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Altitudinal variation of soil organic carbon stocks in temperate forests of Kashmir Himalayas, India

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Abstract Soil organic carbon stocks were measured at three depths (0–10, 10–20, and 20–30 cm) in seven altitudes dominated by different forest types viz. *Populus deltoides*, 1550–1800 m; *Juglans regia*, 1800–2000 m; *Cedrus deodara*, 2050–2300 m; *Pinus wallichiana*, 2000–2300 m; mixed type, 2200–2400 m; *Abies pindrow*, 2300–2800 m; and *Betula utilis*, 2800–3200 m in temperate mountains of Kashmir Himalayas. The mean range of soil organic carbon (SOC) stocks varied from 39.07 to 91.39 Mg C ha^{-1} in *J. regia* and *B. utilis* forests at 0–30 cm depth, respectively. Among the forest types, the lowest mean range of SOC at three depths (0–10, 10–20, and 20–30 cm) was observed in *J. regia* (18.55, 11.31, and 8.91 Mg C ha^{-1}, respectively) forest type, and the highest was observed in *B. utilis* (54.10, 21.68, and 15.60 Mg C ha^{-1}, respectively) forest type. SOC stocks showed significantly (R^2=0.67, P=0.001) an increasing trend with increase in altitude. On average, the percentages of SOC at 0–10-, 10–20-, and 20–30-cm depths were 53.2, 26.5, and 20.3 %, respectively. Bulk density increased significantly with increase in soil depth and decreased with increase in altitude. Our results suggest that SOC stocks in temperate forests of Kashmir Himalaya vary greatly with forest type and altitude. The present study reveals that SOC stocks increased with increase in altitude at high mountainous regions. Climate change in these high mountainous regions will alter the carbon sequestration potential, which would affect the global carbon cycle.

Keywords Soil organic carbon · Coniferous forests · Altitudinal variation · Broadleaved forest · Kashmir Himalayas · Soil bulk density

Introduction

Himalayan ecosystems are vulnerable to climate change and play an important role in global carbon cycle because of their large carbon stocks and potential sensitivity to climate change (Yang et al. 2007). High-altitude forests have greater potential of soil carbon sequestration compared to forests at lower altitudes (Zhu et al. 2010; Charan et al. 2012; Wei et al. 2013). Forests act as one of the largest carbon sinks and helps to control atmospheric CO_2 concentrations. Soil organic carbon (SOC) is considered to be one of the largest carbon pools of the terrestrial ecosystems and also plays a vital role in the global carbon (C) cycle (Batjes 1996; Lal 2004, 2005; Piao et al. 2009). Forest soil contains a globally significant amount of C, approximately half of earth's terrestrial C (1146×10^{15} g), and of this amount, about two thirds is

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retained in soil pools (Dixon et al. 1994; Johnson and Curtis 2001; Goodale et al., 2002). Temperate forest ecosystems contain a significant amount of SOC, both globally (Zhu et al. 2010; Pan et al. 2011) and regionally (Dar and Sundarapandian 2013). There is a great spatial variability on SOC stocks in mountainous regions due to their heterogeneous environment, soil type, land use and topography (Hoffmann et al. 2014). Matus et al. (2014) have stated that climate, vegetation types, soil microbiology and particularly altitude are the effective predictors of SOC stocks in mountainous regions and have opined that decomposition and accumulation of C in these soils are related to processes of stabilization.

It has been estimated that present C stock in the world's forests is 861±66 Pg C, of which 383±30 Pg (44 %) is in soil up to a depth of 1 m (Pan et al. 2011). Temperate forest contribution to world forest C stock is 14 % (119±6 Pg, Pan et al. 2011). Based on average global or regional soil C densities estimated in Indian forest soils, it has been calculated that SOC pool ranges from 5.4 to 6.7 Pg (Ravindranath et al. 1997; Dadhwal et al. 1998), while Chhabra et al. (2003) have estimated that the total SOC pools in Indian forests in the top 50 cm and top 1 m soil depths were 4.13 and 6.81 Pg, respectively. SOC is normally estimated to a depth of 0–30 cm since most of it is present in the top layers and root activity is also concentrated in this horizon (Ravindranath and Ostwald 2008). It is estimated that the global stock of SOC is in the range 684–724 Pg to a depth of 30 cm and 1462–1548 Pg to a depth of 1 m (Batjes 1996). Thus, the quantity of SOC in the 0–30 cm layer is about twice the amount of C in atmospheric carbon dioxide (CO_2) and three times that in global aboveground vegetation (Powlson et al. 2011). It was estimated in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) that the annual release of CO_2 from deforestation (coming from both vegetation and soil) is currently about 25 % of that from fossil fuel burning (IPCC 2007). A small change in soil C results in a large change in atmospheric concentration (Raich and Schlesinger 1992; IPCC 2000; Johnston et al. 2004). It is essential to study the mechanisms and changes of forest SOC to better understand and mitigate climate change (Fang et al. 1996; Powlson et al. 2011). There is a great influence of forest types on SOC stocks in subalpine regions, which constitutes the major proportion of the ecosystem C (Uri et al. 2012; Zhang et al. 2013).

Mountainous cold temperate areas have high SOC content but have large spatial variability, due to differences in climate and vegetation (Li et al. 2010). This spatial variability has made it difficult to predict the spatial distribution of SOC in forest soils (Yanai et al. 2000; Fahey et al. 2005). Various studies have reported the influence of topography (Yoo et al. 2006), climatic conditions (Leirós et al. 1999; Davidson and Janssens 2006), soil composition (Jobbágy and Jackson 2000), litter quality and its decomposition rate (Yang et al. 2005; Sariyildiz 2008), and species composition or vegetation type (Liski 1995; Schulp et al. 2008; Li and Han 2008) on the spatial distribution of SOC.

The Himalayas are among the youngest mountain ranges on the planet and consist mostly of sedimentary and metamorphic rocks. In India, the Himalaya occupies 16.2 % of the total geographical area and spans over 12 states of the country. The Himalayas in India are categorized into Northern Himalaya, Western Himalaya, Central Himalaya, and Northeastern Himalaya (Nautiyal et al. 2005). The geographical area of the Jammu and Kashmir state is 101,387km^2, and from which, 20,230km^2 is under forest cover. The vegetation of the area is described as temperate type with conifers as the main component. There is a great altitudinal variation among the forest types. The low-lying (1550–2000 m) temperate forests in the area are mainly composed of broad-leaved species such as *Populus deltoides*, *Juglans regia*, *Salix* species, *Ulmus villosa*, etc., whereas the mid-altitude (2000–2800 m) forests are composed of conifers like *Pinus wallichiana*, *Cedrus deodara*, *Abies pindrow* and *Picea smithiana*; however, in high altitude (2800–3250 m), *Betula utilis* is dominant and constitutes as the timber line. These seven forest types are the major ones in the study area. *Populus deltoides* and *J. regia* forest types are managed plantations and are mono-dominant. Understory shrub vegetation is absent in these forest types, as they are managed plantations, and these are highly disturbed due to anthropogenic pressure and grazing by local livestock. The mid-elevation coniferous (*C. deodara*, *Pinus wallichiana*, mixed coniferous, and *A. pindrow*) forests are natural and understory vegetation is dominated by shrub and herb species of *Viburnum grandiflorum* and *Stipa sibirica*, respectively. However, in high altitude, broad-leaved natural forest has low tree density and understory vegetation is dominated by *Rhododendron anthopogon* and *Malva neglecta*. In Kashmir Himalayas, no work on SOC stocks along an altitudinal gradient has been done so far; hence, the present study was aimed to the following: (1) estimate SOC stocks along an altitudinal gradient of 1550 to 3250 m in temperate forests of Kashmir Himalayas and (2) estimate bulk density along an altitudinal gradient in temperate forests of Kashmir Himalayas. This study will provide a baseline soil C stock data, which helps to assess the plausibility of diverse published inventory data.

