



# Estimation of soil carbon pools in the forests of Khyber Pakhtunkhwa Province, Pakistan

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Received: 25 May 2019 / Accepted: 18 July 2019 / Published online: 19 October 2019  
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**Abstract** Forest soils have high carbon densities compared to other land-uses. Soil carbon sequestration is important to reduce CO<sub>2</sub> concentrations in the atmosphere. An effective climate change mitigation strategy involves limiting the emissions of greenhouse gases from soils. Khyber Pakhtunkhwa is the most forested province of Pakistan, hosting about one-third of the country's  $4.5 \times 10^6$  ha forest area. Soil organic carbon in the province's forests was estimated through a field-based study carried out during 2014–17 covering the whole province. Data was collected from 373 sample plots laid out in different forest types using a stratified cluster sampling technique. The total quantity of soil organic carbon was estimated at  $59.4 \times 10^6$  t with an average of  $52.4 \pm 5.3$  t/ha. About 69% of the total soil carbon is present in temperate forests. Subtropical broad-leaved and subtropical pine forests constitute 11.4% and 8.8% of the soil carbon stock respectively. Similarly, subalpine and oak forests have respective shares of 5.1% and 5.7% in the soil

carbon pool. The lowest carbon stock (0.1%) was found in dry-tropical thorn forests. The highest soil carbon density was found in subalpine forests ( $69.5 \pm 7.2$  t/ha) followed by moist temperate forests ( $68.5 \pm 6.7$  t/ha) and dry temperate forests ( $60.7 \pm 6.5$  t/ha). Oak forests have carbon density of  $43.4 \pm 7.1$  t/ha. Subtropical pine, subtropical broad-leaved and dry tropical thorn forests have soil carbon densities of  $36.3 \pm 3.7$ ,  $32.8 \pm 6.2$  and  $31.5 \pm 3.5$  t/ha, respectively. The forests of the Khyber Pakhtunkhwa province have substantial amounts of soil carbon which must be conserved for climate change mitigation and maintenance of sound forest health.

**Keywords** Soil carbon · Carbon sequestration · Climate change · Carbon sink · Forests · Khyber Pakhtunkhwa

## Introduction

Soil organic carbon (SOC) is the principal carbon pool in terrestrial ecosystems. The quantity stored depends on several influencing factors, for example, climate, and vegetation type and density, as well as soil characteristics. The rates of biodegradation and decomposition processes also regulate the quantity of carbon (Lal 1999). The basic carbon pools in a forest ecosystem include dead wood, litter, above and below ground biomass and soil carbon. Overall, global SOC stock in the top 1-m layer is approximately  $1500 \times 10^9$  t. This is twice the amount found in the atmosphere (FAO 2017). Forests contribute to the soil carbon in the form of litter (leaves and twigs), large woody debris, roots and leaching from the litter layer. About 40% of the world's SOC is present in forest ecosystems (Hudson et al. 1994; Sheikh et al. 2009). Deforestation, forest degradation and global warming have increased greenhouse gas emissions from the soil.

Project funding: This research is supported by Annual Development Programme (ADP) Project "Carbon Stock Assessment of Forests of Khyber Pakhtunkhwa" (No. 487/120577/2017-180).

The online version is available at <http://www.springerlink.com>

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However, carbon sequestration can be achieved by restoration of eroded and degraded lands (Ali et al. 2013).

The dynamics of SOC in forest soils has been investigated by numerous researchers. Total soil carbon stock in the forests of India has been estimated at  $4.1 \times 10^9$  t in the top 50 cm layer. Soil carbon densities varied from 37.5 t/ha in tropical dry-deciduous forests to 92.1 t/ha in littoral and swamp forests of India (Chabhra et al. 2003). There have been few studies in Pakistan to determine soil organic carbon in forest soils. Soil carbon in subtropical pine forests of Murree and Lethrar provinces has been estimated as 9.2 and 8.0 t/ha, respectively, (Nizami 2010) and in rangelands of the Dir-Kohistan region, SOC was in the range of 29.8–35.6 t/ha (Shah et al. 2015). The average SOC was 30.2 t/ha in riverine forests of the Jhelum District (Saeed et al. 2016). However, these studies had a small geographical coverage and were confined to small forest areas of a few forest types. There has been no study to estimate soil organic carbon at the landscape level in Pakistan.

