmir. We restricted our study to old-growth high forests having mostly native tree species, thus excluding plantations or managed forests. The study was conducted in seven forest types on four different aspects, viz. NE, NW, SE and SW each (total 28 stands). All the four forest stands in a particular forest type were part of same forest and had same age and upper diameter ranges. All the studied forest stands were part of the reserved forests, and therefore, anthropogenic disturbances were almost absent in these forest stands. However, a few natural disturbances, viz. cloud burst, landslides and wind fall were present at higher elevations, whereas at lower elevations the fires in the *Pinus roxburghii* forest were common during the warm and dry months (from mid-April to mid-June) especially on the drier southern aspects. Physiographic factors, i.e. elevation and slope aspect across different forest types, were measured by GPS (Garmin, Rino-130) and Abney's level. The trees were identified with the help of floras of Brandis (1906) and Gaur (1999).

Ten sample plots of 0.1 ha each were systematically laid out on each stand (total of 7×4×10=280) to represent the entire elevational gradient of a particular forest type (table 1). The height and dbh (diameter at breast height) of all the trees falling within the sample plot were measured. The 0.1 ha square plots were laid out by determining the plot centre. After laying out the plot, measurements were done on individual tree basis. 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. The true horizontal distance for those arms going against the slope was calculated using the following formula:

<EQUATION>$L = L_s \times \cos S$,

where L is the true horizontal plot distance, L_s is the standard distance measured in the field along the slope and S is the slope in degrees. The area of the sample plot was then calculated as:

<EQUATION>Area= Plot width × calculated true plot length (L).

The tree height was measured using a Ravi multimeter. The height of the trees on different slope positions was measured following MacDicken *et al.* (1991). Trees were considered to be individuals ≥ 10 cm dbh (i.e. 1.37 m) as per Knight (1963). The growing stock volume density (GSVD) was estimated using volume tables or volume equations based on the Forest Research Institute (FRI) and Forest Survey of India (FSI) publications for the respective species (FSI 1996). These volume equations were earlier developed by FRI and FSI using multiple regression methods in which basal area, girth or dbh along with height or form factor were taken into consideration. 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 as per convention by 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) (Brown *et al.* 1999). The BEF ($Mg\ m^{-3}$) is defined as the ratio of AGBD of all living trees at diameter at breast height (dbh) ≥ 2.54 cm to GSVD for all trees of dbh ≥ 12.7cm. The BEFs for hardwood, spruce-fir and pine were calculated using the following equations:

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

<EQUATION>BEF=1.0 (for GSVD $> 200\ m^3\ ha^{-1}$)

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

<EQUATION>BEF= 1.0 (for GSVD $> 160\ m^3\ ha^{-1}$)

<EQUATION>Pine: BEF= 1.68 $Mg\ m^{-3}$ (for GSVD $< 10\ m^3\ ha^{-1}$),

<EQUATION>BEF= 0.95 (for GSVD = 10–100 $m^3\ ha^{-1}$);

<EQUATION>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 by Cairns *et al.* (1997), the belowground biomass density (BGBD) (fine and coarse roots) was estimated for each forest type as following:

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

AGBD and BGBD were added to get the total biomass density (TBD). The total C density (TCD) was computed by using the following formula:

<EQUATION>TCD ($CMg\ ha^{-1}$) = Biomass ($Mg\ ha^{-1}$) × Carbon %

The C percentage of 46% was used for the forest types, where *Abies pindrow*, *Cedrus deodara*, *Pinus roxburghii* and all conifers together constituted more than 50%. For forest types where broadleaved species constituted more than 50%, the C percentage was taken as 45% (Negi *et al.* 2003; Manhas *et al.* 2006).

In each forest stand soil samples were collected from 0–30 cm depth from each sample plot (28 forest stands × 10 sample plots = 280 samples). To reduce variability, soil samples from five randomly selected points in each sample plot were collected and mixed together to form a composite soil sample. Soil samples were packed in bags and brought to the laboratory for organic C estimation. For organic C determination, the soil samples were sieved through a 2 mm sieve and then thoroughly mixed. Walkley and Black's rapid titration method (Walkley 1947) was used for organic C estimation, which is a widely used procedure (Brown 2004; Pearson *et al*. 2005) for organic C estimation because it is simple, rapid and has minimal equipment needs (Nelson and Sommers 1996). It is well established that about 60–86% of soil organic C (SOC) is only oxidized in the Walkley and Black method, therefore, a standard correction factor of 1.32 (considering recovery of 76% organic C) was used to obtain the corrected SOC values (De Vos *et al*. 2007).