Materials and methods

Study area

The present study was conducted in temperate zone (1550 to 3200 m) of Anantnag district of Kashmir Himalayas in the Jammu and Kashmir (J&K) state of India (Fig. 1). Anantnag is situated in southern part of the Kashmir Himalaya and is one of the southern-most districts of the J&K state, between 33° 45′–34° 15′ N latitude and 74° 02′–75° 32′ E longitude, covering about 3984 km^2, out of which 36.09 % (1438 km^2) of the total geographical area is forested (FSI 2011). This temperate region receives moderate to high snowfall from December to February. Average annual precipitation in this area ranged between 844 and 1213 mm, and the mean monthly temperatures range from −8.3 to 26 °C (Fig. 2). The study was carried out in seven different altitudes and the forest types have been selected based on the dominant tree species: *Populus deltoides*, 1550–1800 m; *J. regia*, 1800–2000 m; *C. deodara*, 2050–2300 m; *Pinus wallichiana*, 2000–2300 m; mixed type, 2200–2400 m; *A. pindrow*, 2300–2800 m; and *B. utilis*, 2800–3200 m. A total of 59 plots of 50×50 m^2 (0.25 ha) each were selected along an altitudinal gradient for the detailed study (Table 1). The number of plots (50 m×50 m) selected in each forest type was proportional to total cover of each forest type in this mountainous region.

Soil sampling and laboratory analysis

Fifteen soil samples were collected randomly from each forest plot at three depths 0–10, 10–20, and 20–30 cm. Five composite samples (three are mixed together for each) from each forest plot were brought to the laboratory for further analysis. Soil samples were collected with the help of soil core sampler from July to October of 2013 and analysis for the determination of SOC was done after air-drying and sieving the soil samples through a 1 mm mesh sieve. For organic C estimation, Walkley and Black's method (Walkley 1947) was used, which is a widely used procedure (Pearson et al. 2005). In Walkley and Black's method, about 60–86 % of soil organic carbon (SOC) is oxidized; therefore, a highly recommended standard correction factor of 1.58 was used to obtain the corrected SOC values (de Vos et al. 2007; Latte et al. 2013).

For bulk density in each forest type, 15 aggregated undisturbed soil cores from each depth (0–10, 10–20, and 20–30 cm) were taken by soil core sampler having 5 cm internal diameter. While taking cores for measurement of bulk density, extra care was taken to avoid any loss of soil from the samples. The soil samples were weighed immediately and transported to the laboratory where they were oven-dried at 105±5 °C for 72 h and weighed. In the soils containing coarse rocky fragments, the coarse fragments were separated by a sieve and weighed. The bulk density of the soil core was calculated with the help of the following formula described by Pearson et al. (2005):

$$\text{Bulk density}\left(\text{g/m}^3\right) = \frac{\text{Oven dry mass}\left(\text{g/m}^3\right)}{\text{Core volume}\ (\text{m}^3) - \left(\text{Mass of coarse fragments (g)} \ / \ 2.65\left(\text{g/cm}^3\right)\right)}$$

whereas 2.65 was taken as constant for the density of rock fragments (g/cm^3).

Soil C stock was then calculated for each soil layer based on the thickness of the soil layer, its bulk density and C concentration. The total C content of 30-cm depth was finally estimated by summing up the C content of all layers (Pearson et al. 2005).

$$\text{SOC}\ \left(\text{Mg ha}^{-1}\right) = \left[\left(\text{soil bulk density}\left(\text{gm}^{-3}\right)\ \times\ \text{soil depth (cm)}\ \times\ \text{C}\right)\right]\ \times\ 100$$

Soil moisture (%) was measured at three different depths (0–10, 10–20, and 20–30 cm) by the gravimetric method.

The forest floor standing crop litter in soil surface was collected randomly from ten quadrates by using a 1×1 m^2 wooden frame in each plot, weighed in situ and then taken the representative samples in triplicate to laboratory and were kept in an oven at 65 °C for 48 h, and dry weight was measured.

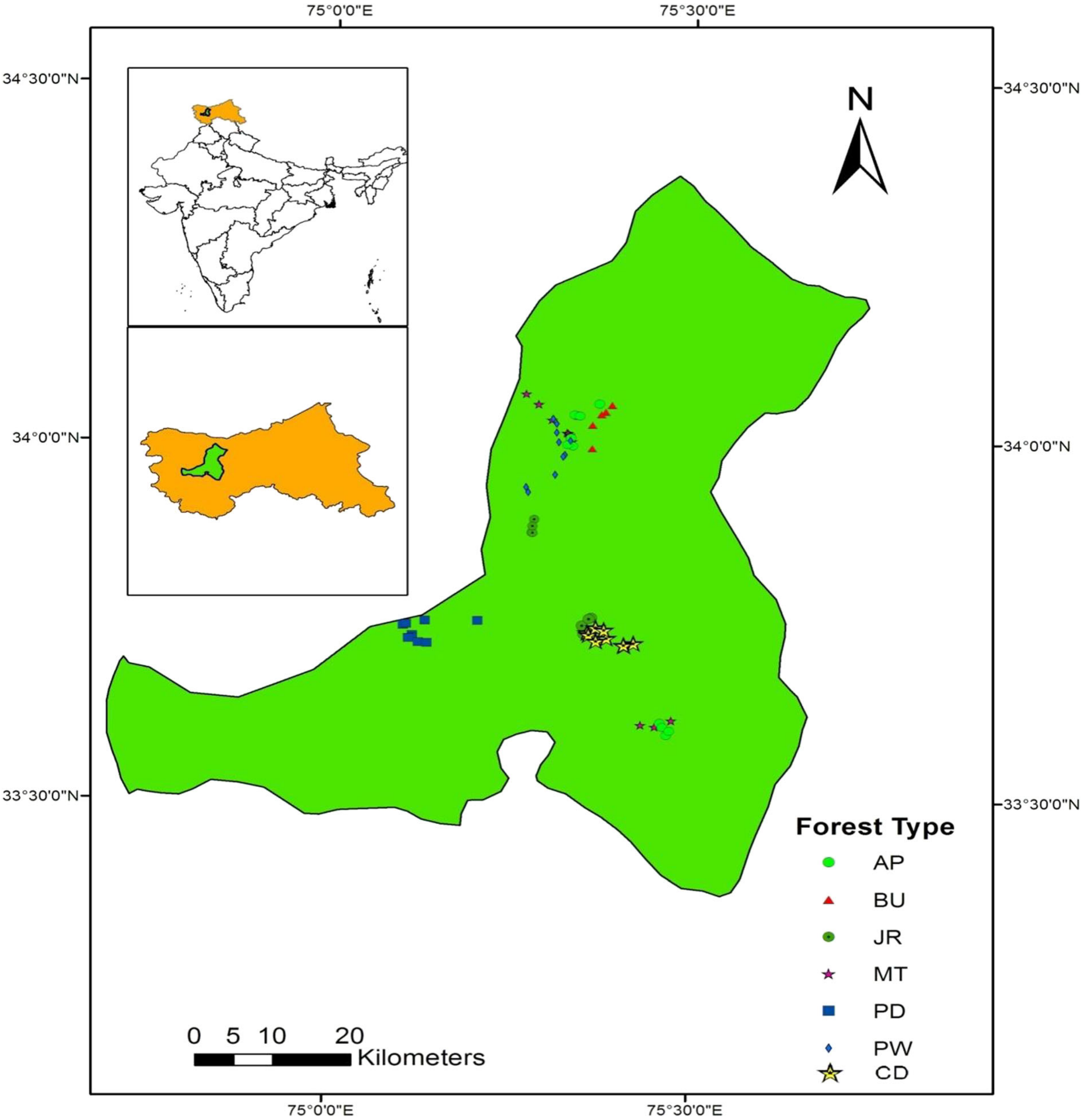
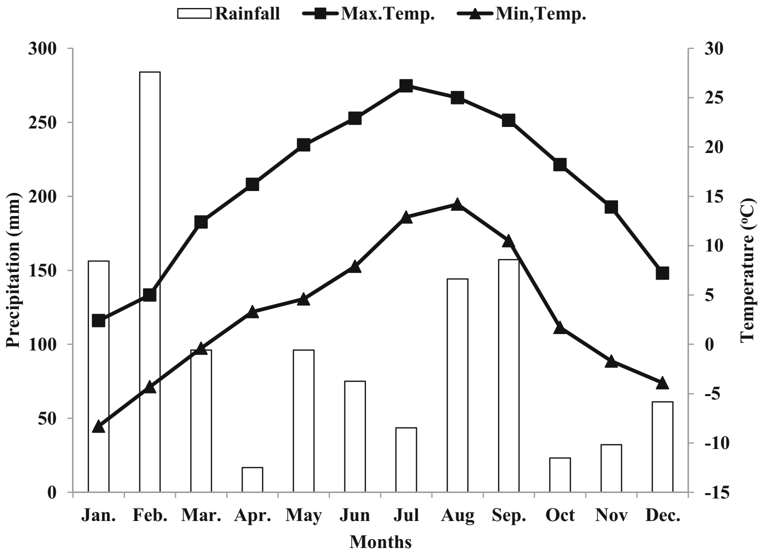


Fig. 1 Location of the study sites in seven forest types (*Populus deltoides* (PD), *Juglans regia* (JR), *Cedrus deodara* (CD), *Pinus wallichiana* (PW), mixed coniferous (MC), *Abies pindrow* (AP), and *Betula utilis* (BU)) at different altitudes in Kashmir Himalayas

The growing stock volume (GSV; m^3 ha^{-1}) of each tree species was estimated by using species-specific volume equations that were developed using multiple regression methods by the Forest Survey of India (FSI 1996), in which girth or DBH, basal area along with height, or form factor was taken into account (Javid 2014).

