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Biomass and carbon stock estimation across the timberline of Khangchendzonga National Park, Eastern Himalaya, India

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ABSTRACT: Globally it is recognized that the productive capacity, energy potential and capability to sequester carbon of forests can be conveniently indicated by the forest biomass and its carbon stocks. For the first time, present study explored the timberlines of Khangchendzonga National Park, Eastern Himalaya, India, with an aim to assess the status of biomass and carbon stock. Along 3800 m asl to 4000 m asl, in Dzongri landscape, we assessed nine major timberline sites for the estimation of total basal area, aboveground biomass, belowground biomass, total carbon and stem density. The total basal area varied between 99.55±1.90 and 4.50±2.41m^2 ha^{-1}. The total above ground biomass differed between 279.25±3.04 and 15.35±7.38Mg ha^{-1}, while the total below ground biomass ranged between 144.76±8.10 and 9.85±4.82Mg ha^{-1}. The total carbon content estimated between 195.03±2.32 and 11.59±5.61 Mg ha^{-1}. Among the studied environmental factors, elevation and humus were observed the determining factors for the tree growth and forest composition in the study area. The present investigation in the timberlines offers a potential platform for long term monitoring of climate change induced changes.

KEY WORDS: Biomass, Carbon stock, Eastern Himalaya, India, Khangchendzonga National Park, Timberline.

INTRODUCTION

The carbon dioxide (CO_2) is one of the principle greenhouse gases, which is responsible for the greenhouse effect, potentially influencing the global climate pattern (Brown, 1993). The global mean temperature has risen by 0.5°C during the last century (Kellomaki, 2000) and by 0.4°C during the last 70 years for the Indian sub-continent (Negi *et al*., 2003). About 60% of the global climate change is driven by the increasing level of CO_2 concentration in the atmosphere (Grace, 2004). In maintaining the regional and global carbon cycle, forest plays an important role (Brown *et al*., 1999). However, the global forest area changed from 31.6% of global land area in 1990 to 30.6% in 2015 (FAO, 2016). Amongst various ecosystems such as soil, grassland, forest and ocean, the forest ecosystem is considered as an important carbon sink (Vashum *et al*., 2012). Out of 2,050 gigatons (Gt) of carbon stored in the earth's terrestrial ecosystem, the forests contain an estimated 638 Gt carbon in the ecosystem as a whole and 238 Gt carbon as biomass alone (Nabuurs *et al*., 2007). In the forest ecosystem, the carbon is stored in five different pools *viz.* above ground biomass, below ground biomass, dead wood, litter and soil organic matter (Malhi *et al*., 2002). The above ground biomass includes all living biomass above the soil (stem, stump, branches, bark, seeds and foliage). Below ground biomass includes all live roots (Penman et al., 2003). The forest stores 86% of the above ground carbon and 73% soil carbon of the earth (Sedjo, 1993). Approximately 50% of the total woody biomass stored in the trees is present in the form of carbon (Birdsey, 1992; Brown and Lugo, 1982). Hence, quantification of biomass is important as an indicator of carbon stored in the forest ecosystem. Further, biomass estimation helps assessing forest structure and comparing functional and structural attributes of forest ecosystem across wide range of environmental conditions (Brown *et al*., 1999). The estimation of biomass and carbon is gaining importance (Sharma *et al*., 2010; Gairola *et al*., 2011; Beets *et al*., 2012; Ekoungoulou *et al*., 2014; Salunkhe *et al*., 2016), several countries act in accordance with the agreements of greenhouse gas emissions under the United Nations Framework Convention on Climate Change (Brown, 2002).

The protected areas encompass 12% of the land surface and contain over 312 Gt carbon (15.2%) of the global terrestrial carbon stock (Campbell *et al*., 2008). The protected areas may effectively reduce the probability of deforestation (8–9 times less) than non-protected areas (Soares-Filho *et al*., 2009). By the virtue of large amount of carbon stored in the protected areas, they could play a vital role in climate change mitigation (Campbell *et al*., 2008), particularly if they are devoid of any form of anthropogenic pressures. Furthermore, protected areas established in primary forests provide several benefits such as reduced deforestation, reduced forest conversion and climate change mitigation (DeFries *et al*., 2005; Burner *et al*., 2001; Devictor *et al*., 2007; Soares-Filho *et al*., 2010). Carbon emission from deforestation contributes to an estimated 20% of global

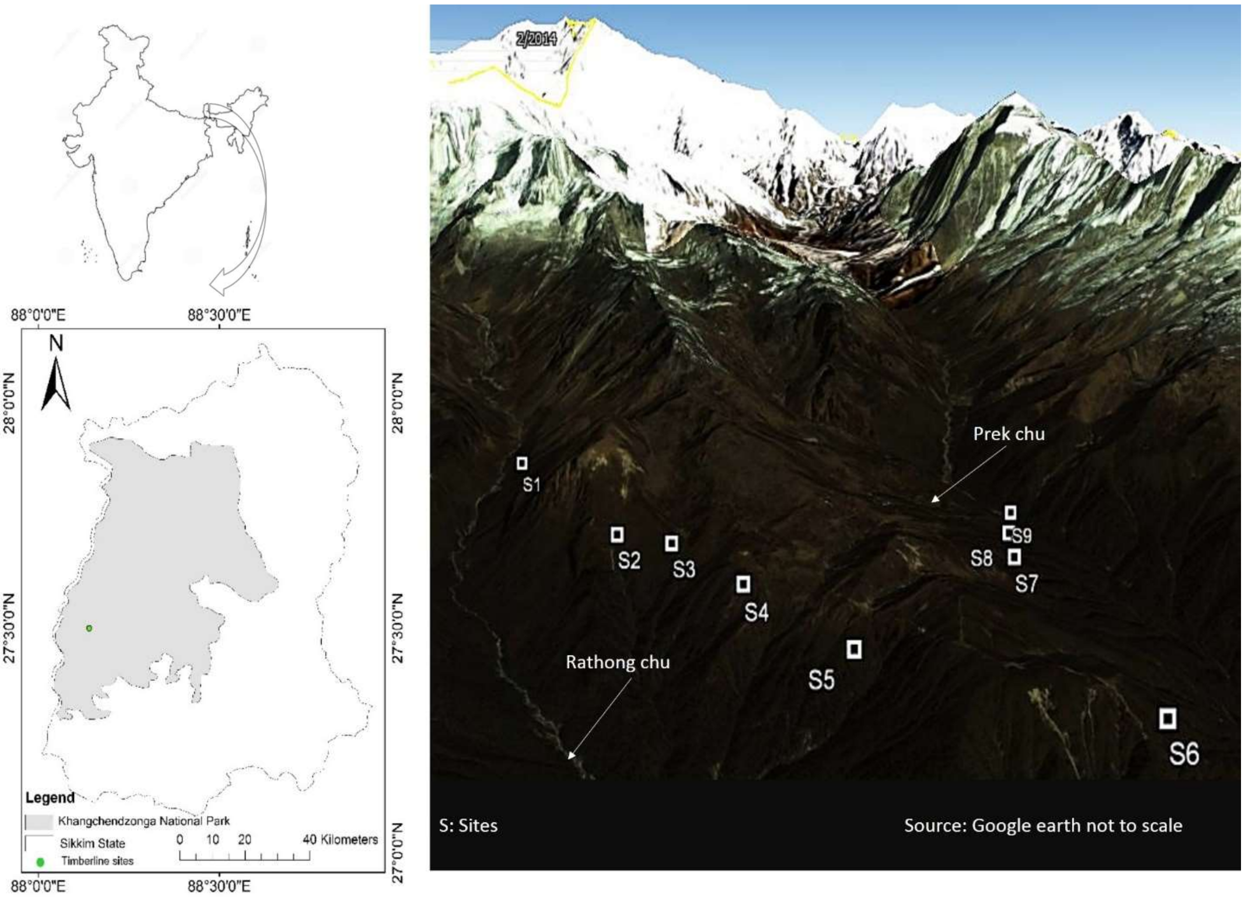

Fig. 1. Study area map of the Khangchendzonga National park with locations of study sites