In each sample plot, the bulk density of soil was measured by taking two aggregated undisturbed blocks of soil by metal cylinder of 30 cm length and 3 cm internal diameter. When taking cores for measurements of bulk density, extra care was taken to avoid any loss of soil from the samples. The exact volume of the soil taken by a metal cylinder was determined by measuring the volume of the cylinder. The soil samples were dried in an oven at 105°C for 72 h and then weighed until two subsequent values were constant. In the soils containing coarse rocky fragments, the coarse fragments were retained and weighed. The bulk density of the mineral soil core was calculated with the help of following formula described by Brown (2004):

<EQUATION: set space between g and cm^{-3}>

$$Bulk.density.(gcm^{-3}) = \frac{Oven.dry.mass.(gcm^{-3})}{Core.volume.(cm^{3}) - \left(\frac{Mass.of.coarse.fragments.(g)}{Density.of.rock.fragments.(gcm^{-3})}\right)}$$

where the bulk density is for the < 2 mm fraction, and coarse fragments are >2 mm. The density of rock fragments was taken as 2.65 g cm^{-3}.

Using the C concentration data obtained by the laboratory analysis the amount of SOC per hectare was calculated as (Brown 2004):

<EQUATION>SOC (Mg ha^{-1}) = [(soil bulk density (g cm^{-3}) × soil depth (cm) × C)] × 100

In this equation the C concentration was expressed as a decimal fraction. The Tukey *post hoc* test was used to test differences among means when the *F*-test was significant ($p \leq 0.05$). Significant differences are indicated by using different letters behind the means. Statistical analysis was performed using Minitab version 16 software.

3. Results and discussion

The associates of dominant tree species on various slope aspects in different forest types are shown in table 2. Results showing variation in stem density, tree biomass and C stocks on different aspects are placed in table 3. Stem density was lowest on NE aspect in moist *Cedrus deodara* forest type (380±34.2 N ha^{-1}) and highest on NE aspect in *Quercus leucotrichophora* forest type (1360±105.6 N ha^{-1}). AGBD varied between minimum of 134.1±10.6 Mg ha^{-1} on SW aspect of *Pinus roxburghii* forest type and maximum of 518.2±44.8 Mg ha^{-1} on NE aspect of *Cedrus deodara* forest type. Values of BGBD ranged from 35.0±2.5 Mg ha^{-1} on SW aspect of *Pinus roxburghii* to 115.6±10.5 Mg ha^{-1} on NE aspect of *Cedrus deodara* forest type. Total biomass density (TBD) was found to be minimum (169.2±13.1 Mg ha^{-1}) on SW aspect of *Pinus roxburghii* forest type and maximum (633.8±55.3 Mg ha^{-1}) on NE aspect of *Cedrus deodara* forest type. Minimum value of total tree C density (TCD) was recorded on SE aspect of *Quercus leucotrichophora* forest type (77.3±10.7 CMg ha^{-1}) and maximum value was recorded on NE aspect of *Cedrus deodara* forest type (291.6±25.4 CMg ha^{-1}). SOC varied between 40.3±5.5 CMg ha^{-1} on SW aspect in Himalayan *Pinus roxburghii* forest type and 177.5±15.4 CMg ha^{-1} on NE aspect in Moist *Cedrus deodara* forest type (figure 1). Total C density (SOC+TCD) values ranged between 118.1±13.3 CMg ha^{-1} on SW aspect in Himalayan *Pinus roxburghii* forest type and 469.1±40.8 CMg ha^{-1} on NE in Moist *Cedrus deodara* forest type (figure 1). SOC was significantly higher on northern aspects as compared with southern aspects. Except for *Quercus leucotrichophora* and *Pinus roxburghii* forest types, all the forest types showed descending trend of TBD and TCD as NE>NW>SE>SW. However, in *Quercus leucotrichophora* forest type, the trend was NE>NW>SW>SE, and in *Pinus roxburghii* forest type, the trend was NE>SE>NW>SE.