The understory included ground vegetation comprising shrubs and herbs. Ten 1 m×1 m quadrats for herbs and 5 m×5 m for shrubs were randomly laid in each plot. All understory vegetation falling within these quadrats was harvested. The fresh weight of the harvested understory biomass was immediately measured with an electronic balance (accuracy±0.01 g) in the field, following which the representative samples were taken in triplicates to the laboratory where they were oven-dried at 65 °C for 48 h, after which the dry weight was

Fig. 2 Mean monthly maximum and minimum temperatures and precipitation pattern (2002–2012) of the study area



measured. The total C was computed by using the following formula:

$$\text{Carbon}\left(\text{C Mg ha}^{-1}\right) = \text{Biomass}\left(\text{Mg ha}^{-1}\right) \times \text{Carbon}\,\%$$

The C percentage for live tree biomass, dead wood, and litter was taken as 46 % for conifers and 45 % for broad-leaved forest types (Negi et al. 2003; Manhas et al. 2006). The understory C was taken as 50 % of the dry weight.

Statistical analysis

The relationship between SOC stocks and altitude was examined with linear regression and a separate analysis was used for each soil depth (0–10, 10–20, 20–30, and 0–30 cm). The ANOVAs were separately conducted for different soil depths (0–10, 10–20, 20–30, and 0–30 cm) to compare the forest types and altitude. The relationship between SOC and nine variables (see Table 3) was first examined with correlation analysis. The relationship between SOC concentration and bulk density was also examined with linear regression.

Results

SOC stocks

The mean SOC stocks ranged from 39.07 to 91.39 Mg C ha^{-1} in *J. regia* and *B. utilis* forests at 0–30-cm depth, respectively (Table 2). SOC stocks decreased significantly ($P<0.001$) with increasing soil depth in all the seven forest types (*Populus deltoides* (PD), *J. regia* (JR), *C. deodara* (CD), *Pinus wallichiana* (PW), mixed type (MT), *A. pindrow* (AP), and *B. utilis* (BU)). The SOC ranges from 18.85–54.10, 11.31–21.68, and 7.19–

Table 1 Study site characteristics along an altitudinal gradient in temperate forests of Kashmir Himalayas

Forest type	Altitude (m)	Latitude (°)	Longitude (°)	No. of plots	Basal area ($\text{m}^2\ \text{ha}^{-1}$)	Tree density (no. ha^{-1})	Total biomass (Mg ha^{-1})
PD	1550–1800	75.08–75.20	33.72–33.78	8	46.5±24.2	1201±301	204
JR	1800–2000	75.25–75.35	33.75–33.89	7	31.6±13	148±23	124
CD	2050–2300	75.31–75.40	33.73–33.99	9	47.8±8.6	195±34	228
PW	2000–2300	75.27–75.35	33.93–34.03	10	46.4±9.9	199±35	218
MT	2200–2400	75.19–75.47	33.60–34.07	10	48.7±6.6	196±29	222
AP	2300–2800	75.28–75.47	33.59–34.10	10	48.5±8.0	197±35	237
BU	2800–3200	75.36–75.50	33.59–33.99	5	18.5±3.5	103±23	79

Table 2 Soil organic carbon (SOC) stocks at different depths along an altitudinal gradient in seven forest types of Kashmir Himalayas

Forest type	Number of samples in each depth	C Mg ha^{-1} (0–10 cm)	C Mg ha^{-1} (10–20 cm)	C Mg ha^{-1} (20–30 cm)	*F* value	*P* value
PD	*n*=40	19.39 ± 2.1^{a}	12.78 ± 0.9^{a}	8.96 ± 1.0^{a}	432	0.0001
JR	*n*=35	18.85 ± 1.3^{a}	11.32 ± 0.9^{b}	8.91 ± 0.8^{a}	4.19	0.0001
CD	*n*=45	34.64 ± 1.6^{b}	15.20 ± 0.9^{c}	12.45 ± 0.6^{b}	1029	0.0001
PW	*n*=50	30.50 ± 2.1^{c}	20.22 ± 0.9^{d}	16.51 ± 1.3^{c}	487.4	0.0001
MT	*n*=50	36.70 ± 2.1^{d}	14.35 ± 0.4^{e}	$11.60\pm1.5b^{d}$	1637	0.0001
AP	*n*=50	32.15 ± 1.8^{e}	17.07 ± 0.6^{f}	$12.03\pm0.9b^{d}$	1922	0.0001
BU	*n*=25	54.10±1.6f	21.69 ± 0.5^{g}	15.60 ± 0.3^{c}	1.41	0.0001
	F value	939.98	383.99	53.98		

15.60 Mg C ha^{-1} at 0–10-, 10–20-, and 20–30-cm soil depths in JR and BU, JR and BU, and JR and PW, respectively. On average, the percentages of SOC at 0–10, 10–20, and 20–30 cm depths were 53.2, 26.5 and 20.3 %, respectively. The highest percentage of C in 0–10 cm depth was observed in BU (59.2 %) forest whereas the lowest was observed in PW (45.4 %) forest. In 10–20 and 20–30 cm depths, the highest was observed in PD and PW (31.1 and 24.6 %) forests while the lowest was observed in MT and BU (22.9 and 17.1 %) forests (Fig. 3).

Bulk density of different forest types is given in Fig. 4. A significantly ($P<0.05$) increasing trend was observed in soil bulk density with increasing soil depth in all the forest types (PD, JR, CD, PW, MT, AP and BU). Bulk density of 0–10 and 10–20 cm soil depths showed a significant variation ($P<0.001$) among all the forest types except the bottom layer (20–30 cm).

SOC showed a negative relationship with bulk density (Table 3), as bulk density increased, SOC decreased and vice versa among all the forest types. Soil bulk density showed a decreasing trend with increase in altitude ($R^2=0.06$; Fig. 6). Low-altitude *J. regia* (1800–2000 m) forest has showed the highest bulk density (0–30 cm), whereas the high-altitude *B. utilis* (2800–3200 m) forest has showed the lowest bulk density (Fig. 4).

The test of ANOVA indicates that there are significant ($P<0.001$) differences in SOC stocks among the forest types at 0–30-cm depth (Table 2). A similar trend was observed distinctly at all the three depths ($P<0.001$, $P<0.001$, and $P<0.001$ at 0–10, 10–20, and 20–30 cm, respectively). SOC stocks at 0–30-cm

Fig. 3 Relative C percentage at three depths (0–10, 10–20 and 20–30 cm) in seven temperate forests of Kashmir Himalayas