carbon emission (IPCC, 2007). Therefore, protection of the existing carbon sinks is attaining prominence and being recognized (Campbell *et al*., 2008). Despite protected areas being recognized globally as an important mechanism for the conservation of biodiversity, their potential in reducing deforestation and greenhouse gas emission has so far not been fully investigated (Soares-Filho *et al*., 2009; Campbell *et al*., 2008). Studies concerning the contribution of temperate forests having protected status in carbon benefits are limited. Over 26.5% (39.3 million km^2) of the global terrestrial area is covered with mountains; whereas, the mountain protected areas constitute 32.5 % (17.3 million km^2) of the world's terrestrial protected area network (Rodriguez *et al*., 2011; Blyth, 2002; IUCN and UNEP-WCMC, 2010). The mountain forests cover 26.5% or 9.5 × 106 km^2 of the global closed forest area i.e., land with tree cover of canopy density greater than 70% (Kapos *et al*., 2000; Kapos, 2000; FAO, 2003). Further, these mountain forests hold a major carbon stock, with their ongoing carbon sequestration they can critically mitigate the climate change (Price *et al*., 2011)

The mountain ecosystems at temperate latitudes are considered to be the largest biotic carbon reserves (Schimel *et al*., 2002; Hassan *et al*., 2005). These regions are experiencing rapid climate change since the past few decades (Solomon, 2007). The Himalayas are considered as one of the biodiversity richest ecosystems of the world and harbor a wide range of forest types from foothills to alpine peaks (Mani, 1978). These regions encompass the highest timberline in the world (Shi and Wu, 2013). The timberline which forms the upper limit of forest on a mountain (Wardle, 1974) is consider to be sensitive to climate change (Korner, 2012) because climate related ecological factors dominating at the high altitude mainly control its distribution (Telwala *et al*., 2013). The rising atmospheric CO_2 concentration enhances the tree growth and further extends the timberline position (Korner, 2012). The response of the timberline to regional and global climate change can be better understood by understanding the carbon storage and allocation along the timberlines.

Numerous studies pertaining to biomass and carbon stock assessment have been carried out around the world (Brown *et al*., 1999; Segura and Kanninen, 2005; Beets *et al*., 2012; Ekoungoulou *et al*., 2014; etc.) and in India (Manhas *et al*., 2006; Gairola *et al*., 2011; Bhat and Ravindranath, 2011; Sharma *et al*., 2010; Salunkhe *et*

Table 1: List of volume equation and specific gravity used in the present study.

Species	Volume equation[1]	Type of equation[1]	Specific gravity[2]
Abies densa Griff.	$(0.01945/D^2+0.00009565+0.00002896H)*D^2$	G	0.336
Pieris villosa Hk. F.	$0.024659+0.00003492D^2H$	G	0.6
Prunus nepalensis (Ser) Stendel	$0.3555-0.037D+0.001259D^2$	L	0.51
Rhododenderon arboreum Sm.	$(0.306492+4.315360D-1.749908\sqrt{D})^2$	L	0.6
Rhododenderon hodgsonii Hk.F.	$(0.306492+4.315360D-1.749908\sqrt{D})^2$	L	0.6
Rhododenderon thomsonii Hk.F.	$(0.306492+4.315360D-1.749908\sqrt{D})^2$	L	0.6
Rhododendron fulgens Hk.f.	$(0.306492+4.315360D-1.749908\sqrt{D})^2$	L	0.6
Rhododendron lanatum Hk.F.	$(0.306492+4.315360D-1.749908\sqrt{D})^2$	L	0.6
Rhododendron wightii Hk.F.	$(0.306492+4.315360D-1.749908\sqrt{D})^2$	L	0.6
Sorbus thomsonii Decne.	$0.024659+0.00003492D^2H$	G	0.54

G: general; L: local; [1] FSI: 1996; [2] FRI, 1996

al., 2016; Subashree and Sundarapandian, 2017; etc.), yet, the studies pertaining to biomass and carbon stock assessment along the timberlines seem to be limited. Furthermore, the status of biomass and carbon present within a protected area is not fully explored. Keeping in view the aforementioned facts and lacuna, the present study was carried out in the timberline area of Dzongri, Khangchendzonga National Park, a UNESCO world heritage site, in Eastern Himalaya with the following objectives: (1) what is the status of the biomass and carbon stock along the upper elevational limit of forest i.e. timberline, in a protected area (2) how the carbon stock varied between different forests across the Himalaya (3) to understand the relationships between species composition, basal area, biomass, and environmental variables.

MATERIALS AND METHODS

Study area

The state of Sikkim situated in the Eastern Himalayas, India, lies between 27°00′46″ and 28°07′28″ N latitude and 88°00′58″ and 88°55′25″ E longitude (Fig.1), along 284 m asl to 8586 m asl. As biodiversity-rich state (O'Neill *et al*., 2017), it shares border with Nepal in the west, China in the north and northeast, Bhutan in the east and West Bengal in the south. Geographically, Sikkim covers 7096 sq km area. The total forest and tree cover of the state is 3392 sq km and covers 47.80 % of state's geographical area (ISFR, 2015). The present study was carried out in the timberline areas of Dzongri landscape along 3800-4000 m asl. Dzongri is situated within Khangchendzonga National Park (KNP; 1784 km^2), a recently inscribed UNESCO's World Heritage site and lies at a distance of 26 km or two days trek from Yuksam, West Sikkim. Whereas, the KNP is the core zone of Khangchendzonga Biosphere Reserve, which is included in the UNESCO World Network of Biosphere Reserves in July 2018. In the present study, the timberline is defined as the upper limit of timber yielding trees with crown cover ≥30% and connected with the subalpine conifer mix forest below.