The province of Khyber Pakhtunkhwa (KP), situated in the north-west, is the most forested province of Pakistan. About one-third of the country's forest area is situated in the province. The total forest area of the province has been estimated at  $1.5 \times 10^6$  ha (Bukhari et al. 2012), which constitutes 20.3% of its land surface. Recently, Ali (2017) assessed the forest cover as  $1.1 \times 10^6$  ha. The difference in these two estimates is due to the definition of forest used for forestland classification. The former study classified all perennial vegetation as forest and the latter study classified land with at least 0.5 ha area, 10% canopy cover, and 2 m plant height as forest. KP's forests have considerable potential for climate change mitigation as they contain significant amounts of carbon both in soil and biomass. Soil carbon is particularly important as it is a stable pool in forest ecosystems. However, these forests are facing severe pressures due to anthropogenic and climatic factors. Deforestation and forest degradation are reducing carbon stocks both in vegetation biomass and soils. Ali (2017) has estimated that deforestation rate in KP was about 8000 ha per year during 2007–2012. Forest fires, mining and grazing are also causing the depletion of carbon stocks.

Realizing the importance of forests for climate change mitigation, the Government of Khyber Pakhtunkhwa has started a subnational REDD+ Programme to protect and enhance its forest resources through shifting the focus of forest management from timber to carbon sequestration. REDD+ is an international mechanism under the United Nations Framework Convention on Climate Change to incentivize developing countries to reduce emissions from deforestation, forest degradation, sustainable forest management, conservation and enhancement of carbon stocks. REDD+ requires data on carbon stocks in different carbon pools and changes in these pools over time. However, no

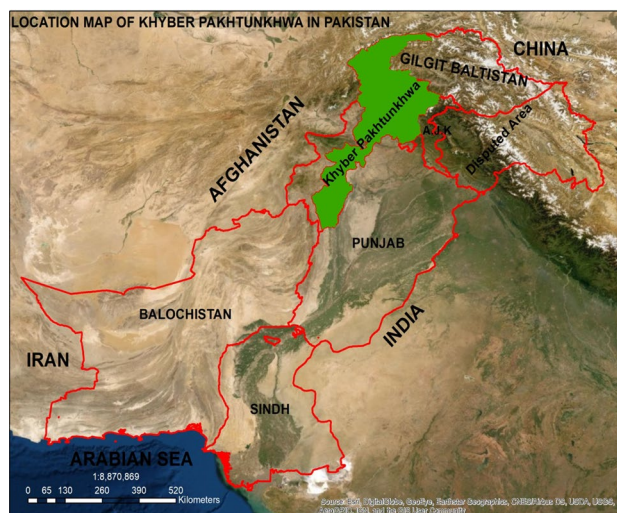
reliable data is available about the amounts of carbon in different forest carbon pools in KP. This study was designed to fill this gap by estimating the levels of soil organic carbon in various forest types of the province. It has high significance as it is the first-ever study based on field investigations at a landscape level covering all seven forest types of the province. This study will enable policy makers to devise appropriate strategies for forest carbon conservation and realize the benefits of REDD+ Programme.

## Materials and methods

### Study area

The study was focused on the province of Khyber Pakhtunkhwa situated in Pakistan's north-west between  $31^{\circ}15'$  and  $36^{\circ}57'$  N and  $69^{\circ}5'$  and  $74^{\circ}7'$  E (Fig. 1). The province has diverse ecological conditions arising from sharp altitudinal variations: ranging from 250 m a.s.l. in Dera Ismail Khan in the south to 7708 m a.s.l. in Tirich Mir, Chitral in the north. There is a range of temperatures from the lowest of  $-14^{\circ}\text{C}$  in the north to the highest of  $51^{\circ}\text{C}$  in the south. Precipitation varies from  $\sim 130$  mm per year in southern areas to  $\sim 3200$  mm in the north (Sarfaraz et al. 2016).

Seven of the nine forest types of Pakistan are present in Khyber Pakhtunkhwa, including subalpine, dry temperate, moist temperate, oak, subtropical broad-leaved, subtropical pine, and dry tropical thorn forests (Sheikh 1993). Subalpine forests are the upper-most formation in the Himalayas at elevations of 3350 to 3800 m. The dominant species are silver fir (*Abies pindrow* Royle) and kail (*Pinus wallichiana* A.B. Jackson) alone or in groups. Birch (*Betula utilis* D. Don) is typically prominent with batangi (*Pyrus pashia* Ha. Ex-D.