In this study we have recorded statistically higher values of tree biomass and tree C stocks on northern aspects as compared with southern aspects, which can be attributed to occurrence of moister and favourable environment on the northern aspects. This is because in Himalayas, the north- and south-facing slopes receive unequal solar radiation particularly from June 21 onwards when the Sun shifts towards the southern hemisphere. The north-facing slopes are relatively cooler as they receive less sunlight, while the south-facing slopes are considered as warmer and drier due to higher insolation (longer exposure) period during the day. This forms better growing conditions on the northern aspects than on the southern aspects. Moreover, the forests growing on the southern aspects are generally exposed to harsh climatic conditions and are prone to various natural disturbances like wind fall, wild fire, etc., which hinder accumulation of large amount of biomass on these aspects.

The soil and vegetation have a complex interrelation, because they develop together over a long period of time. As northern aspects are generally moister and cooler as compared with southern aspects, it also affected values of SOC. On southern aspects of pine forests in Garhwal Himalaya, frequent fires are common. This is due to the high inflammability of igniting material due to a low water content and high surrounding temperature. Moreover, higher temperature also favours the drying of woody and leafy components lying on the forest floor in these forests (Sharma and Rikhari 1997). The violent fires especially in the summer season results in the rapid deterioration of soil fertility, minimizing the possibility of invasion by new species. This helps in dominance of fire hardy pine forests on lower elevations and southern aspects. It can be attributed as the main cause of higher stem density and lower biomass and C stocks on southern aspects as compared with northern aspects. According to Banerjee and Chand (1981), burning in these forests can lead to an immediate reduction in total organic matter ranging from 33% to 50%. The higher values of SOC and TCD on northern aspects and higher values of stem density on southern aspects have been reported in this study, which may be attributed to prevalence of drier spurs on southern aspects as compared with northern aspects. Higher amounts of SOC are available on cooler and moister northern aspects, which may also be the probable cause for revealing higher live tree biomass on these aspects.

The prevention of deforestation and promotion of afforestation have often been cited as strategies to slow down global warming (Bala *et al.* 2007). Enhancing C sequestration by increasing forested land area (e.g. plantation forests) has been suggested as an effective measure to mitigate elevated atmospheric CO_2 concentrations and hence contributes to the prevention of global warming (Watson 2000). But conservation of forests having large amount of C stocks is also a valuable way to reduce CO_2 emission as it may be more beneficial than afforestation in the short run. Canadell and Raupach (2008) pointed out that the overall potential of management activities to increase C density can be substantial and comparable to that of reforestation. Forests often store C at rates well below their potential and thus could be responsive to management for enhanced C sequestration. The values of C density reported in the present study are higher than those reported by Tiwari and Singh (1987) for nearby forests of Kumaun Central Himalaya. This result may be attributed to the lack of disturbance in these stands. However, these values of aboveground C density are comparable to the values recorded by Singh *et al.* (1985) in nearby forests of Kumaun Central Himalaya. Most of the forest types studied in this study were mature, fully stocked, old-growth forests and had C stocks on the higher end of the values recorded for the forests of India and elsewhere in the world, which infers that these forests have higher amount of C stored in them.

4. Conclusions

Almost all the forest types have shown higher C stocks on the NE aspects followed by NW, SE and SW aspects. This has made clear that in temperate zone of Garhwal Himalaya northern aspects are more suited to have more stable communities along with more fertile soils, which eventually sustain higher C stocks. Temperate plantation forests have significant potential for C storage in tree biomass with an estimated mean value of 64 CMg ha^{-1} (Winjum and Schroeder 1997). For better results plantation silviculture in the temperate Himalayan region should be undertaken on the cooler northern aspects. The storage of higher C in on northern aspects emphasizes the importance of maintaining or increasing the number of protected areas for them. Therefore, for conservation purposes, mature forest stands growing on northern aspects having higher amounts of C should be preferred. This would have the largest per-unit-area-impact on reducing C emissions from deforestation.

Acknowledgements

The authors are thankful to Department of Science and Technology, Government of India, New Delhi, India, for providing financial support vide its Project No. SP/SO/PS-52/2004.