Methods

We assessed a total of nine major sites for the biomass and carbon estimation along the timberline of Dzongri landscape of Khangchendzonga National Park. At each site, we marked three subplots of 50 m × 20 m size, within a plot of 150 m × 20 m. With a total of fifteen quadrates per site, within each three subplots, we laid five quadrates of 10 m × 10 m dimension in a random fashion to enumerate trees (≥10 cm diameter or ≥30 cm girth). All the sites contained one plot with three 50 m x 20m subplots each, except for Site-2 and Site-6 which consisted of two subplots each due to unavailability of accessible sampling area, due to unapproachable steep slopes. Therefore, the nine study sites consist a total of nine plots, 25 subplots and 125 quadrates. We considered trees having the diameter above 10 cm at breast height or girth above 30 cm. The diameter of the tree was recorded at a height of 1.37 m from the ground with the help of measuring tape. The height of the tree was measured using a hypsometer. The aspects of all the plots were recorded with the help of in built GPS compass (Garmin, Oregon 650).

Biomass and carbon estimation

Growing Stock density (GS): Our study involves the calculation of GS using the volume equation established by the Forest Survey of India (FSI, 1996). Species specific regional and local volume equation have been used for the different tree species (Table 1). In case of unavailability of the species-specific volume equation, we used a non-species-specific general volume equation. Local volume equations have limited application for a forest or small locality and are based only on diameter at breast height. Regional volume equations are normally based on two variables *viz.* diameter at breast height and height of the tree. It covers a wide range of distribution of species. General volume equations are broader based and covers the full geographical distribution of the species (FSI, 1996).

Above ground biomass density (AGB): We calculated AGB by multiplying the GS with the biomass expansion factor and volume weighted average wood density (Brown and Lugo, 1992).

Table 2: Total basal area, above ground biomass, below ground biomass, total carbon and stem density in different sites of Dzongri timberline of Khangchendzonga National Park.

Site	Aspect	Altitude (m asl)	TBA (m^2ha^{-1})	AGB ($Mg\ ha^{-1}$)	BGB ($Mg\ ha^{-1}$)	TC ($Mg\ C\ ha^{-1}$)	Stem density ($stem\ ha^{-1}$)
1	SW	3899	95.93±60.98a	242.92±154.32ab	117.20±72.00ab	165.38±104.17ab	287.22±89.37bc
2	W	3973	68.98±6.11a	185.63±11.31ab	94.23±1.00ab	128.74±5.67ab	376.0±104.0bc
3	W	3834	88.40±34.65a	230.08±90.42ab	115.07±42.67ab	158.77±61.21ab	307.0±71.63bc
4	E	3902	95.79±20.48a	221.23±56.14ab	124.19±30.89ab	158.92±40.02ab	497.11±93.54ab
5	NE	3950	78.86±14.93a	205.84±40.32ab	119.54±24.12ab	149.67±29.64ab	735.67±161.67a
6	SE	3787	99.55±1.90a	279.25±3.04a	144.76±8.10a	195.03±2.32a	414.0±106.0bc
7	SE	3950	24.61±9.29a	67.49±29.24ab	38.53±16.65ab	52.21±18.32ab	256.67±36.55bc
8	NE	3815	78.46±5.72a	273.89±27.96a	137.73±12.79a	187.36±20.41a	434.56±21.95b
9	SE	3989	4.50±2.41a	15.35±7.38b	9.85±4.82b	11.59±5.61b	118.0±30.29c
Total			**70.56367**	**191.30**	**100.12**	**134.19**	**380.69**

TBA: total basal area; AGB: aboveground biomass; BGB: belowground biomass; TC: total carbon; SD: stem density Values in each column represents mean±SD, the values followed by the same letter within a column are not significantly different from each other.

$$\mathrm{AGB} = \mathrm{V} \times \mathrm{D} \times \mathrm{BEF}$$

Where, AGB = Aboveground biomass, Mg of dry matter ha^{-1}, V = tree volume, $m^3\ ha^{-1}$, D = Volume weighted average wood density, Mg of oven-dry matter per m^3 of green volume, BEF = Biomass expansion factor (ratio of aboveground oven-dry biomass of trees to oven-dry biomass of commercial volume), dimensionless (Penman *et al.*, 2003).

Below ground biomass density (BGB): The BGB was calculated using the regressing equation $\mathrm{BGB} = \exp\{-1.059 + 0.884 \times \mathrm{In}\ (AGB) + 0.284\}$ given by Crains *et al.* (1997). However, the Total Biomass Density (TB) was calculated by adding-up the AGB and BGB. Similarly, the Total carbon density (TC) was calculated using the formula: $\mathrm{TC} = \mathrm{TB} \times \mathrm{Carbon}\ \%$. The 46% carbon content was applied for forest type where conifers constitute more than 50%. For the forest type constituting (i) more or less an equal proportion of conifers and broadleaf species (ii) more than 50% broad leaved species in the zone above 1500 m altitude, the 45% carbon content was applied (Negi *et al.*, 2003; Manhas *et al.*, 2006, Sharma *et al.*, 2010).

Statistical analysis

We used Analysis of variance (ANOVA) to compare the differences in means of total basal area (TBA), above ground biomass (AGB), below ground biomass (BGB), total carbon (TC) and stem density (SD) of tree species between different sites and their significant differences were tested using Duncan's multiple range test (DMRT). We used linear regression analysis (Snedecor and Cochran, 1967) to find out the relationship between total carbon and other parameters *viz.*, i) elevation; ii) species dominance; iii) species diversity; iv) species richness; v) stem density of the sites using SPSS (Version 20; SPSS Inc., Chicago, USA) statistical software package. Further, the Canonical correspondence analysis (CCA) was performed to understand the relationships between vegetation composition, basal area, biomass, total carbon and environmental variables across the nine study sites using PAST v.3.0 data analysis package (Hammer *et al.,* 2001).

RESULTS

The nine major study sites along Dzongri timberline of Khangchendzonga National Park consists a total of 25 subplots (50 m × 20 m) and nested within the subplots, 125 quadrates (10 m × 10 m). Longitudinally, the timberline of study area varied in topography and forest compositions; this variability in topography has shaped the elevational extant of the timberline vegetation between 3787–3989 m asl (Table 2). We recorded the lowest elevation at Site-6 and the highest at Site-9. Belonged to three families, *viz.*, Pinaceae, Rosaceae, and Ericaceae, we enumerated a total of ten tree species, *viz. Abies densa, Prunus rufa, Sorbus microphylla, Rhododendron arboreum, Rhododendron hodgsonii, Rhododendron lanatum, Rhododendron wightii, Rhododendron thomsonii, Rhododendron fulgens* and *Pieris villosa*. Table 2 summarizes the result of the present study pertaining to TBA, AGB, BGB, TC and SD in different study sites of Dzongri timberline in Khangchendzonga National Park.