**Fig. 1** Study area in Khyber Pakhtunkhwa province

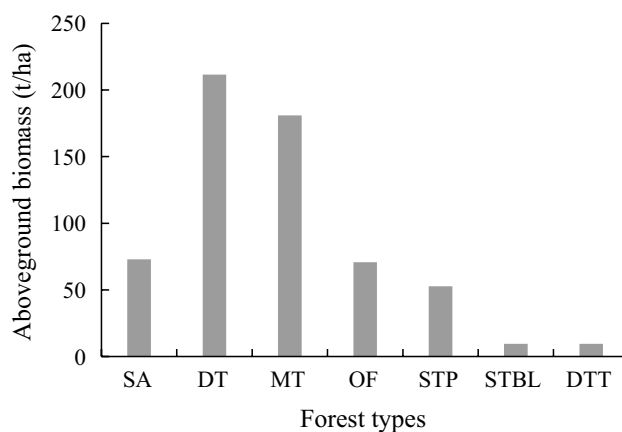
Don), Indian willow (*Salix tetrasperma* Roxb.) and *Viburnum* spp. Dry temperate forests are distributed throughout the inner mountain ranges of the Hindukush-Himalayas beyond the effective reach of monsoon rains. Major tree species include deodar (*Cedrus deodara* Roxb. Ex Lamb G. Don) with patches of spruce (*Picea smithiana* Wall Boiss), kail (*Pinus wallichiana*), chilghoza pine (*Pinus gerardiana* Wall Ex Lamb.) and juniper (*Juniperus excelsa* M. Bieb). Forests of oak (*Quercus ilex*) occur as distinct patches at lower elevations (1600–2200 m a.s.l.) inside the dry temperate zone. Moist Temperate forests are situated on the outer ranges of the Himalayas at altitudes of 1600 to 3100 m a.s.l and receive sufficient rains in summer and snow in winter. Kail is the dominant tree species followed by deodar, fir and spruce. Subtropical pine forests occur at 800–1600 m a.s.l. Chirpine (*Pinus roxberghii* Sarg.) is dominant in the upper canopies. Rein (*Quercus incana* Roxb) is the main broad-leaved associate. Kahu (*Olea ferruginea* Royle), Phulai (*Acacia modesta* Linn. Wall.) and Sanatha (*Dodonaea viscosa* Linn.) are key plant species of subtropical broad-leaved forests. The common tree species of the dry tropical thorn forests are kiker (*Acacia nilotica* Linn. Delile), Pilu (*Salvadora oleoides* Dene), kandi (*Prosopis cineraria* Linn. Druce), Ghaz (*Tamarix aphylla* L.Karst), and Ber (*Ziziphus mauritiana* Lam.) (Sheikh 1993).

Soils in the forested areas of the Khyber Pakhtunkhwa are shallow to moderately deep, sandy loams formed on slopes between 4 and 80%. More than 40% of the soils on steep slopes are shallow due to extensive water erosion and their organic matter is low (EPA 2017). Soils in the Malakand region are mainly sandy loams with slopes varying from flat to 8%. Maximum slopes of hilly parts of the watershed are up to 22% and soil depth is up to 45 cm. The area has high rates of erosion, especially where vegetation is sparse (Nafees et al. 2008).

According to Ali (2019), the highest aboveground biomass is found in dry temperate forests as 211.5 t/ha, followed by moist temperate forests as 180.9 t/ha. On average, temperate forests have aboveground biomass of 192.6 t/ha. In sub-alpine and oak forest ecosystems, average aboveground biomass estimates were 72.9 t/ha and 73.6 t/ha, respectively. For subtropical pine forests, aboveground biomass was 52.7 t/ha (Fig. 2). Similarly, in subtropical broad-leaved evergreen forests and dry tropical thorn forests, aboveground biomass values are 9.6 t/ha and 9.5 t/ha, respectively.

**Sampling design**

A stratified cluster sampling technique was adopted to collect data in the field using existing forest type maps of the province prepared by the Pakistan Forest Institute, Peshawar. These maps have been prepared from 2012 spot-5 satellite imageries (2.5 m resolution) through segmentation using



**Fig. 2** Aboveground biomass in different forest types; SA subalpine, DT dry temperate, MT moist temperate, OF oak forest, STP subtropical pine, STBL sub-tropical, broad-leaved, DTT dry tropical thorn

the object-based image analysis technique with semi-automated classification. The definition adopted was based on the definition of ‘forest’ by FAO (2015): an area of 0.5 ha, a canopy cover of at least 10% and tree height of at least 2-m at maturity.