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MS received 21 January 2011; accepted 30 May 2011
*e*Publication: 00 August 2011
Corresponding editor: R GEETA

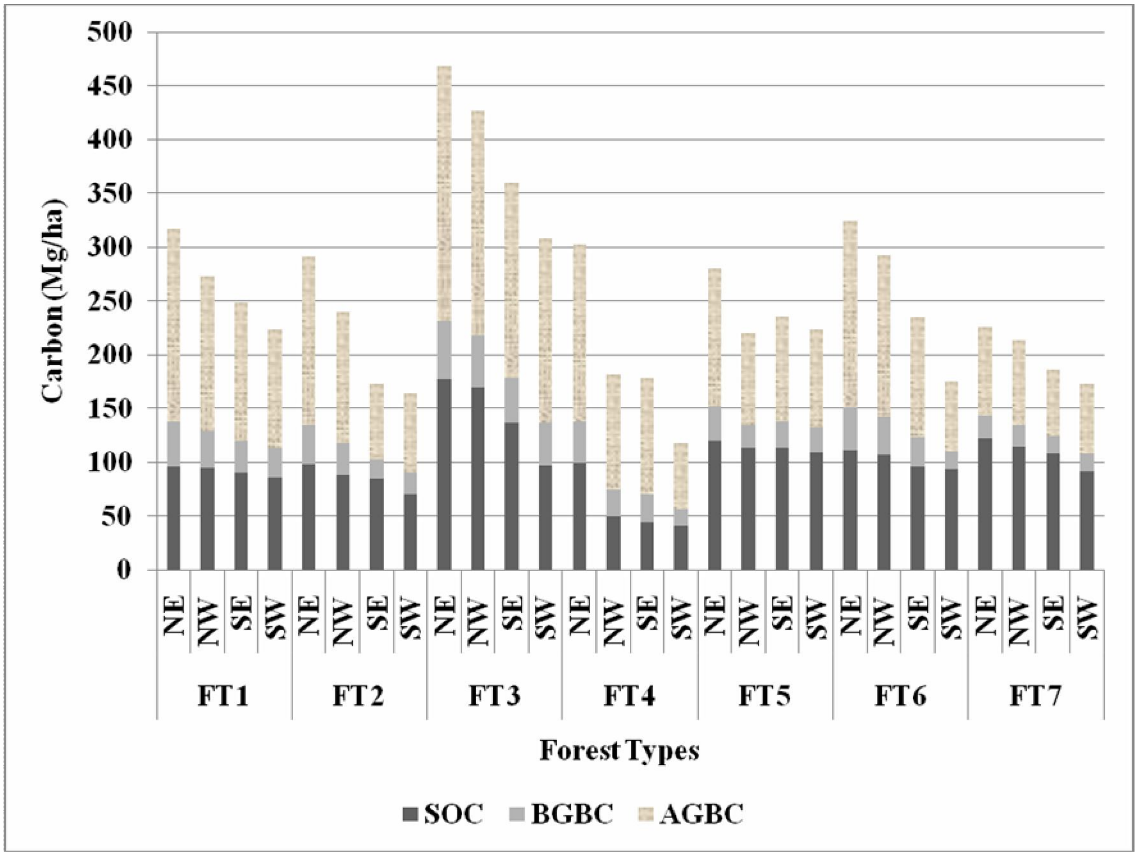

Figure 1. Density of Carbon in soil and tree biomass in various forest types on different slope aspects [SOC= soil organic carbon (up to 30 cm depth); BGBC= belowground biomass carbon (fine and coarse roots); AGBC= aboveground biomass carbon (in tree biomass > 10 cm diameter at breast height, i.e. 1.37 m); FT= forest type (for details see table 1)].