In the present study, the total carbon content (mean±SD) ranged between 195.03±2.32 Mg ha^{-1} (Site-6) and 11.59±5.61Mg ha^{-1} (Site-9). The total above ground biomass (AGB) varied between 279.25±3.04 Mg ha^{-1} (Site 6) and 15.35±7.38 Mg ha^{-1} (Site 9) while the total below ground biomass ranged between 144.76±8.10 Mg ha^{-1} (Site 6) and 9.85±4.82 Mg ha^{-1} (Site 9). The total basal area (TBA) differed between 99.55±1.90 $m^2\ ha^{-1}$ (Site-6) and 4.50±2.41 $m^2\ ha^{-1}$ (Site-9). The stem density ranged between 735.67±161.67 stem ha^{-1} (Site-5) and 118.0±30.29 stem ha^{-1} (Site-9) (Table 2). Sites having the highest and the lowest values of TBA, AGB, BGB and TC correspond to the SE aspect. The regression analysis revealed that, across the sites total carbon possess a significant negative relationship with the elevation ($R^2 = 0.583$, $p<0.05$) and tree dominance ($R^2 = 0.634$, $p<0.05$), and a significant positive relationship with tree diversity ($R^2 = 0.580$, $p<0.05$), richness ($R^2 = 0.481$, $p<0.05$) (Fig. 2). Among the nine study sites, the diameter of the trees ranged

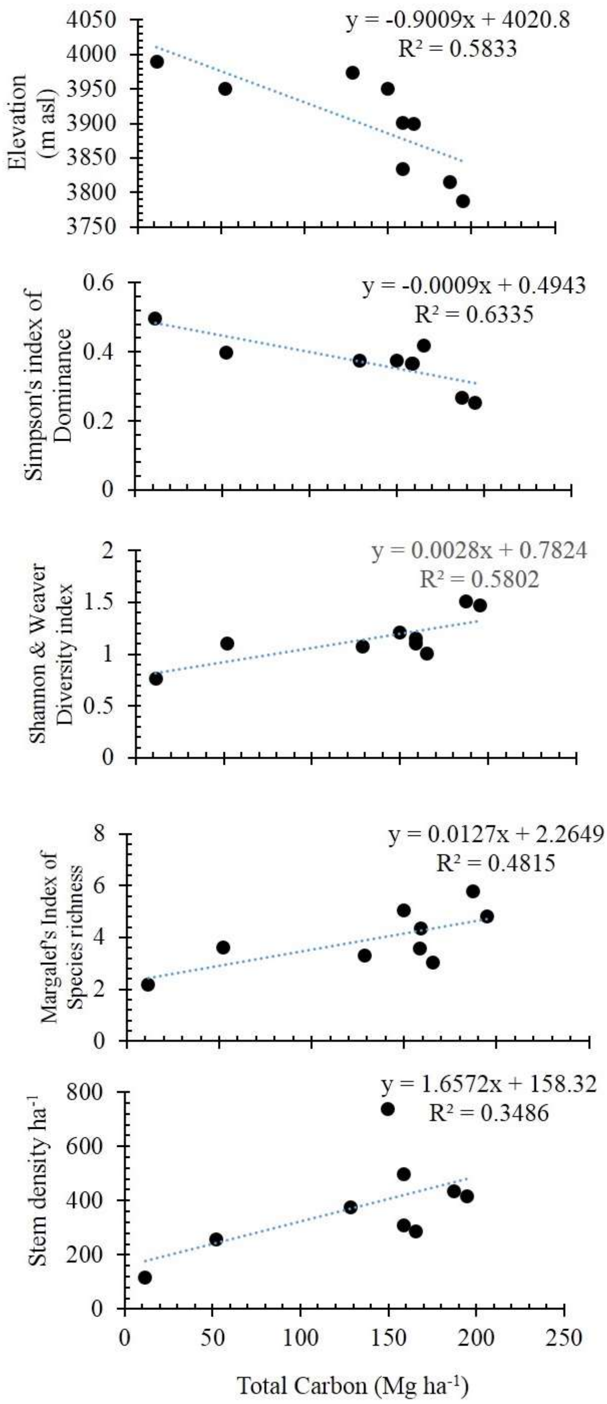

Fig. 2. Relationship of total carbon with elevation and vegetation composition Dominance index (Simpson, 1981), Diversity index (Shannon & Weaver, 1963), Species richness index (Margalef, 1958). N=9

between 9.87 cm to 151.54 cm at Site 2, we observed tree with highest diameter (151.54 cm). Of the total enumerated trees, 71.75% had diameter below 20 cm, which contributed to only 22.05% (1907.462 m^2 ha^{-1}) of the total basal area. Whereas the trees having diameter between 20-40 cm accounted to only 21.31% of the total tree enumerated and were responsible for 24.57% (2125.304 m^2 ha^{-1}) contribution to the basal area. The trees having diameter between: 40-60, 60-80 and 80-100 cm contributed to 3.41%, 1.77% and 0.88% of the total tree enumerated and 12.66% (1095.05 m^2 ha^{-1}), 12.83% (1109.51 m^2 ha^{-1}) and 10.94 % (946.18 m^2 ha^{-1}) of the total basal area, respectively. The trees with diameter > 100 cm contributed to 0.88% of the total tree enumerated and 16.96% (1466.707 m^2 ha^{-1}) of the total basal area (Fig. 3).

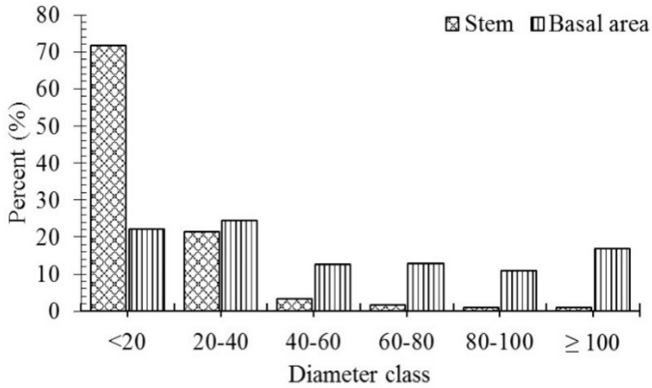

Fig. 3. Contribution of different diameter classes to the stem density and total basal area

The figure 4 shows the scattered plots generated through CCA (Hammer *et al.*, 2001). Among three environmental variables, elevation showed good positive correlation with axis 1 and other two (humus and slope) has shown a negative correlation with the axis 1 and axis 2. The total basal area (TBA) of the tree species has exhibited strong negative correlation with axis 3, above ground biomass with axis 1, total carbon with axis 2, tree species diversity with axis 2 and richness with axis 2 respectively. However, a strong positive correlation was observed in the below ground biomass (BGB) with axis 2, species dominance with axis 2, tree species richness, evenness and stem density with axis 3. Among study sites, site 9 has shown a good correlation with axis 1 (Supplement 1). The tree species dominance, evenness and stem density were most likely to be higher in the high elevations and under low humus. Clockwise, the quadrant I and II represents the sites of higher elevations with high dominance and evenness, the sites of quadrant I (site 5, 7, 9) were dominated by *Rhododendron* spp. and *Sorbus microphylla.* Quadrant III and IV represents the sites with greater values of humus, moderate slope and comparatively low elevation. Within these quadrants, sites (1 and 6) were purely, and sites (6 and 8) were partially dominated by *Abies densa* corresponding to the high biomass and carbon content. Further, the availability of good humus can be correlated to the high tree richness and diversity in quadrant III (Fig. 4).