The forest area was stratified on the basis of climatic conditions and floristic composition, i.e., dry temperate conifer, dry temperate oak, moist temperate, subtropical pine, subtropical broad-leaved evergreen forests and dry tropical thorn forests (Sheikh 1993). As these forests are found at well-defined altitudes, stratification was relatively easy using a digital elevation model (DEM) process and the expert opinion of foresters familiar with the area. Random sampling techniques were used to distribute sample plots on geo-referenced maps. Geographic coordinates of plots were recorded and uploaded into the GPS device for navigation in the field. In addition to forest cover maps, general topographic sheets were also used to locate the of sample plots.

Sample size was determined independently for each stratum. Based on the results of the 2000 Provincial Forest Resource Inventory, the coefficient of variations (CV) of growing stock for open, medium-dense and dense forests were 65%, 36% and 41%, respectively. The objective was to achieve a standard error of less than ± 10%; sample sizes for the three strata were determined using Eq. 1 (Assefa et al. 2013):

$$N = \frac{(C_V)^2 * t^2}{E^2} \times 100 \tag{1}$$

where *N* is the number of required sample plots, *C<sub>V</sub>* is the coefficient of variation, *t* is the Student *t* test value, (1.96 at 95% confidence level), and *E* is the allowable error. The required number of sample plots for different strata were calculated using Eq. 1 as follows:

For open forest:

$$N = \frac{(65)^2 \times (1.96)^2}{10^2} = 162 \tag{2}$$

For medium-dense forest:

$$N = \frac{(36)^2 \times (1.96)^2}{10^2} = 50 \tag{3}$$

For dense forest:

$$N = \frac{(41)^2 \times (1.96)^2}{10^2} = 64 \tag{4}$$

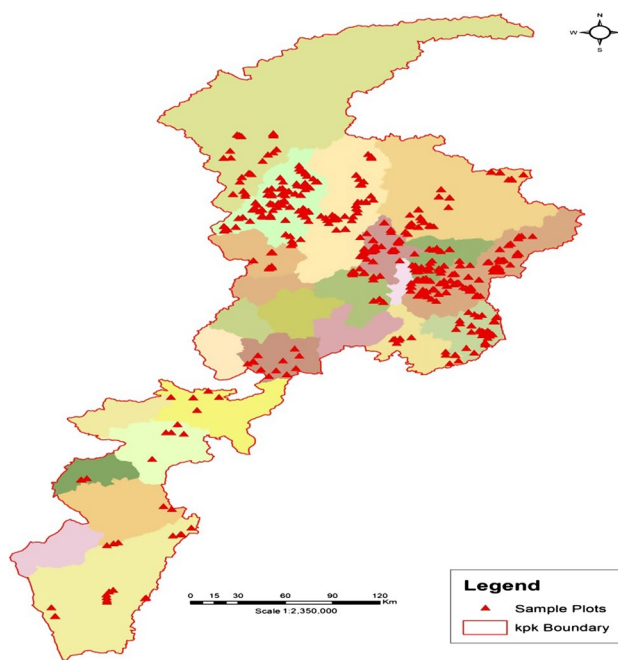
Accordingly, it was determined that 276 plots would be sufficient to achieve the desired sampling precision of  $\pm 10\%$ . However, to achieve high accuracy, 373 plots were laid out in the field. A stratified random sampling technique was used. Since > 90% of the provincial forest cover is in the northern Hazara and Malakand regions, the majority of sample plots were located here. The allocation of sample plots is given in Table 1 and the locations are shown in Fig. 3.

**Data collection**

Soil samples were collected with a soil auger from the upper 30-cm layer for the determination of SOC. According to IPCC (2003), samples from this depth are adequate as most of the SOC is concentrated here. It is also difficult to collect samples from more than a 30-cm depth due to shallow soils and the occurrence of rocks in the subsurface. A composite sampling technique was employed for the estimation of carbon concentration and bulk density of soil (Subedi et al. 2010). Information on forest type, stand composition, crown cover, slope and aspect was also collected.