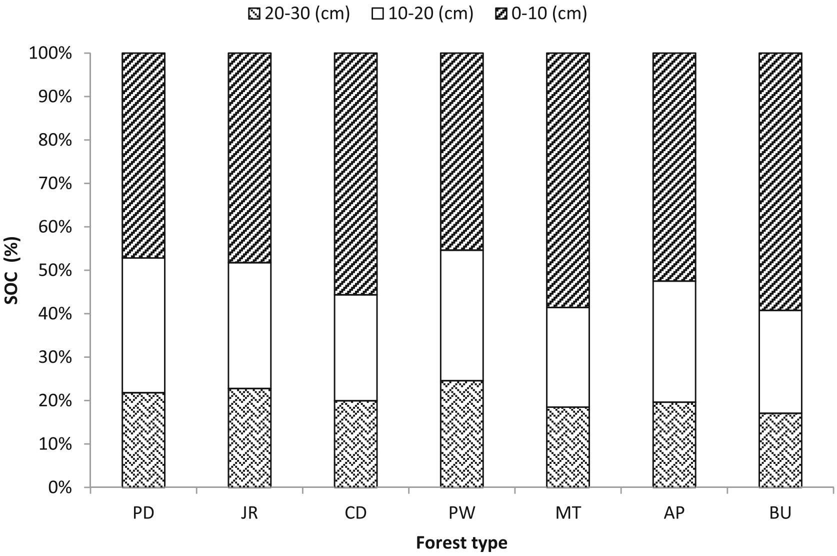
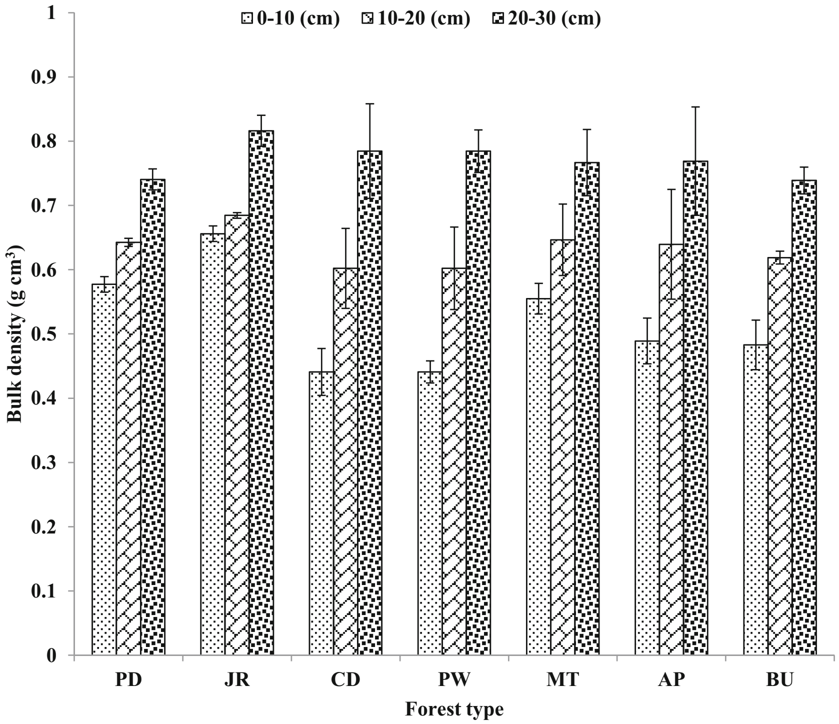


Fig. 4 Soil bulk density (g/cm^3) at different depths along an altitudinal gradient in seven forest types of Kashmir Himalayas



depth were significantly greater in BU forest (91.39 Mg C ha^{-1}) compared to other forest types: 39.07 (JR), 41.12 (PD), 61.25 (AP), 62.28 (CD), 62.64 (MT), and 67.23 (PW) Mg C ha^{-1}. A similar trend was also observed at depth wise.

Table 3 Correlations (*R* values) between soil organic carbon (SOC) and predictor variables in temperate forests of Kashmir Himalayas

Predictor variables	*R* values
Basal area (BA)	−0.17
Density	−0.53
Aboveground biomass (AGB)	−0.11
Belowground biomass (BGB)	−0.11
Herbaceous biomass	−0.24
Shrub biomass	−0.10
Dead wood (both standing, fallen, and stumps)	0.14
Forest floor litter	0.06
Bulk density (0–10 cm)	−0.33
Bulk density (10–20 cm)	−0.42
Bulk density (20–30 cm)	−0.07
Bulk density (0–30 cm)	−0.45

Relationship between SOC stocks and altitude

SOC stocks increased significantly with increase in altitude ($P<0.05$, Fig. 5) at all the three depths (0–10, 10–20 and 20–30 cm). At low altitude, SOC stocks of 39.07 Mg C ha^{-1} at 0–30-cm depth were observed in JR forest (1800–2000 m) and the highest value of 91.39 Mg C ha^{-1} at 0–30 cm depth was observed in high-altitude BU (2800–3200 m) forest. The SOC stock values at low-altitude PD (1550–1800 m) and JR (1800–2000 m) forests have showed almost the similar trend and then increased in mid-altitude coniferous forests of AP, PW, CD, and MT forests with very little variation. However, they increased sharply and have reached at their peak at high-altitude BU (2800–3200 m) forest.

Correlations between SOC stocks and ecosystem variables

Correlation analysis was used to examine the relationship between SOC and the aboveground vegetation properties (aboveground biomass, belowground biomass, herbs and shrubs biomass, tree density, tree basal area) as well as soil properties (soil bulk density, soil moisture, forest floor standing crop litter, deadwood and detritus) which are given in Table 3 and Fig. 5. SOC has

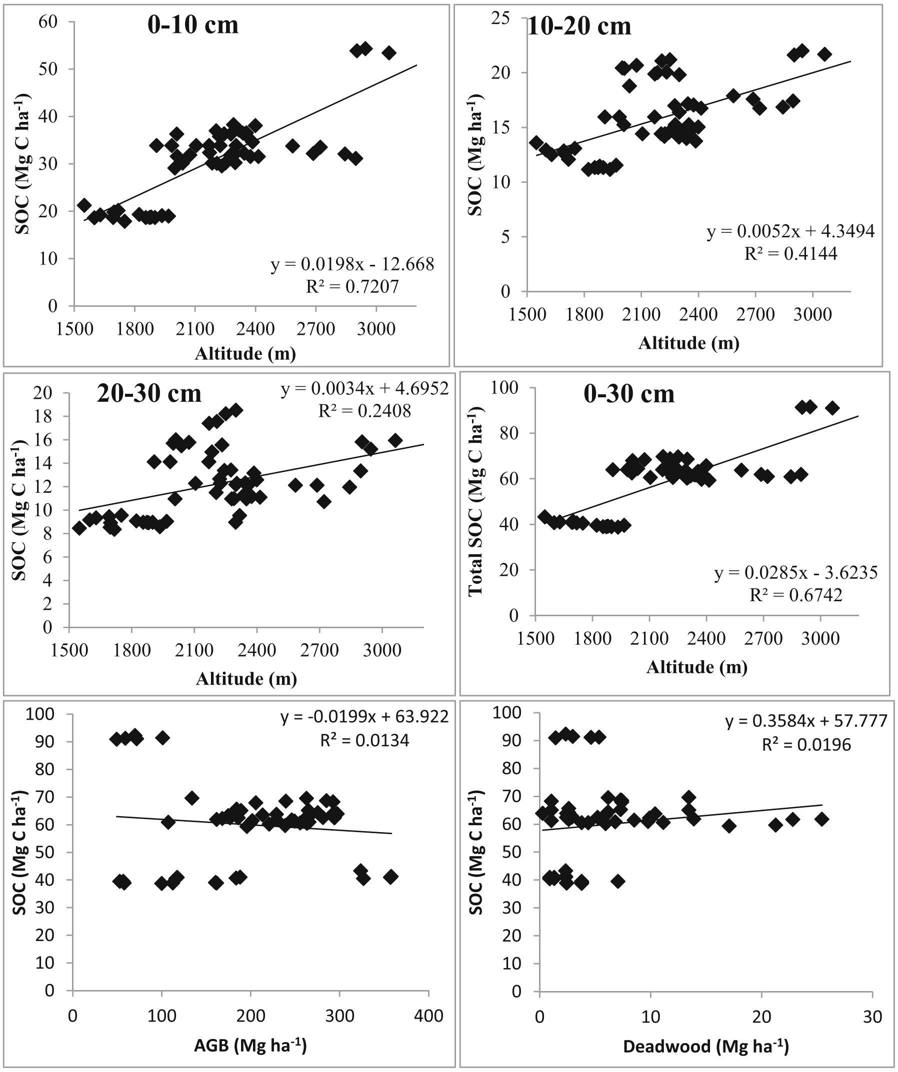


Fig. 5 Relationship between SOC with vegetation and environmental parameters and altitude in seven temperate forests of Kashmir Himalaya

showed a significantly ($P<0.05$) positive correlation with altitude at all the depths, and deadwood has also a weak positive relationship with altitude. However, the aboveground biomass, herb and shrub biomass, tree density, and tree basal area have showed a negative correlation with SOC. Similarly, bulk density has also showed a negative correlation at all the depths (0–10, 10–20 and 20–30 cm) with SOC and altitude (Fig. 6).