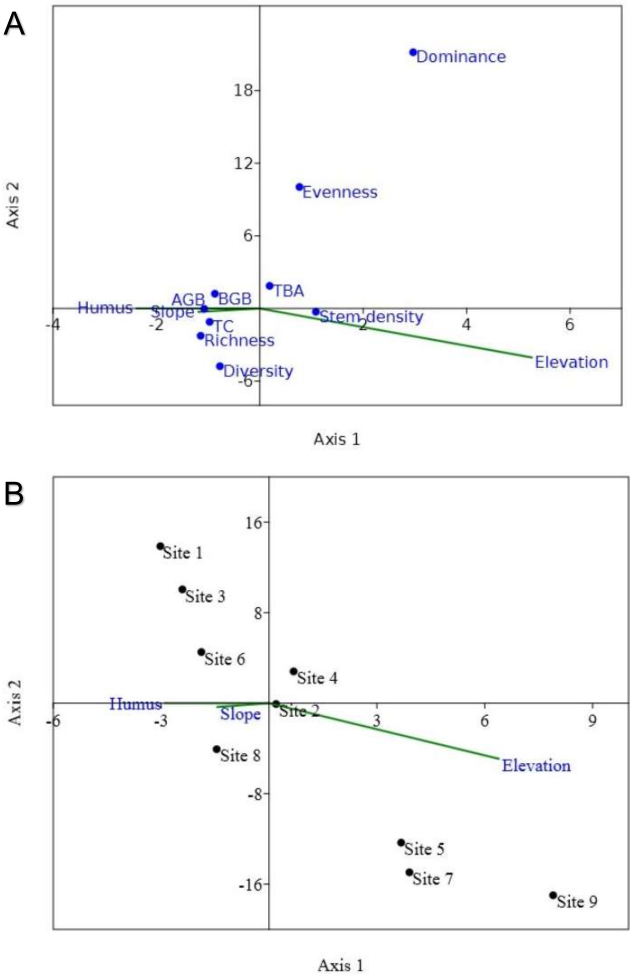

Fig. 4. Ordination diagram showing the result of CCA analysis. **A**. between vegetation composition and environmental variables, **B**. between environmental variables and the nine study sites. Abbreviations: TBA: total basal area; AGB: aboveground biomass; BGB: belowground biomass; TC: total carbon.

The forest of the nine study sites was categorized in to forest communities based on the dominant tree species of the stand. Based on dominant tree species, we categorized the timberline forests of nine study sites in to three major forest communities, *viz. Abies densa*, *Rhododendron* and conifer mixed forest community (Fig. 5). The *Abies densa* forest community (comprises of sites 1, 2, 4, and 6) was dominated by a conifer *Abies densa* (Gobre salla), however, the conifer mixed forest community (includes site 3, 5, 7, and 8) composed of of *A. densa* mixed with *Sorbus microphylla* and/or *Rhododendron* species (*R. lanatum, R. wightii, R. thomsonii, R. hodgsonii*). Similarly, the *R. lanatum, R. wightii* were the dominant tree species in the *Rhododendron* forest community (Site 9). The species richness varied among the forest communities and maximum species number was observed in coniferous mix community (10) followed by *Abies densa* (7) and *Rhododendron* (4). The total biomass (TB) and total carbon (TC) was contributed in their highest proportion (52%) by the *Abies densa* forest community (TB-352.428±193.456 Mg ha^{-1}; TC-162.046±89.025 Mg ha^{-1}), followed by (44%) conifer mixed (TB-297.0421±168.36 Mg ha^{-1}; TC-137.00±75.88 Mg ha^{-1}) and the least (4%) by the *Rhododendron* forest community (TB-25.202±21.138 Mg ha^{-1}; TC-11.593±9.723 Mg ha^{-1}). The Conifer mixed forest type made 44% contribution to the total biomass (297.045±168.363 Mg ha^{-1}) and total carbon (137.003±75.885 Mg ha^{-1}) (Fig. 5).

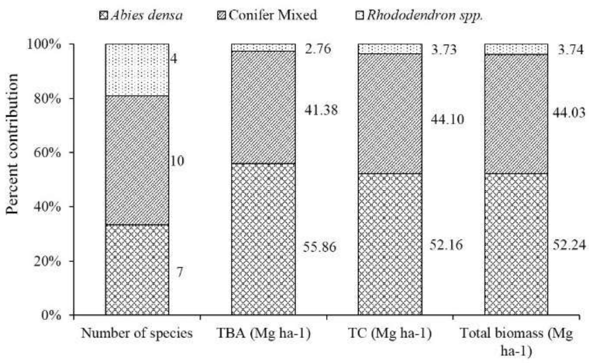

Fig. 5. Weightage of different forest communities in studied parameters of Dzongri timberline, Khangchendzonga National Park.

DISCUSSION

The global forests not only hold more than 75 percent of the world's terrestrial biodiversity (FAO, 2014) but also serve as huge carbon sink. One of the most important measures to mitigate the increasing level of atmospheric carbon dioxide is by increasing area under forest cover (Watson *et al*., 2000). Conservation of areas having large amount of carbon stock also proves to be an effective measure to sequester carbon dioxide (Sharma *et al*., 2010). For normally having rich floral diversity as well as high carbon stock, National Parks and Biosphere Reserves play an important role in reducing carbon dioxide concentration from the atmosphere. Our study site falls within Khangchendzonga National Park, in Sikkim, contributes to carbon sequestration process.

The timberline forms the upper elevational limit of forest (Holtmeier, 2009) and known for its high sensitivity to climate change (Korner, 2012), which responds through enhanced tree growth or upward movement or increased recruitment (Shi and Wu, 2013). Study on the status of biomass and carbon stock along the timberline is very crucial in order to monitor the response of the vegetation to climate change. The basal area and height of the trees helps estimation of biomass and carbon content of the forest. There exists a strong association between the basal area and the biomass content (Chiba, 1998) and as well as the carbon content. The larger basal area is responsible for a greater biomass

Table 3: Comparison of estimated biomass and biomass carbon of present study with other forest types of different regions.

Forest types	Regions	AGB (Mg ha-1)	AGC (Mg C ha-1)	TCD (AGC+BGC) (Mg C ha-1)	References
Asian forests	Asia	-	132.00-174.00	-	IPCC (1996)
Good forests	Central Himalaya	-	131.50-225.60	-	Singh *et al.* (1985)
Medium forests	Central Himalaya	-	75.20-131.50	-	Singh *et al.* (1985)
Poor forests	Central Himalaya	-	35.00-75.20	-	Singh et al. (1985)
Abies pindrow	India	-	65.03	-	Manhas *et al.* (2006)
Abies pindrow	India	209.80	104.90	-	Haripriya (2000)
Cedrus deodara	India	141.20	70.60	-	Haripriya (2000)
Mixed Conifers	India	-	46.79	-	Manhas *et al.* (2006)
Mixed Conifers	India	247.55	73.65	-	Haripriya (2000)
Abies pindrow	North-West Himalaya	305.33	140.45	173.72	Sharma *et al.* (2010)
Cedrus deodara	North-West Himalaya	434.43	199.84	245.31	Sharma *et al.* (2010)
Pinus roxburghii	North-West Himalaya	239.86	110.34	137.10	Sharma *et al.* (2010)
Cupressus torulosa	North-West Himalaya	271.63	124.95	154.82	Sharma *et al.* (2010)
Deciduous timberline	Central Himalaya	27-241	-	-	Garkoti and Singh (1995)
Tropical Rain Forests	Western Ghats	181.6-331.93	-	90.58-165.96	Bhat and Ravindranath (2011)
Moist deciduous	Western Himalaya	338.4-438.17	-	169.2-219.08	Shahid and Joshi (2015)
Savannah	Western Ghats	379.6-331.3	-	206.6-216.2	Subashree and Sundarapandian (2017)
Abies densa timberline	Eastern Himalaya	15.35-279.25	7.06-128.46	11.59-195.03	Present study
Abies densa forest	Eastern Himalaya	221.23-279.25	101.76-128.46	158.92-195.03	Present study
Conifer mixed forest	Eastern Himalaya	67.49-230.08	31.05-105.84	48.77-158.77	Present study
Rhododendron forest	Eastern Himalaya	15.35-205.84	7.06-94.69	11.59-149.67	Present study