Table 1. General details of the forest types

FT	Forest type*	Type (according to Champion and Seth 1968)	Elevation (m, a.s.l.)	Location	Locality	Mean temperature range (°C)**		Mean annual rainfall (mm)**	Forest Area in Pauri District (ha)†
						Max	Min		
FT1	Upper West Himalayan *Abies pindrow* Spach. (Fir)	12/C_2 b	2600-3100	29° 43′ N, 79° 46′ E	Dudhatoli	20.8 (May)	1.2 (Jan)	1825	4595.80 (FT1+FT2)
FT2	*Quercus floribunda* Lindle (Moru Oak)	12/C_1b	2300-2600	29° 43′ N, 79° 46′ E	Dudhatoli	27.5 (Jun)	4.0 (Jan)	1475	
FT3	Moist *Cedrus deodara* Loud. (Deodar)	12/C_1c	2200-2500	30° 00′ N, 79° 09′ E	Binsar	26.4 (May)	5.7 (Jan)	1300	19.80
FT4	Himalayan *Pinus roxburghii* Sarg. (Chir Pine)	9/C_1b	1500-1800	30° 02′ N, 79° 03′ E	Thalisain	32.0 (May)	11.2 (Dec)	1320	26548.40
FT5	Upper West Himalayan *Quercus semecarpifolia* Sm. (Kharsu Oak)	12/C_2a	2500-3000	30° 09′ N, 78° 45′ E	Pauri	18.6 (May)	2.8 (Dec)	2350	2173.20
FT6	Himalayan *Cupressus torulosa* Don. (Cypress)	12/E_1	2100-2500	30° 08′ N, 78° 46′ E	Jhandidhar	25.5 (Jun)	5.5 (Jan)	1125	13.20
FT7	Lower West Himalayan *Quercus leucotrichophora* A. Camus (Banj Oak)	12/C_1a	1600-2100	30° 08′ N, 78° 47′ E	Buvakhal	28.7 (May)	6.8 (Jan)	1450	30373.80

*Forest types used as FT1 to FT7 in the successive tables, **source: Uttarakhand Forest Department and State Observatories of Uttarakhand, †source: Uttarakhand Forest Department.

Table 2. Associates of the dominant species on the different slope aspects

Forest Type	Dominant (Diameter range)	Associates			
		North-East Aspect	**North-West Aspect**	**South-East Aspect**	**South-West Aspect**
FT1	*Abies pindrow*	*Quercus semecarpifolia* *Rhododendron arboreum*	*Q. semecarpifolia* *R. arboreum* *Ulmus wallichiana* *Taxus baccata*	*Aesculus indica* *Q. semecarpifolia* *R. arboreum* *U. wallichiana*	*Q. semecarpifolia* *R. arboreum*
FT2	*Quercus floribunda*	*R. arboreum* *A. pindrow* *Lindera pulcherrima*	*R. arboreum* *Symplocos crataegoides* *Prunus cornuta* *Acer acuminatum*	*R. arboreum* *S. crataegoides* *Fraxinus micrantha*	*R. arboreum* *Q. leucotrichophora* *I. dipyrena*
FT3	*C. deodara*	*Q. leucotrichophora* *Lyonia ovalifolia*	*Pinus wallichiana* *R. arboreum*	*Q. floribunda* *Q. leucotrichophora* *R. arboreum*	*C. torulosa* *R. arboreum*
FT4	*Pinus roxburghii*	*M. esculenta*	*Q. leucotrichophora*	*Q. leucotrichophora* *L. ovalifolia*	–
FT5	*Q. semecarpifolia*	*A. pindrow* *R. arboreum*	*Q. floribunda*	*R. arboreum* *Ilex dipyrena* *C. deodara*	*R. arboreum* *I. dipyrena*
FT6	*C. torulosa*	*Pinus wallichiana* *R. arboreum* *Q. semecarpifolia* *Myrica esculenta*	*C. deodara* *R. arboreum* *M. esculenta*	*C. deodara*	*P. wallichiana* *R. arboreum* *Q. semecarpifolia* *C. deodara*
FT7	*Q. leucotrichophora*	*M. esculenta*	*M. esculenta* *R. arboreum*	*M. esculenta* *P. roxburghii*	*P. roxburghii* *R. arboreum*