Discussion

SOC increased with increasing in precipitation and clay content and decreased with increasing in temperature (Jobbágy and Jackson 2000). In this study, we observed a significant positive relationship ($R^2=0.67$, $P=0.05$) between SOC density at 0–30-cm soil depth and altitude; this may be due to the reason of decrease in temperature at higher altitudes with increase in precipitation, but changes in forest type and large spatial heterogeneity in SOC stocks masked the effect of altitude/climate to certain extent. Several workers have also reported the increasing trend of SOC stocks with increase in altitude (Zhu et al. 2010; Tewksbury and Miegroet 2007; Zhang et al. 2011; Charan et al. 2012; Gupta and Sharma 2013; Wei et al. 2013). Despite of the variations in forest types and decrease in litter fall quantity to the soil with an increase in altitude, SOC showed an increasing trend along an altitudinal gradient in the present study, because SOC

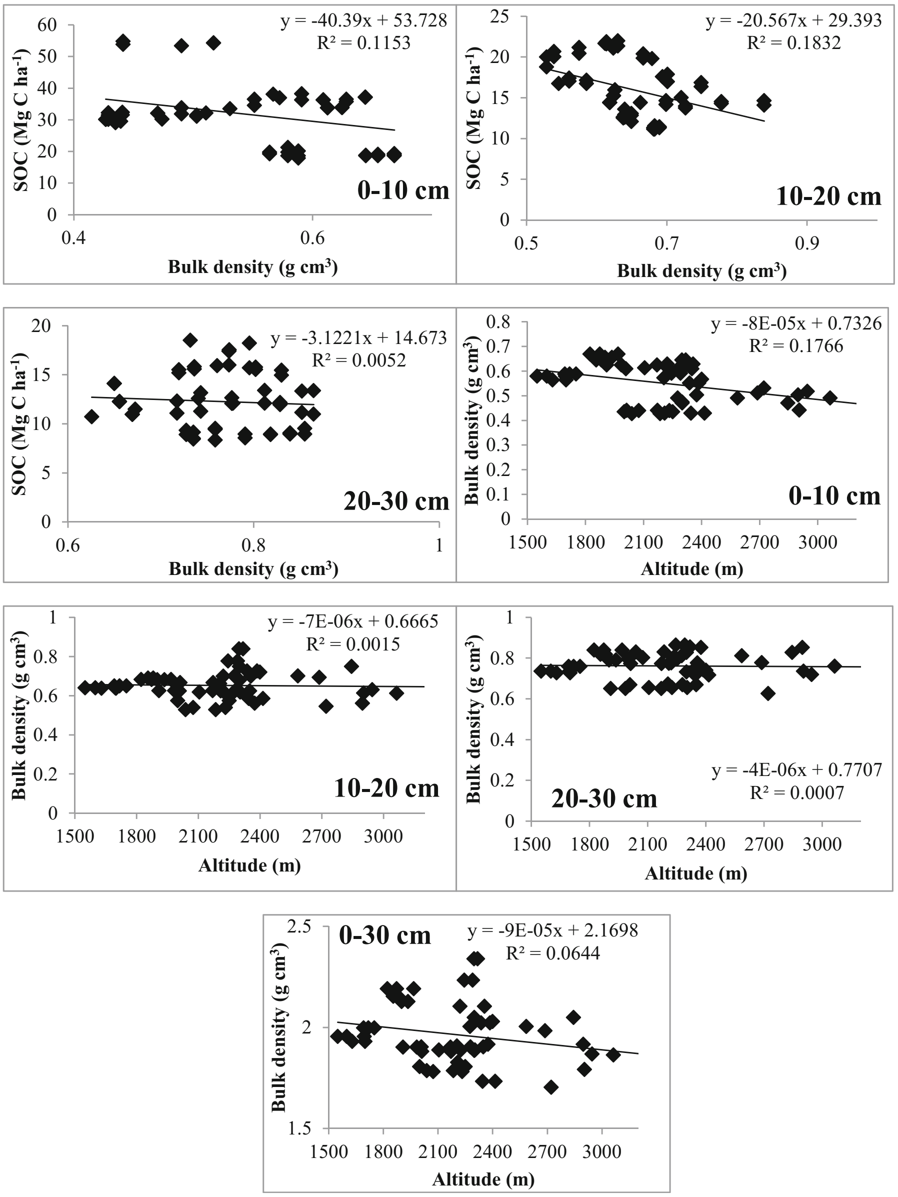


Fig. 6 Relationship between SOC with bulk density and altitude in seven temperate forests of Kashmir Himalayas

is mainly determined by C output (decomposition), which generally decreases with increasing altitude as observed by Garten and Hanson (2006). The SOC content in forest ecosystems is determined not only by plant litter production but also by litter decomposition (Blair et al. 1995). Low temperature at higher altitude is most useful for maintaining a low decomposition rate of soil organic matter (Wei et al. 2013). SOC accumulation alters not only by climate but also by vegetation type. Coniferous forests contain lower SOC compared with the soils of broad-leaved forests because the former has a high net primary production (Smolander et al. 2005; Jiang and Xu 2006). Our results also showed the lower values of SOC in mid-altitude coniferous forests when compared to high-altitude broad-leaved BU forest. However, the soils of broad-leaved forests at lower elevation accumulate low C which may be due to the reason of climatic factors. At low altitude, temperature increase raises the rate of decomposition and soil biological activity, which ultimately reduces the C accumulation in soil.

The SOC in all soil depth also showed significant correlation with altitude (Fig. 5); the upper layer (R^2=

Table 4 Comparisons of estimates of soil C densities (Mg C ha^{-1}) of present and previous studies

Vegetation/forest type	Country/location	Depth (cm)	C stocks (Mg ha^{-1})	Source
Populus deltoides	India/Kashmir Himalaya	0–30	41.12	Present study
Juglans regia	India/Kashmir Himalaya	0–30	39.1	Present study
Cedrus deodara	India/Kashmir Himalaya	0–30	62.28	Present study
Pinus wallichiana	India/Kashmir Himalaya	0–30	67.23	Present study
Mixed type	India/Kashmir Himalaya	0–30	62.6	Present study
Abies pindrow	India/Kashmir Himalaya	0–30	61.3	Present study
Betula utilis	India/Kashmir Himalaya	0–30	91.4	Present study
Pinus kesiya Royle ex. Gordon/subtropical	India/Northeast Meghalaya	0–100	58.7	Baishya and Barik (2011)
Tropical moist deciduous	India/Uttar Pradesh	0–50	27.3–130.7	Banerjee et al. (1990)
Various climate zones	Europe	0–10	11.3–126.3	Baritz et al. (2010)
Tropical evergreen forests	India/Dadra and Nagar Haveli	0–50	31.6–94.6	Biswas (1985)
Montane temperate forests	India	0–50	12.1–184.3	Chhabra et al. (2003)
Mixed strands	USA	0–15	56	Compton et al. (1998)
Scots pine	Europe	0–80	57	de Vries et al. (2003)
Scot pine	Mediterranean	0–50	35–70	Diaz-Pines et al. (2011)
Permafrost soil	China	0–30	19–193	Dorfer et al. (2013)
Pinus roxburghii	India/Garhwal Himalaya	0–30	62.80	Gupta and Sharma (2011)
Pinus wallichiana	India/Garhwal Himalaya	0–30	102.96	Gupta and Sharma (2011)
Picea smithiana and *Abies pindrow*	India/Garhwal Himalayas	0–30	132	Gupta and Sharma (2011)
Grasslands	India/Uttrakhand	0–30	37.09–142.14	Gupta and Sharma (2013)
Montane temperate	India/Shimla Himachal Pradesh	0–50	26.2–112.8	Gupta and Singh (1990)
Tropical evergreen	India/J&K	0–50	44.0	Mahapatra et al. (2000)
Temperate deciduous forests	Eastern US	0–60	55–229	Mcfarlane et al. (2013)
Coniferous forests	Sweden	0–50	69–73	Ortiz et al. (2013)
Scot pine	Central Spain	0–8	49	Schindlbacher et al. (2010)
Broadleaf and coniferous	Netherlands	0–10	39.5–66	Schulp et al. (2008)
Pinus roxburghii (SW aspect)/temperate	India/Garhwal Himalaya	0–30	40.3	Sharma et al. (2011)
Pinus roxburghii/Subtropical	India/Garhwal Himalayas	0–60	124.8–141.6	Sheikh et al. (2009)
Pinus roxburghii/Subtropical	India/Garhwal Himalaya	0–60	56.80	Sheikh et al. (2012)
Schima-Castanopsis	Nepal	0–20	52.45	Shrestha (2009)
Abies, *Rhododendron* (upper alpine)	India	0–30	80	Singh et al. (2011)
Pine forest (lower alpine)	India	0–30	88	Singh et al. (2011)
Norway spruce white-fir	Italy	0–20	53	Thuille et al. (2000)
Volcanic ash soils	Taiwan	0–30	15.7–163.2	Tsui et al. (2013)
Moist evergreen and submontane forests	Uganda	0–30	54.6–82.6	Twongyirwe et al. (2013)
Pinus patula	Colombia	0–25	87.2	Usuga et al. (2010)
Tropical forests	Colombia	0–25	35.8–92.6	Usuga et al. (2010)
Tropical evergreen	India/J&K	0–50	38.9–181.7	Verma et al. (1990)
Temperate forests	Northeast China	0–20	66.8–85.8	Wei et al. (2013)
Picea crassifolia	China	0–30	89.3	Yang et al. (2007)
Old growth temperate forests	Changbai Mountain, China	0–10	23.1–377	Yuan et al. (2013)
Spruce fir	China	0–30	62.3	Zhang et al. (2011)