AGB: aboveground biomass; AGC: aboveground carbon density; BGC: belowground carbon density; TCD: total carbon density; Mg: mega gram; ha: hectare; C: carbon; -: not available

and carbon content. Thus, our study Site-6 having the maximum basal area also reflects to maximum carbon content. The carbon allocation varies among the study sites depending upon their altitude and aspect. The basal area and the carbon content shows a decreasing trend against increasing altitude. The Site-9 identified at the highest altitude exhibited the lowest basal area and carbon content. We observed significant negative correlation of biomass and carbon with the increasing altitude, which can be attributed to the climatic variables (precipitation and temperature), that directly affect the net primary productivity (Wright, 1983; Currie, 1991; Carpenter, 2005). The climatic variables being the limiting factors at the higher altitude, responsible in reducing the net primary productivity of the plants despite of having the highest stem density, the Site-5 recorded the lower basal area and the carbon content. Due to the dominance of *Rhododendron* species, about 94% of the trees in the Site-5 had less than 100 cm circumference.

Various studies (Sharma *et al*., 2010; Gairola *et al*., 2011; Manhas *et al*., 2006; Haripriya, 2000) has shown a higher carbon density of the conifer dominated forest in comparison to the broadleaf dominated forest (Table 3). Studies reported that various tree types store carbon in the order - conifers > deciduous > evergreen > bamboo (Negi *et al*., 2003). In the present study, the *Abies densa* forest community and the conifer mixed forest community made a significant contribution of 52% and 44% to the total carbon content, respectively. There are indications that all the forest communities growing above 2000 m asl (conifer dominating communities) had more carbon stock than the forest of lower altitude (Sharma *et al*., 2010), this is an agreement with the results of our study that the conifer dominated forest plays vital role in carbon accumulation. In our study, the total carbon density ranged between 195.03±2.32 Mg/ha and 11.59±5.61 Mg/ha with *Abies densa* as the most dominant tree species. The maximum recorded carbon density in our study seems to be higher than those recorded for *Abies pindrow* and *Cedrus deodara* forests (Sharma *et al*., 2010; Gairola *et al*., 2011; Manhas *et al*., 2006 and Haripriya *et al*., 2000) (Table 3).

The old-growth forests may continue to sequester carbon and act as a carbon sinks, contrary to the view of old-growth forests to be carbon neutral (Luyssaert *et al*., 2008). The site having mature (large-diameter) trees harbors a higher amount of biomass and carbon as compared to sites maintaining greater density of young trees with lesser diameter (Salunkhe *et al*., 2016). In our study, despite the trees having diameter greater than 100 cm attributed to only 0.88 % of the total tree enumerated, however, they contributed to an impressive 16.96 % of the total basal area. With this, a positive correlation between the basal area and total carbon content strongly suggests that the large-diameter trees contribute significantly to the carbon sequestration process. Our study site located in a National Park, the large-diameter trees can continue to act as a carbon sink and help in climate change mitigation. The trees having lesser circumference but their substantial contribution to the total basal area (< 20 cm: 22.05%; 20–40 cm: 24.57%)) project great possibility that they will grow as large-diameter/mature trees and help in continuous carbon sequestration.

The canonical correspondence analysis congregates the sites of the high elevation (>3900m asl) with low humus in quadrant I and II, and sites with good humus with moderate sloppy terrain with comparatively low elevation range are represented by quadrant III and IV. The low tree diversity and richness leads to the species evenness and dominance, which results the lower TBA, AGB, BGB, and TC of sites particularly (site 9, site 7, site 5 and site 2), and can be held accountable to the high altitude where the growth limiting factors *viz.* precipitation and temperature play a vital role on their productivity (Wright, 1983; Currie, 1991; Rhode, 1992; Carpenter, 2005). The remaining sites, comparatively located at lower altitudes, clustered in a quadrant III and IV having higher side of TBA, AGB, BGB, and TC. Interestingly, in the present study, most of the sites located in the higher elevation are dominated by the *Rhododendron lanatum, Rhododendron wightii* and *Sorbus microphylla*. This indicates their adaptability to the drier habitats as only few tree species are capable to tolerate this threshold. Therefore, these sites possess high dominance and leads to the high species evenness. However, the sites in the lower elevation with good humidity represented the high species diversity and richness, and dominated by the *Abies densa,* which corresponds to the high TBA, AGB, BGB, and TC of these sites. In general, based on the CCA, the altitude can be regarded as one of the influencing factors for biomass production and subsequent carbon storage.

CONCLUSION

The biomass and carbon stock estimated in the timberline areas of Dzongri landscape in Khangchendzonga National Park, Eastern Himalaya was found out to be considerably higher despite of being situated at an altitude range of 3787–3989 m asl. This offers an advantage for carbon sequestration as our study site being a protected area benefits from the conservation practices with restricted anthropogenic disturbances. Furthermore, the timberline areas, one of the most sensitive ecosystems, situated within the protected areas can be monitored efficiently for their response to climate change. The protected areas, apart from their contribution towards biodiversity conservation, can be considered as carbon stocks and a potential solution for climate change mitigation. Further, our study sites within Khangchendzonga National Park can act as a potential study area for long term monitoring of climate induced vegetational changes and our opted methodology can be replicated across the Himalayas for a wider understanding in general.

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LITERATURE CITED

Beets, P.N., M.O. Kimberley, G.R. Oliver, S.H. Pearce, J.D. Graham and A. Brandon. 2012. Allometric equations for estimating carbon stocks in natural forest in New Zealand. Forests **3(3)**: 818-839.

Bhat, D.M. and N.H. Ravindranath. 2011. Above – Ground Standing Biomass and Carbon Stock Dynamics under a Varied Degree of Anthropogenic Pressure in Tropical Rain Forests of Uttara Kannada District, Western Ghats, India. Taiwania **56(2)**: 85-96.

Birdsey, R.A. 1992. Carbon storage and accumulation in United States forest ecosystems. United States Department of Agriculture, Forest Service, General Technical Report WO-59.