**Table 1** Distribution of sample plots in the study area

Forest type	Number of sample plots
Subalpine	30
Dry temperate (conifer)	84
Dry temperate (oak)	51
Moist temperate	84
Subtropical pine	84
Scrub (subtropical broad-leaved evergreen and dry tropical thorne)	40
Total	373



**Fig. 3** Sample plot distribution in the study area

**Soil analysis**

*Soil bulk density*

The dry weight of a unit volume of soil is defined as bulk density. Both solid particles and pore spaces are considered for the estimation of bulk density, which is influenced by factors such as the degree of compaction, the consolidation of particles and the amount of organic matter present. High level of organic matter results in low soil bulk density (Morisada et al. 2004). The wet weights of the samples were measured on site with a digital balance. Samples were packed in polythene bags and transported to the Pakistan Forest Institute where these were air-dried, and then placed in an oven at 105 °C for 24 h. The dehydrated samples were weighed and moisture content (MC %) determined using Eq. 5 (Hartley and Marchant 1995).

$$M_C(\%) = \frac{W_w - W_d}{W_d} \times 10 \tag{5}$$

where  $M_C$  (%) is moisture content,  $W_w$  is wet weight, and  $W_d$  is the dry weight. Stones were removed from the samples and net weights recorded. The volume of the soil auger was determined by measuring its diameter and length. Bulk density was calculated using Eq. 6 (Agus et al. 2011).

$$B_D = \frac{W_d}{V_s} \tag{6}$$

where  $B_D$  is bulk density,  $W_d$  oven dry weight of sample (g),  $V_s$  volume of soil core (cm<sup>3</sup>).

*Soil organic matter*

Organic matter in soil was estimated through the loss on ignition (LoI) method (Schumacher 2002; Rehman et al. 2011). This involves the burning of organic matter at high temperatures of 350–440 °C (Nelson and Sommers 1996; Schumacher 2002). A 50-g sample of dehydrated soil was placed in a china dish in a muffle furnace and the temperature was set at 400 °C. The furnace was run continuously for 8 h to burn the samples to ash. The weight of ash was recorded for each sample and organic matter was determined using Eq. 7 (Rehman et al. 2011).

$$O_M = W_d - W_a \tag{7}$$

where  $O_M$  is organic matter (g),  $W_d$  weight of oven-dried sample (g),  $W_a$  weight of ash (g)

*Soil organic carbon (SOC)*

Soil organic carbon (SOC) was calculated using a factor of 0.58 (Rehman et al. 2011). Soil carbon density i.e., SOC per hectare for different forest types was calculated using Eq. 8 (IPCC 2003).

$$S_{OC} = \rho \times d \times C \times 10 \tag{8}$$

where  $S_{OC}$  is soil organic carbon,  $\rho$  the soil bulk density,  $d$  the depth of soil sample, and  $C$  carbon content in the sample.

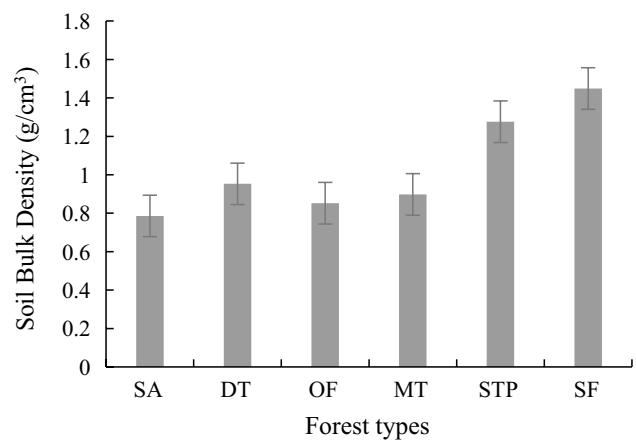
*Soil carbon stocks*

Soil carbon stocks of different forest types were determined by multiplying carbon density with respective forest area. The total soil carbon pool of the province was estimated by adding the carbon stocks of all forest types.