Table 4 (continued)

Vegetation/forest type	Country/location	Depth (cm)	C stocks (Mg ha^{-1})	Source
Temperate forest	Mt. Changbai, Northeast China	0–100	62.7–88.7	Zhu et al. (2010)

0.72, 0–10 cm) was more strongly related with altitude than the middle (R^2=0.41, 10–20 cm) and bottom (R^2= 0.24, 20–30 cm) layers. Results obtained in the present study are in accordance with the results of Jobbágy and Jackson (2000) and Wei et al. (2013). The higher SOC density in the upper layer may be attributed to cool temperatures and increase in precipitation, or it may also be due to shallower root distribution of high-altitude ecosystems (Jobbágy and Jackson 2000; Yang et al. 2007; Zhu et al. 2010; Yang et al. 2007), whereas the trend of decrease in SOC with increase in depth may be due to the increased proportion of slower cycling of SOC pools at depth or vegetation types (Paul et al. 1997; Trumbore 2000; Jobbágy and Jackson 2000). Yang et al. (2005) and Zhang et al. (2011) had also reported that climate and vegetation were important factors in controlling the vertical distribution pattern of SOC in forest ecosystems.

The SOC stocks decreased with increasing soil depth in all the forest types. Similar results have also been observed by Jobbágy and Jackson (2000). The trend of decreasing SOC with increasing depth may be due to the increased proportion of slower cycling of SOC pools at depth and compaction of soil (Paul et al. 1997; Trumbore 2000; Jobbágy and Jackson 2000). The SOC stocks observed in the present study are well within the range of other studies (Table 4). Our results are lower than the results observed by Sheikh et al. (2009) in coniferous subtropical and broad-leaved temperate forests of Garhwal Himalaya, India; this difference may be because they have taken the estimates up to 60 cm of soil depth. Zhu et al. (2010) and Zhang and Wang (2010) observed lesser values of SOC density in temperate forests on Mt. Changbai, China, and which may be due to lower altitudinal range compared to the present study. In the present study, lowest SOC was observed in low-altitude JR and PD forests, whereas highest SOC was observed in high-altitude BU forest; this may also be due to the higher mineralization rate at low-altitude JR and PD forests than at high-altitude BU forest where rate of mineralization is low due to cool temperatures and high precipitation. Similar results have been reported by others (Townsend et al. 1996; Conant et al. 1998; Jobbágy and Jackson 2000; Trumbore 2000; Zhu et al. 2010; Charan et al. 2012; Wei et al. 2013) in temperate forests.

In the present study, we found significant differences in SOC stocks in all the depths (0–10, 10–20 and 20–30 cm) at all the forest types, which could be explained by the changes in forest types, quality and quantity of litter, aboveground biomass belowground biomass, and basal area of the trees. In addition to that, climate and changes in mean annual temperature and precipitation along an altitudinal gradient also play an important role.

In the present study, the bulk density has showed a negative trend with increase in altitude. Sharma et al. (2010) and Hanawalt and Whittaker (1976) have also reported a negative correlation of bulk density with increasing altitude. Generally, bulk density and organic matter are inversely proportional and low bulk density in soil indicates occurrence of higher organic matter content, good granulation, high infiltration and good aeration conversely. Our findings also confirm the above explanation. Bulk density also showed a negative correlation with moisture content; this may be attributed to compaction of soil. Sharma et al. (2010) also reported a negative relationship of bulk density with moisture in central-western Himalayas, India. The current study has also indicated that higher bulk density results in lower SOC stocks at low-altitude forests than at high-altitude forests. Li et al. (2010) have also reported that SOC stock variation could be attributed to SOC concentration or simply due to the spatial variation of soil bulk density. Bulk density differed between the forest floor horizons in the present study and it showed an increasing trend with increase in depth in all forest types. The soil organic matter content was one of the main factors in explaining the bulk density variation in forest floor horizons. At greater depths in the forest floor, there is more mixing with mineral material in the profile, which leads to a higher bulk density (Schulp et al. 2008).

Soil bulk density showed the significant differences among the forest types. Yimer et al. (2006) have also observed that soil bulk density can be quite variable in different forest types and changes in bulk density in the forest floor can alter SOC stocks. This could be the reasons for the variation in SOC stocks among the forest types as well as the distribution in soil profile in temperate forests of Kashmir Himalayas.

Conclusion

SOC stocks increased significantly with increase in altitude. SOC decreased with increase in soil depth. In contrast, soil bulk density decreased significantly with increase in altitude and increased with increase in soil depth. SOC stocks showed a significant positive correlation with detritus, whereas basal area, density, aboveground biomass, herb and shrub biomass, and soil properties (bulk density and forest floor litter) were negatively correlated with altitude. Our results revealed that the soils of temperate forests of Kashmir Himalayas have greater potential of soil C sequestration particularly at higher altitudes. According to IPCC AR4, the global temperatures will rise by 2–3 °C by the end of this century. Literatures suggested that high-elevation forests of Himalayas are more vulnerable to climate change. We have also found more SOC stocks at higher altitude than at low altitude, in temperate forests of Kashmir Himalayas. So, any further rise in atmospheric temperature will result in decrease of SOC stocks in these forests. The present study suggests that the high-altitude forests should be given more importance in terms of conservation for not only for restoration of biodiversity but also for mitigation of C.

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References

Baishya, R., & Barik, S. K. (2011). Estimation of tree biomass, carbon pool and net primary production of an old growth *Pinus kesiya* Royle ex. Gordon forest in north-eastern India. *Annals of Forest Science, 68*, 727–736.

Banerjee, S. P., Mathur, K. C., & Sharma, S. D. (1990). Soils of south Kheri forests of Uttar Pradesh. *Indian Forester, 116*(6), 479–486.

Baritz, R., Seufert, G., Montanarella, L., & Ranst, E. V. (2010). Carbon concentration and stocks in forest soils of Europe. *Forest Ecology and Management, 260*, 262–277.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science, 47*, 151–163.

Biswas, R. (1985). Classification of some typical soils from Dadra and Nagar Haveli. *Journal of Indian Society of Soil Science, 33*, 945–947.

Blair, G. J., Lefroy, R. D. B., & Lisle, L. (1995). Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research, 46*, 1459–1466.

Charan, G., Bharti, V. K., Jadhav, S. E., Kumar, S., Angchok, D., Acharya, S., Kumar, P., & Shrivastava, R. B. (2012). Altitudinal variations in soil carbon storage and distribution patterns in cold desert high altitude microclimate of India. *African Journal of Agricultural Research, 7*(47), 6313–6319.

Chhabra, A., Palria, S., & Dadhwal, P. K. (2003). Soil organic pool in Indian forests. *Forest Ecology and Management, 173*, 187–199.

Compton, J. E., Boone, R. D., Motzkin, G., & Foster, D. R. (1998). Soil carbon and nitrogen in a pine-oak sand plain in central Massachusetts: role of vegetation and land use history. *Oecologia, 116*, 536–542.

Conant, R. T., Klopatek, J. M., Malin, R. C., & Klopatek, C. C. (1998). Carbon pools and fluxes along an environmental gradient in Northern Arizona. *Biogeochemistry, 43*, 43–61.

Dadhwal, V. K., Pandya, N., & Vora, A. B. (1998). *Carbon cycle for Indian forest ecosystems—a preliminary estimate, global change studies, scientific results from ISRO geosphere-biosphere programme, India* (pp. 411–429). Bangalore: ISRO.

Dar, J. A., & Sundarapandian, S. M. (2013). Soil organic carbon stock assessment in two temperate forest types of western Himalaya of Jammu and Kashmir, India. *Forest Research, 3*, 1. doi:10.4172/2168-9776.1000114.

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature, 440*, 165–173.