Blyth, S. 2002. Mountain watch: environmental change & sustainable developmental in mountains (No. 12). UNEP/Earthprint.

Brown, S. 1993. Tropical forests and the global carbon cycle: The need for sustainable land-use patterns. Agri., Ecos. Envir. **46(1-4)**: 31-44.

Brown, S. 1997. Estimating biomass and biomass change of tropical forests: A Primer. FAO Forest Resources Assessment Publication No. 134: 55

Brown, S. 2002. Measuring carbon in forests: current status and future challenges. Environ. Pollu. **116(3):** 363-372.

Brown, S. and A.E. Lugo. 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. Biotropica **14(3):** 161-187.

Brown, S. and A.E. Lugo. 1992. Aboveground biomass estimates for tropical moist forests of the Brazilian Amazon. Interciencia **17 (1)**: 8-27.

Brown, S., A.J. Gillespie and A.E. Lugo. 1989. Biomass estimation methods for tropical forests with applications to forest inventory data. For. Sci. **35(4)**: 881-902.

Brown, S.L., P. Schroeder and J.S. Kern. 1999. Spatial distribution of biomass in forests of the eastern USA. For. Ecol. Mang. **123(1)**: 81-90.

Bruner, A.G., R.E. Gullison, R.E. Rice and G.A. Da Fonseca. 2001. Effectiveness of parks in protecting tropical biodiversity. Science **291(5501)**: 125-128.

Campbell, A., L. Miles, I. Lysenko, A. Hughes and H. Gibbs. 2008. Carbon storage in protected areas: Technical report. The United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK.

Carpenter, C. 2005. The environmental control of plant species density on a Himalayan elevation gradient. J. Biogeograph. **32(6)**: 999-1018.

Chiba, Y. 1998. Architectural analysis of relationship between biomass and basal area based on pipe model theory. Ecol. Model. **108(1-3)**: 219-225.

Crains, M.A., S. Brown, E.H. Helmer and G.A. Baumgardner.1997. Root biomass allocation in the worls's upland forests. Oecologia **111(1)**: 1-11.

Currie, D.J. 1991. Energy and large-scale patterns of animal- and plant-species richness. The Ame. Natu. **137(1)**: 27-49.

DeFries, R., A. Hansen, A.C. Newton and M.C. Hansen. 2005. Increasing isolation of protected areas in tropical forests over the past twenty years. Ecol. Appli. **15(1)**: 19-26.

Devictor, V., L. Godet, R. Julliard, D. Couvet and F. Jiguet. 2007. Can common species benefit from protected areas? Biol. Cons. **139(1-2)**: 29-36.

Ekoungoulou, R., X. Liu, S.A. Ifo, J.J. Loumeto and F. Folega. 2014. Carbon stock estimation in secondary forest and gallery forest of Congo using allometric equations. Int. J Sci. Tech. Res. **3(3)**: 465-474.

FAO. 2003. State of World's Forests 2003. Food and Agriculture organization of the United Nations, Rome

FAO. 2014. State of the World's Forests 2014. Food and Agriculture organization of the United Nations, Rome (available at www.fao.org/forestry/sofo/en/).

FAO. 2016. Global Forest Resources Assessment 2015: How are the world's forests changing? Second edition. Food and Agriculture organization of the United Nations, Rome. P. 44.

FRI. 1996. Indian Wood their Identification, Properties and Uses. Volume 1-6. Forest Research Institute, Dehradun.

FSI. 1996. Volume Equations for Forests if India, Nepal and Bhutan. Forest Survey of India, Ministry of Environment and Forests, Govt. of India, Dehradun.

Gairola, S., C.M. Sharma, S.K. Ghildiyal and S. Suyal. 2011. Live tree biomass and carbon variation along an altitudinal gradient in moist temperate valley slopes of the Garhwal Himalaya (India). Curr. Sci. **100(12)**: 1862.

Garkoti, S. C. and S. P. Singh. 1995. Variation in net primary productivity and biomass of forests in the high mountains of Central Himalaya. J. Veg. Sci. **6(1)**: 23-28.

Grace, J. 2004. Understanding and managing the global carbon cycle. J. Ecol. **92(2)**: 189-202.

Hammer, Ø., D.A.T. Harper and P.D. Ryan. 2001. PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica* **4**: 1–9.

Haripriya, G.S. 2000. Estimates of biomass in Indian forests. Biom. Bioene. **19(4)**: 245-258.

Hassan, R.M., R. Scholes and N. Ash. 2005. Ecosystems and Human Well-being: Current State and Trends: Findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment. The Millennium Ecosystem Assessment Series, 1. Island Press, Washington, DC

Holtmeier, F.K. 2009. Mountain timberlines: ecology, patchiness, and dynamics (Vol. 36). Springer Science & Business Media.

India State of Forest Report, I.S.F.R. 2015. Forest Survey of India. Dehradun, India

IPCC. 1996. Climate change 1995: the science of climate change. Cambridge University Press, Cambridge, UK.

IUCN and UNEP-WCMC. 2010. The World Database on Protected Areas (WDPA): January 2010. UNEP-WCMC, Cambridge, UK.

http://www.wdpa.org/ (accessed 01/07/2017)

Kapos, V. 2000. UNEP-WCMC Web site: Mountains and mountain forests. Moun. Res. Deve. **20(4)**: 378-378.

Kapos, V., J. Rhind, M. Edwards, M.F. Price and C. Ravilious. 2000. Developing a map of the world's mountain forests. In: Price MF, Butt N. (eds.) Forests in Sustainable Mountain Development: A State of Knowledge Report for 2000. Wallingford: CABI: 4-9.

Kellomäki, S. 2000. Forests of the boreal region: gaps in knowledge and research needs. For. Ecol. Manag. **132(1)**: 63-71.

Körner, C. 2012. Alpine treelines: functional ecology of the global high elevation tree limits. Springer Science & Business Media.

Luyssaert, S., E.D. Schulze, A. Börner, A. Knohl, D. Hessenmöller, B.E. Law and J. Grace. 2008. Old-growth forests as global carbon sinks. Nature **455(7210)**: 213-215.

Malhi, Y., P. Meir, and S. Brown. 2002. Forests carbon and global Climate. Philosophi. Transact. Philos. Transact. A Math. Phys. Eng. Sci. **360(1797)**: 1567-1591.

Manhas, R.K., J.D.S. Negi, R. Kumar and P.S. Chauhan. 2006. Temporal assessment of growing stock, biomass and carbon stock of Indian forests. Clim. Chan. **74(1-3)**: 191-221.

Mani, M.S. 1978. Ecology and phytogeography of high altitude plants of the Northwest Himalaya. Oxford &IBH publishing Company, New Delhi, IN.

Margalef, D. R.1958. Information theory in ecology. Genetic. Systematic. 3:36-71

Nabuurs, G.J., O. Masera, K. Andrasko, P. Benitez-Ponce, R. Boer, M. Dutschke, E. Elsiddig, J. Ford-Robertson, P. Frumhoff, T. Karjalainen, W.A. Kurz, M. Matsumoto, W. Oyhantcabal, N.H. Ravindranath, M.J. Sanz Sanchez and X. Zhang. 2007. Forestry. In: Metz, B., O. R. Davidson, P. R. Bosch, R. Dave and L. A. Meyrer (Eds), Climate Change 2007: Mitigation. Contribution of III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York, 541-584.