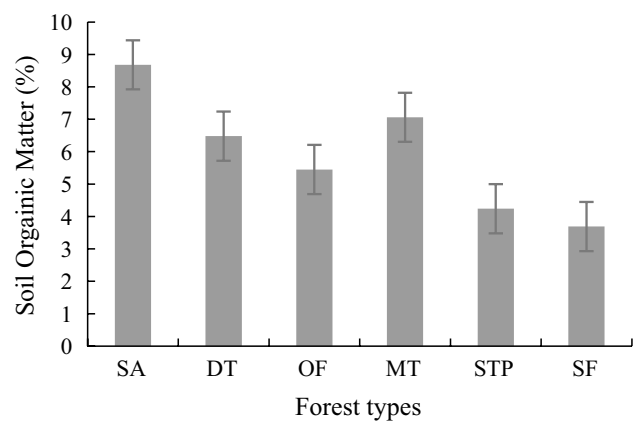
**Results**

**Soil bulk density**

The results for soil bulk density in the top 30-cm layers of various forest types are shown in Fig. 4. Mean bulk densities in subalpine, moist and dry temperate forests were 0.786 g/cm<sup>3</sup>, 0.898 g/cm<sup>3</sup> and 0.953 g/cm<sup>3</sup>, respectively. For the oak forest, mean soil bulk density was 0.852 g/cm<sup>3</sup> and for subtropical pine forests it was 1.276 g/cm<sup>3</sup>. However, scrub forests had the highest level at 1.449 g/cm<sup>3</sup>.



**Fig. 4** Soil bulk density in different forest types; SA subalpine, DT dry temperate, OF oak forest, MT moist temperate, STP subtropical pine, SF scrub forest)



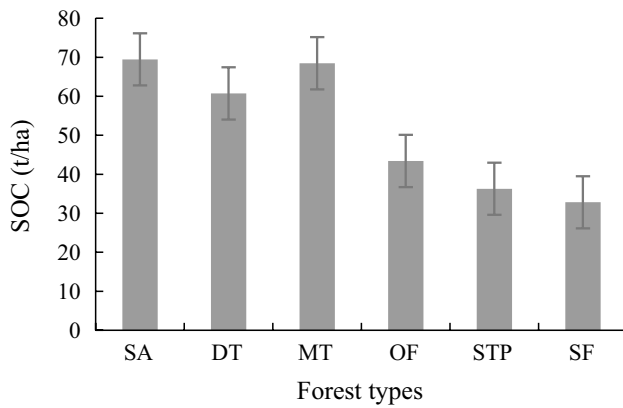
**Fig. 5** Soil organic matter content (%) in different forest types; SA subalpine, DT dry temperate, OF oak forest, MT moist temperate, STP subtropical pine, SF scrub forest)

**Soil organic matter content**

The highest organic matter content was in subalpine forests (8.7%), followed by moist temperate (7.1%), dry temperate (6.5%) and oak forests (5.5%). Subtropical pine, and scrub forests have 4.2% and 3.7% organic matter (Fig. 5).

**Soil organic carbon density**

The estimates of soil carbon organic carbon (SOC) densities for the upper 30-cm layer in various forest types are shown in Fig. 6. The maximum SOC was found in subalpine forests with a mean of 69.5 t/ha, followed by moist temperate forests with 68.5 t/ha and dry temperate forests with 60.7 t/ha. On average, soil carbon density of moist and dry temperate forests was 62.5 t/ha. Oak forests have soil carbon



**Fig. 6** Estimates of soil organic carbon density in different forest types; *SOC* soil organic carbon, *SA* subalpine, *DT* dry temperate, *MT* moist temperate, *OF* oak forest, *STP* subtropical pine, *SF* scrub forest)

**Table 2** Descriptive statistics of soil organic carbon estimation in different forest types

Forest type	N	Mean (t/ha)	SD	CV	SE	RSE	Sampling error	Sampling error (%)
Subalpine forest	30	69.5	19.7	56.9	3.6	5.2	7.2	10.4
Temperate forest	121	62.5	29.3	46.9	2.7	4.3	5.3	8.5
Dry temperate forest	84	60.7	29.9	49.2	3.3	5.4	6.5	10.7
Moist temperate forest	84	68.5	30.6	44.6	3.3	4.9	6.7	9.7
Subtropical pine forest	84	36.3	17.1	47.1	1.8	5.1	3.7	10.3
Scrub forest	24	32.8	46.6	3.1	3.1	9.5	6.2	19.0

*N* number of sample plots, *CV* coefficient of variation, *SD* standard deviation, *SE* standard error, *RSE* relative standard error