De Vries, W., Reinds, G. J., Posch, M., Sanz, M., Krause, G., Calatayud, V., Dupouey, J., Sterba, H., Gundersen, P., Voogd, J., & Vel, E. (2003). *Intensive monitoring of forest ecosystems in Europe* (p. 163). Brussels: 2003 Technical report in EC, UN/ECE.

deVos, B., Lettens, S., Muys, B., & Deckers, J. A. (2007). Walkley–Black analysis of forest soil organic carbon: recovery, limitations and uncertainty. *Soil Use and Management, 23*, 221–229.

Diaz-Pines, E., Rubio, A., Miegroet, H. V., Montes, F., & Benito, M. (2011). Does tree species composition control soil organic carbon pools in Mediterranean mountain forests. *Forest Ecology and Management, 262*, 1895–1904.

Dixon, R. K., Brown, S., Houghton, R. A., Solomon, A. M., Trexler, M. C., & Wisniewski, J. (1994). Carbon pools and flux of global forest ecosystems. *Science, 263*, 185–190.

Dorfer, C., Kuhn, P., Baumann, F., He, J. S., & Scholten, T. (2013). Soil organic pools and stocks in permafrost-affected soils on the Tibetan Plateau. *PLoS ONE, 8*(2), e57024. doi:10.1371/journal.pone.0057024.

F.S.I. (1996). *Volume equations for forests of India, Nepal and Bhutan*. Forest Survey of India, Ministry of Environment and Forests, Govt. of India.

F.S.I. (2011). *State of forest report*, Forest Survey of India, Dehradun India.

Fahey, T. J., Siccama, T. G., Driscoll, C. T., Likens, G. E., Campbell, J., Johnson, C. E., Battles, J. J., Aber, J. D., Cole, J. J., Fisk, M. C., Groffman, P. M., Hamburg, S. P., Holmes, R. T., Schwarz, P. A., & Yanai, R. D. (2005). The biogeochemistry of carbon at Hubbard Brook. *Biogeochemistry, 75*, 109–176.

Fang, J. Y., Liu, G. H., & Xu, S. L. (1996). Soil carbon pool in China and its global significance. *Journal of Environmental Science (China), 8*, 249–254.

Garten, C. T., & Hanson, P. J. (2006). Measured forest soil C stocks and estimated turnover times along an elevational gradient. *Geoderma, 136*, 342–352.

Goodale, C. L., Apps, M. J., Birdsey, R. A., Field, C. B., Heath, L. S., Houghton, R. A., Jenkins, J. C., Kohlmaier, G. H., Kurz, W., Liu, S., Nabuurs, G. J., Nillson, S., & Shvidenko, A. Z. (2002). Forest carbon sinks in the Northern Hemisphere. *Ecological Applications*, 12, 891–899.

Gupta, M. K., & Sharma, S. D. (2011). Sequestered carbon: organic carbon pool in the soils under different forest covers and land uses in Garhwal Himalaya region. *International Journal of Agriculture and Forestry, 1*(1), 14–20.

Gupta, M. K., & Sharma, S. D. (2013). Sequestered organic carbon status in the soils under grassland in Uttarakhand State, India. *Applied Ecology and Environmental Sciences, 1*(1), 7–9.

Gupta, M. K., & Singh, R. P. (1990). Studies on some physical properties of soils under different forest covers and land-uses in Himachal Pradesh. *Van Vigyan, 28*(3), 86–93.

Hanawalt, R. B., & Whittaker, R. H. (1976). Altitudinally coordinated patterns of soils and vegetation in the San Jacinto Mountains, California. *Soil Science, 121*(2), 114–124.

Hoffmann, U., Hoffmann, T., Jurasinski, G., Glatzel, S., & Kuhn, N. J. (2014). Assessing the spatial variability of soil organic carbon stocks in an alpine setting (Grindelwald, Swiss Alps). *Geoderma, 232–234*, 270–283.

I.P.C.C. (2000). *Land use, land-use change and forestry. IPCC Special Report*. United Kingdom: Cambridge University Press.

IPCC. (2007). *Intergovernmental panel on climate change, fourth assessment report (AR4), synthesis report, summary for policy makers* (pp. 1–13). Geneva: IPCC.

Javid, A. D. (2014). *Carbon stock assessment in temperate forests of Kashmir Himalaya, India*. Ph.D. thesis, Pondicherry University.

Jiang, P. K., & Xu, Q. F. (2006). Abundance and dynamics of soil liable carbon pools under different forest types of forest vegetation. *Pedosphere, 16*, 182–188.

Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil carbon and its relation to climate and vegetation. *Ecological Applications, 10*, 423–436.

Johnson, D. W., & Curtis, P. S. (2001). Effects of forest management on soil C and N storage: a meta-analysis. *Forest Ecology and Management, 140*, 227–238.

Johnston, C. A., Groffman, P., Breshears, D. D., Cardon, Z. G., Currie, W., Emanuel, W., Gaudinski, J., Jackson, B. R., Lajtha, K., Nadelhoffer, K., Nelson, D., Post, W. M., Retallack, G., & Wielopolski, L. (2004). Carbon cycling in soil. *Frontiers in Ecology and Environment, 2*(10), 522–528.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science, 304*, 1623–1627.

Lal, R. (2005). Forest soils and carbon sequestration. *Forest Ecology and Management, 220*, 242–258.

Latte, N., Colinet, G., Fayolle, A., Lejeume, P., Hebert, J., Claessens, H., & Bauwens, S. (2013). Description of a new procedure to estimate the carbon stocks of all forest pools and impact assessment of methodological choices on the estimates. *European Journal of Forest Research, 132*, 565–577. doi:10.1007/s10342-0701-6.

Leirós, M. C., Trasar-Cepeda, C., Seosane, S., & Gil-Sotres, F. (1999). Dependence of mineralization of soil organic matter on temperature and moisture. *Soil Biology and Biochemistry, 31*, 327–335.

Li, X., & Han, S. (2008). Preservation of broadleaf species in Korean pine (*Pinus koraiensis*) plantations affects soil properties, carbon storage, biomass allocation, and available nitrogen storage. *Canadian Journal of Forest Research, 38*, 2227–2235.

Li, P., Wang, Q., Endo, T., Zhao, X., & Kakubari, Y. (2010). Soil organic carbon stock is closely related to aboveground vegetation properties in cold-temperate mountainous forests. *Geoderma, 154*, 407–415.

Liski, J. (1995). Variation in soil organic carbon and thickness of soil horizons within a boreal forest stand-effect of trees and implications for sampling. *Silva Fennica, 29*, 255–266.

Mahapatra, S. K., Walia, C. S., Sindhu, G. S., Rana, K. P. C., & Lal, T. (2000). Characterization and classification of the soils of different physiographic units in the sub-humid ecosystem of Kashmir region. *Journal of Indian Soil Science, 48*(3), 572–577.

Manhas, R. K., Negi, J. D. S., Kumar, R., & Chauhan, P. S. (2006). Temporal assessment of growing stock, biomass and carbon stock of Indian forests. *Climate Change, 74*, 191–221.

Matus, F., Rumpel, C., Neculman, R., Panichini, M., & Mora, M. L. (2014). Soil carbon storage and stabilization in andic soils: a review. *Catena, 120*, 102–110.

McFarlane, K. J., Torn, M. S., Hanson, P. J., Porras, R. C., Swanston, C. W., Callaham, M. A., Jr., & Guilderson, T. P. (2013). Comparison of soil organic matter dynamics at five temperate deciduous forests with physical fractionation and radiocarbon measurements. *Biogeochemistry, 112*, 457–476.

Nautiyal, S., Rajan, K. S., & Shibasaki, R. (2005). Interaction of biodiversity and economic welfare—a case study from the Himalayas of India. *International Journal Ecology and Environmental Informatics, 6*, 111–119.

Negi, J. D. S., Manhas, R. K., & Chauhan, P. S. (2003). Carbon allocation in different components of some tree species of India: a new approach for carbon estimation. *Current Science, 85*(11), 1528–1531.

Ortiz, C. A., Liski, J., Gardenas, A. I., Lehtonen, A., Lundblad, M., Stendahl, J., Argen, G. I., & Karltun, E. (2013). Soil organic carbon stock changes in Swedish forest soils—a comparison of uncertainties and their sources through a national inventory and two simulation models. *Ecological Modelling, 251*, 221–231.

Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., Mcguire, A. D., Piao, S., Rautiainen, A., Sitch, S., & Hayes, D. (2011). A large and persistent carbon sinks in the world's forests. *Science, 333*, 988–993.

Paul, E. A., Follet, R. F., Leavitt, S. W., Halvorson, A., Peterson, G. A., & Lyon, D. J. (1997). Radiocarbon dating for determination of soil organic pool sizes and dynamics. *American Journal Soil Science Society, 61*, 1058–1067.