Table 3. Variation in tree biomass and carbon stocks on different slope aspects

Parameters	**SA**	**FT1**	**FT2**	**FT3**	**FT4**	**FT5**	**FT6**	**FT7**
Density (N ha^{-1})	NE	530±24.8a	490±30.2a	380±34.2a	550±48.6a	540±33.5a	840±73.4a	1360±105.6a
	NW	450±20.6b	480±27.4a	500±41.3b	500±37.4a	620±44.5b	610±79.6b	840±98.5b
	SE	500±19.4a	560±20.4b	520±39.2b	710±52.2b	520±31.4a	780±92.2ab	540±47.8c
	SW	550±35.4a	610±19.8c	390±29.4a	980±60.8c	580±45.6ab	1010±89.5c	660±75.7bc
AGBD (Mg ha^{-1})	NE	389.9±32.5a	348.9±29.4a	518.2±44.8a	359.1±36.8a	287.1±26.7a	376.8±35.6a	182.4±15.6a
	NW	313.3±17.5b	272.7±23.5b	454.6±42.3ab	231.4±20.4b	190.5±20.8b	326.8±30.4a	176.5±21.2ab
	SE	278.5±15.3c	155.3±14.3c	393.3±32.3bc	234.8±24.5b	217.4±18.7b	241.9±19.8b	136.3±19.4b
	SW	239.7±24.4c	164.0±12.4c	371.7±36.8c	134.1±10.6c	202.1±19.8b	140.9±12.6c	142.5±14.5b
BGBD (Mg ha^{-1})	NE	89.9±7.5a	81.5±6.8a	115.6±10.5a	83.6±8.2a	68.6±6.2a	87.2±8.5a	45.9±3.6a
	NW	74.1±3.9b	65.6±5.6b	102.9±9.2ab	56.7±4.6b	47.7±5.1b	76.9±7.6a	44.6±4.8ab
	SE	66.8±3.3c	39.8±3.4c	90.6±8.3bc	57.4±5.6b	53.7±4.6b	58.9±4.9b	35.5±4.4b
	SW	58.5±5.6c	41.8±3.0c	86.2±9.4c	35.0±2.5c	50.3±5.2b	36.6±3.1c	36.9±3.8b
TBD (Mg ha^{-1})	NE	479.9±40.0a	430.4±36.2a	633.8±55.3a	442.7±45.0a	355.7±32.9a	464.0±44.1a	228.3±19.2a
	NW	387.4±21.4b	338.3±29.1b	557.6±51.5ab	288.1±25.0b	238.2±25.9b	403.7±38.0a	221.1±26.0ab
	SE	345.2±18.6c	195.1±17.7c	483.9±40.6bc	292.2±30.1b	271.0±25.3b	300.9±24.7b	171.8±23.8b
	SW	298.1±30.0c	205.9±15.4c	457.9±46.2c	169.2±13.1c	252.4±25.0b	177.5±15.7c	179.4±18.3b
TCD (CMg ha^{-1})	NE	220.7±18.4a	193.7±16.3a	291.6±25.4a	203.7±20.7a	160.1±14.8a	213.5±20.3a	102.8±8.6a
	NW	178.2±9.8b	152.2±13.1b	256.5±23.2ab	132.5±11.5b	107.2±11.7b	185.7±17.5a	99.5±11.7ab
	SE	158.8±8.6c	87.8±8.0c	222.6±18.7bc	134.4±13.9b	121.9±10.5b	138.4±11.4b	77.3±10.7b
	SW	137.1±13.8c	92.6±6.9c	210.6±21.2c	77.8±7.8c	113.6±11.2b	81.7±7.2c	80.7±8.2b
SOC (CMg ha^{-1})	NE	95.8±9.4a	97.6±8.5a	177.5±15.4a	99.3±11.1a	120.5±10.3a	111.1±10.3a	122.7±7.7a
	NW	94.9±8.2a	87.9±5.9a	170.0±12.7a	49.2±6.1b	112.9±8.9a	106.9±9.1ab	114.0±10.0ab
	SE	89.8±7.8a	85.0±7.5a	136.6±11.1b	44.4±5.0b	113.1±9.8a	95.7±9.5ab	108.4±6.1b
	SW	86.3±8.2a	71.0±5.7b	97.3±8.5c	40.3±5.5b	109.3±8.6a	93.2±6.8b	91.7±6.9c

Values in the rows followed by the same letter(s) are not significantly different ($P < 0.05$) according to the Tukey test.

± denotes standard error; AGBD, aboveground biomass density; BGBD, below round biomass density; SOC, soil organic carbon; SA, slope aspect; NE, north-east; NW, north-west; SE, south-east; SW, south-west; TBD, total tree biomass density; TCD, total tree carbon density.