**Table 3** Soil carbon estimates for the study area

Forest type	SOC (t/ha)	Area (ha)	Total SOC (t)	Percent (%)
Subalpine	69.5	48,782	3,051,314	5.1
Temperate	62.5	654,277	40,925,026	68.9
Oak forests	43.4	77,491	3,363,884	5.7
Subtropical pine	36.3	144,424	5,239,703	8.8
Scrub (subtropical broad-leaved)	32.8	206,810	6,787,504	11.4
Scrub (dry tropical thorn)	32.8	1,776	58,288	0.1
Total		1,133,560	59,425,720	100

**Table 4** Soil carbon densities in different land-uses

Land-use system	Geographical coverage	Soil depth (cm)	Carbon density (t/ha)
Forest land	Khyber Pakhtunkhwa	0–30	52.4
Agricultural land	Kumrat Dir, Khyber Pakhtunkhwa	0–30	29.8
Rangeland	Khyber Pakhtunkhwa	0–30	32.7
Agricultural land	Kashmir (India)	0–30	20.3
Rangeland	Himachal Pradesh (India)	0–20	31.6
Agricultural land	Himachal Pradesh (India)	0–20	25.1

density of 43.4 t/ha, subtropical pine forests have 36.3 t/ha, and scrub forests (sub-tropical broad-leaved evergreen and dry-tropical thorn forests) have 32.8 t/ha. Table 4 shows that all the strata have acceptable sampling precision, i.e., 10%, except for scrub forests which have sampling precision of 19.0%. Descriptive statistics of SOC calculation are shown in Table 2.

#### Estimates of soil carbon stocks for total forest area

The total soil carbon pool in the forests of Khyber Pakhtunkhwa was estimated at  $59.4 \times 10^6$  t with a mean of  $52.4 \pm 5.3$  t/ha. The highest level was in temperate forests (68.9%), followed by subtropical broad-leaved forests (11.4%) and subtropical pine forests (8.8%). Subalpine forests and oak forests contribute 5.1% and 5.7% to the total soil carbon stocks, respectively (Table 3). The high amounts

stored in temperate forests is due to their large aerial extent and high carbon density. This data indicate that soil organic carbon is an all-important pool of forest carbon in the province, with significant potential for climate change mitigation and must be conserved and enhanced through sustainable forest management.

### Comparison of forest soil carbon with agriculture and other land uses

Forest soils contain higher amounts of carbon than soils of other land uses such as agriculture, rangelands and wastelands. The average soil carbon density in forests was approximately 52.4 t/ha, which is significantly higher than values for agriculture (29.8 t/ha) and rangelands (32.7 t/ha) in similar areas of the north western Himalayas of India (Shah et al. 2015). Chisanga et al. (2018) reported soil carbon densities in the upper 20-cm layers of agricultural lands and grasslands in Himachal Pradesh, India, of 31.6 t/ha and 25.1 t/ha respectively (Table 4).

### Discussion

Soil carbon stocks of Khyber Pakhtunkhwa forests are comparable with estimates by other researchers in the region. The lowest bulk density in subalpine forests is because these forests occur at high elevations where temperatures are mostly low and soil organic matter accumulates, making the soil porous and rich. Similarly in temperate forests, soils are generally deep, loamy and have high organic matter, resulting in low bulk density. On the other hand in subtropical and tropical zones, soils are generally sandy, compact with low organic matter, and bulk density is high.

Liu et al. (2016) reported soil bulk density in cold temperate forests of north-eastern China as 1.3 g/cm<sup>3</sup> which is slightly higher than our estimates (0.85–0.95 g/cm<sup>3</sup>). This is possibly due to the fact that soil samples were taken from greater depths, i.e., 40 cm compared to our sampling depth of 30 cm. Bulk density generally increases with increasing soil depth. For estimation of soil carbon in forests, 0–30 cm depth is considered sufficient as it contains about half the soil carbon present in the upper 100 cm (IPCC 2003). Liu et al. (2016) also estimated bulk density for subtropical broad-leaved forests in south-eastern China as 1.28 g/cm<sup>3</sup> which is closer to our estimate of 1.45 g/cm<sup>3</sup>. Our estimates for oak and subtropical pine forests are closer to Shrestha and Devkota (2004) who reported mean bulk densities in oak and pine forests of Nepal as 0.64–0.75 g/cm<sup>3</sup> and 1–1.13 g/cm<sup>3</sup>, respectively.