Negi, J.D.S., R.K. Manhas and P.S. Chauhan. 2003. Carbon allocation in different components of some tree species of India: A new approach for carbon estimation. Curr. Sci. **85(11)**: 1528-1531.

O'Neill, A.R., H.K. Badola, P.P. Dhyani and S.K. Rana. 2017. Integrating ethnobiological knowledge into biodiversity conservation in the Eastern Himalayas, J. Ethnobiol. Ethnomed. **13(1)**:21.

Penman, J., M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe and F. Wagner. 2003. Good practice guidance for land use, land-use change and forestry IPCC National Greenhouse Gas Inventories Programme and Institute for Global Environmental Strategies, Kanagawa, Japan.

http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/GPG_LULUCF_FULL.pdf (accessed 11/06/ 2017).

Price, M.F., G. Gratzer, L.A. Duguma, T. Kohler, D. Maselli and R. Romeo. (eds) 2011. Mountain Forests in a Changing World - Realizing Values, addressing challenges. Published by FAO/MPS and SDC, Rome.

Rodríguez, D., B. Bomhard, S.H. Butchart and M.N. Foster. 2011. Progress towards international targets for protected area coverage in mountains: a multi-scale assessment. Biol. Cons. **144(12):** 2978-2983.

Salunkhe, O., P.K. Khare, T.R. Sahu and S. Singh. 2016. Estimation of tree biomass reserves in tropical deciduous forests of Central India by non-destructive approach. Trop. Ecol. **57**: 153-161.

Schimel, D., T.G. Kittel, S. Running, R. Monson, A. Turnipseed and D. Anderson. 2002. Carbon sequestration studied in western US Mountains. EOS **83(40):**445-449.

Secretariat of the Convention on Biological Diversity. 2009. Review of the Literature on the Links between Biodiversity and Climate Change: Impacts, Adaptation, and Mitigation (No. 42). UNEP/Earthprint.

Sedjo, R. A. 1993. The carbon cycle and global forest ecosystem. Water, Air, and Soil Pollution, **70**(1-4): 295-307.

Segura, M and M. Kanninen. 2005. Allometric models for tree volume and total aboveground biomass in a tropical humid forest in Costa Rica1. Biotropica **37(1)**: 2-8.

Shahid, M. and S.P. Joshi. 2015. Biomass and Carbon Stock Assessment in Moist Deciduous Forests of Doon Valley, Western Himalaya, India. Taiwania **60(2)**: 71-76.

Shannon, C.E. and W. Weaver. 1963. The Mathematical Theory of Communication. University of Illinois Press, Urbana, Illinois.

Sharma, C.M., N.P. Baduni, S. Gairola, S.K. Ghildiyal and S. Suyal. 2010. Tree diversity and carbon stocks of some major forest types of Garhwal Himalaya, India. For. Ecol. Manag. **260(12)**: 2170-2179.

Shi, P. and N. Wu. 2013. The timberline ecotone in the Himalayan region: an ecological review. In: Ning, Wu., G.S. Rawat, S. Joshi, M. Ismail, and E. Sharma (eds), *High-altitude rangelands and their interfaces in the Hindu Kush Himalayas*. Kathmandu: ICIMOD, pp 108-116.

Simpson, G.B. 1981. Meaning dominance and semantic context in the processing of lexical ambiguity. J. Verbal Learn. Verbal Behave. **20(1)**:120-136.

Singh, J.S., A.K. Tiwari and A.K. Saxena. 1985. Himalayan forests: a net source of carbon for the atmosphere. Env. Cons. **12(1)**:67-69.

Snedecor, G.W. and W.G. Cochran. 1967. Statistical methods. Iowa state. University Press, 327, pp-12.

Soares-Filho, B., P. Moutinho, D. Nepstad, A. Anderson, H. Rodrigues, R. Garcia and R. Silvestrini. 2010. Role of Brazilian Amazon protected areas in climate change mitigation. PNAS **107(24)**: 10821-10826.

Soares-Filho, B.S., L. Dietzch, P. Moutinho, A. Falieri, H. Rodrigues, E. Pinto, C.C. Maretti, C. Scaramuzza, A. Anderson, K. Suassuna, M. Lanna and F. Araujo. 2009. Reducing carbon emissions from deforestation: the role of ARPA's protected areas in the Brazilian Amazon. Federal University of Minas Gerais, Amazon Institute for Environmental Research (IPAM), Woods Hole Research Centre (WHRC), WWF-Brazil.

Solomon, S. (Ed.). 2007. Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC (Vol. 4). Cambridge University Press.

Subashree, K. and S. Sundarapandian. 2017. Biomass and carbon stock assessment in two savannahs of Western Ghats, India. Taiwania **62(3)**: 272-282.

Vashum, K.T. and S. Jayakumar. 2012. Methods to estimate above-ground biomass and carbon stock in natural forests - A Review. J. Ecos. Ecograp. **2(4)**:1-7.

Wardle, P. 1974. Alpine timberlines. In: Ives JD, Barry RG (eds) Arct alp environments. Methuen, London, pp 371-402

Watson, R.T., I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo and D.J. Dokken. 2000. Land use, land-use change and forestry. A special report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge: Cambridge University.

World Bank. 2009. Convenient Solutions to an Inconvenient Truth: Ecosystem-based Approaches to Climate Change. The International Bank for Reconstruction and Development, Washington D.C. available at https://siteresources.worldbank.org/ENVIRONMENT/Resources/ ESW_EcosystemBasedApp.pdf (accessed 01/07/2017)

Supplement 1. Inter-set correlations of 21 variables with CCA axes.

Variables	Axis 1	Axis 2	Axis 3
Elevation	0.751257	-0.578052	0.591833
Humus	-0.340171	0.00117271	-0.160157
Slope	-0.169221	-0.0398878	-0.235156
TBA	0.190641	1.86981	-2.45219
AGB	-1.07504	-0.0266383	0.145855
BGB	-0.868364	1.22012	1.04013
TC	-0.970302	-1.10056	-0.56328
Dominance	2.96651	21.1699	14.1388
Diversity	-0.77179	-4.76759	2.70057
Richness	-1.14388	-2.25268	5.39064
Evenness	0.768134	10.041	10.338
Stem density	1.08493	-0.271073	0.205198
Site 1	-0.214247	0.0678155	-0.0855552
Site 2	0.0139381	-.000361697	-.00497061
Site 3	-0.170798	0.0491568	-0.0594403
Site 4	0.0484697	0.0137378	-0.0192199
Site 5	0.260491	-0.0602304	0.0547536
Site 6	-0.133462	0.0220858	-0.0305827
Site 7	0.276815	-0.0730646	0.110872
Site 8	-0.103298	-0.0198758	0.020222
Site 9	0.560286	-0.0829823	0.301248