Pearson, T., Walker, S., & Brown, S. (2005). *Sourcebook for land use, land-use change and forestry* (p. 35). USA: Projects Winrock International.

Piao, S., Fang, J., & Ciais, P. (2009). The carbon balance of terrestrial ecosystems in China. *Nature, 458*, 1009–1013.

Powlson, D. S., Whitemore, A. P., & Goulding, K. W. T. (2011). Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *European Journal Soil Science, 62*, 42–55.

Raich, J. W., & Schlesinger, W. H. (1992). The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate. *Tellus, 44B*, 81–99.

Ravindranath, N.H., & Ostwald, M. (2008). *Carbon inventory methods: handbook for greenhouse gas inventory, carbon mitigation and round wood production projects*. Netherlands: Springer.

Ravindranath, N. H., Somashekhar, B. S., & Gadgil, M. (1997). Carbon flows in Indian forests. *Climate Change, 35*, 297–320.

Sariyildiz, T. (2008). Effects of gap-size classes on long-term litter decomposition rates of beech, oak and chestnut species at high elevations in northeast Turkey. *Ecosystems, 11*, 841–853.

Schindlbacher, A., De Gonzalo, C., Diaz-Pines, E., Gorria, P., Mathews, B., Inclan, R., Zechmeister-Boltenstern, S., Rubio, A., & Jandl, R. (2010). Temperature sensitivity of forest soil organic matter decomposition along two elevation gradients. *Journal of Geophysical Research, Biogeosciences, 115*, G03018.

Schulp, C. J. E., Nabuurs, G. J., Verburg, P. H., & de Waal, R. W. (2008). Effect of tree species on carbon stocks in forest floor and mineral soil and implications for soil carbon inventories. *Forest Ecology and Management, 256*, 482–490.

Sharma, C. M., Gairola, S., Ghildiyal, S. K., & Sarvesh, S. (2010). Physical properties of soils in relation to forest composition in moist temperate valley slopes of the central western Himalaya. *Journal Forest Science, 26*(2), 117–129.

Sharma, C. M., Gairola, S., Baduni, N. P., Ghildiyal, S. K., & Suyal, S. (2011). Variation in carbon stocks on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya, India. *Journal of Bioscience, 36*(4), 701–708.

Sheikh, M. A., Kumar, M., & Bussmann, R. W. (2009). Altitude variation in soil organic carbon stock in coniferous subtropical and broad leaf temperate forests in Garhwal Himalaya. *Carbon Balance Management, 4*, 1–6. doi:10.1186/1750-0680-4-6.

Sheikh, M. A., Kumar, S., & Kumar, M. (2012). Above and belowground organic carbon stocks in a sub-tropical *Pinus roxburghii* Sargent forest of the Garhwal Himalayas. *Forest Studies in China, 14*(3), 205–209.

Shrestha, B. P. (2009). Carbon sequestration in *Schima-Castanopsis* forest: a case study from Palpa District. *The Greenery, 7*(1), 34–40.

Singh, S. K., Panda, C. B., Sigh, G. S., Starker, D., & Sager, R. (2011). Concentration and stock of carbon in the soils affected by land uses and climates in the Western Himalaya, India. *Catena, 87*, 78–89.

Smolander, A., Loponen, J., Suominen, K., & Kitunen, V. (2005). Organic matter characteristics and C and N transformations in the humus layer under two tree species, *Betula pendula* and *Picea abies. Soil Biology and Biochemistry, 37*, 1309–1318.

Tewksbury, C. E., & Miegroet, H. V. (2007). Soil organic carbon dynamics along a climatic gradient in a southern Appalachian spruce-fir forest. *Canadian Journal Forest Research, 37*, 1161–1172.

Thuille, A., Buchmann, N., & Schulze, E. D. (2000). Carbon stocks and soil respiration rates during deforestation, grassland use and subsequent Norway spruce afforestation in the Southern Alps, Italy. *Tree Physiology, 20*, 849–857.

Townsend, A. R., Vitousek, P. M., & Amundson, R. R. (1996). Soil organic matter dynamics along gradients in temperature and land use on the island of Hawaii. *Ecology, 76*, 721–733.

Trumbore, S. E. (2000). Age of soil organic matter and soil respiration: radiocarbon constraints on belowground carbon dynamics. *Ecological Applications, 10*, 399–411.

Tsui, C. C., Tsai, C. C., & Chen, Z. S. (2013). Soil organic carbon stocks in relation to elevational gradients in volcanic ash soils of Taiwan. *Geoderma, 209–210*, 119–127.

Twongyirwe, R., Sheil, D., Majaliwa, J. G. M., Ebanyat, P., Tenywa, M. M., van Heist, M., & Kurmar, L. (2013). Variability of soil organic carbon stocks under different land uses: a study in an afro-montane landscape in south-western Uganda. *Geoderma, 193–194*, 282–289.

Uri, V., Varik, M., Aosaar, J., Kanal, A., Kukumagi, M., & Lohmus, K. (2012). Biomass production and carbon sequestration in a fertile silver birch (*Betulapendula* Roth) forest chronosequence. *Forest Ecology and Management, 267*, 117–126.

Usuga, J. C. L., Toro, J. A. R., Alzate, M. V. R., & Tapias, A. D. J. L. (2010). Estimation of biomass and carbon stocks in plants, soil and forest floor in different tropical forests. *Forest Ecology and Management, 260*, 1906–1913.

Verma, K. S., Shyampura, R. L., & Jain, S. P. (1990). Characterization of soils under forest of Kashmir valley. *Journal Indian Society of Soil Science, 38*, 107–115.

Walkley, A. (1947). An estimation of methods for determining organic carbon and nitrogen in soils. *Journal of Agricultural Science, 25*, 598–609.

Wei, Y., Li, M., Chen, H., Lewis, B. J., Yu, D., Zhou, W., Fang, X., Zhao, W., & Dai, L. (2013). Variation in carbon storage and its distribution by stand age and forest type in boreal and temperate forests in Northeast China. *PLoS ONE, 8*(8), e72201. doi:10.1371/journal.pone.oo72201.

Yanai, R. D., Arthur, M. A., Siccama, T. G., & Federer, C. A. (2000). Challenges of measuring forest floor organic matter dynamics, repeated measures from a chronosequence. *Forest Ecology and Management, 138*, 273–283.

Yang, L. Y., Luo, T. X., & Wu, S. T. (2005). Root biomass and underground C and N storage of primitive Korean pine and broad-leaved Climax forest in Changbai Mountains at its different succession stages. *Chinese Journal Applied Ecology, 16*, 1195–1199.

Yang, Y. H., Mohammat, A., Feng, J. M., Zhou, R., & Fang, J. Y. (2007). Storage, patterns and environmental controls of soil organic carbon in China. *Biogeochemistry, 84*, 131–141.

Yimer, F., Stig, L., & Abdu, A. (2006). Soil organic carbon and total nitrogen stocks as affected by topographic aspect and vegetation community in the Bale Mountains, Ethiopia. *Geoderma, 135*, 335–344.

Yoo, K., Armundson, R., Heimsath, A. M., & Dietrich, W. E. (2006). Spatial patterns of soil organic carbon on hill slopes: integrating geomorphic processes and the biological C cycle. *Geoderma, 130*, 47–65.

Yuan, Z., Gazol, A., Lin, F., Ye, J., Shi, S., Wang, X., Wang, M., & Hao, Z. (2013). Soil organic carbon in an old growth temperate forests: spatial pattern, determinants and bias in its quantification. *Geoderma, 195–196*, 48–55.

Zhang, Q. Z., & Wang, C. K. (2010). Carbon density and distribution of six Chinese temperate forests. *Science China Life Science, 53*, 831–840.

Zhang, M., Zhang, X. K., Liang, W. J., Jiang, Y., Dai, G. H., Wang, X. G., & Han, S. J. (2011). Distribution of soil organic carbon fractions along the altitudinal gradient in Changbai Mountain, China. *Pedosphere, 21*, 615–620.

Zhang, Y., Gu, F., Liu, S., Liu, Y., & Li, C. (2013). Variations of carbon stock with forest types in subalpine region of southwestern China. *Forest Ecology and Management, 300*, 88–95.

Zhu, B., Wang, X., Fang, J., Piao, S., Shen, H., Zhao, S., & Peng, C. (2010). Altitudinal changes in carbon storage of temperate forests on Mt Changbai, Northeast China. *Journal Plant Research, 123*, 439–452.