The highest amounts of soil organic matter in subalpine forests is because this ecosystem experiences extremely low temperatures throughout the year except for a few months of

summer. Due to low temperatures, organic matter accumulation is high and decomposition is slow. Moist temperate forests also have cold, wet months in which organic matter accumulates. This forest type has thick undergrowth and high litter contents which continuously adds to the soil organic matter. Siddiqui et al. (2014) reported that organic matter ranged from 2.6 to 10.5% in moist temperate forests of Malakand, Hazara and Azad Kashmir. Khan (2000) found soil organic matter as 4.57% in moist temperate forests of Hilkot, Pakistan. Khattak and Hussain (2007) reported soil organic matter in subtropical forests of Abbottabad as 4.2%. Maren et al. (2015) noted organic matter levels in semi-arid trans-Himalayan forests as 3.8% in Nepal.

The estimates of soil organic carbon in this study for moist temperate forests (68.5 t/ha) is closer to the IPCC (2003) estimate of 71.0 t/ha for mountain temperate forests, and to the 70.0–162.0 t/ha in temperate forests of India (Chabhra et al. 2003). [Liu et al. (2016) reported soil carbon levels of 81.9 t/ha for cold temperate forests of north-eastern China which is higher than our estimate. This is probably due to the fact that they have taken samples from greater depth i.e. 40 cm compared to our sampling depth of 30 cm]. [Soil organic carbon is higher in moist temperate forests (68.5 t/ha) than dry temperate forests (60.7) due to the reasons that soils are deep and wet in the moist temperate forests due to which dense undergrowth develops in these forests resulting in the accumulation of humus. On the other hand, in dry temperate forests moisture is a limiting factor due to which undergrowth is rare and humus accumulation is low].

Soil carbon in subtropical pine forest was estimated at 36.3 t/ha which is comparable with IPCC (2003) who reported 31–38 t/ha in dry tropical forest. Our estimates of soil organic carbon in subtropical pine forests (36.3 t/ha) and oak forests (43.4) are comparable with the findings of Shrestha and Devkota (2004) who reported soil carbon in subtropical pine forest and oak forest in Nepal as 46.1 t/ha and 60.8 t/ha respectively.

The average soil carbon density in forests is 52.4 t/ha, significantly higher than soil carbon densities of agriculture (29.8 t/ha) and rangelands (32.7 t/ha) (Shah et al. 2015), and is closer to the aboveground biomass carbon density (60 t/ha) in the study area. The amount of carbon stored in forest soil pool is  $59.4 \times 10^6$  t, equal to 87% of the aboveground carbon pool and 41% of the entire carbon stocks present in the forests of Khyber Pakhtunkhwa. This indicates that soil organic carbon is an important carbon pool in the forest ecosystems of Khyber Pakhtunkhwa and needs to be protected for climate change mitigation.

Based on the outcomes of this study, it is strongly recommended that soil carbon be conserved for climate change mitigation and realizing REDD+ benefits. It is very important in the subalpine and temperate forests of the study area.

Any activities involving soil disturbance such as agricultural expansion or mining in this zone will result in high amount of carbon emissions. Forest fires and open grazing are also detrimental for the maintenance of soil organic carbon.

It is also recommended that the impacts of deforestation and forest degradation on soil carbon levels and the changes in soil carbon associated with afforestation and reforestation be investigated. This will quantify carbon emissions and removals arising from land-use changes in forested areas. The correlation between stand structure and forest management practices should also be studied to develop options for sustainable forest management. The use of GIS and remote sensing data for forest soil mapping will help a decision-support system regarding soil carbon management.

## Conclusions

The findings of present study indicated that forests of Khyber Pakhtunkhwa have significant stocks of soil organic carbon. Total soil carbon was estimated at  $59.4 \times 10^6$  t with an average of  $52.4 \pm 5.3$  t/ha. About 69% of all soil carbon stocks are found in temperate forests. Scrub forests and subtropical pine forests constitute 11.5% and 8.8% of total soil carbon stocks, respectively, with subalpine and oak forests contributing 5.1% and 5.7%, respectively.

Soil carbon density is highest in subalpine forests (69.5 t/ha) followed by moist temperate (68.5 t/ha) and dry temperate forests (60.7 t/ha). Oak forests have soil carbon densities of 43.4 t/ha. Subtropical pine and scrub forests have comparatively low carbon densities, i.e., 36.3 t/ha and 32.8 t/ha, respectively. Forests at higher altitudes such as subalpine and temperate forests have high amounts of soil organic carbon. As most of the forests of Khyber Pakhtunkhwa are situated at higher altitudes, therefore, it is concluded that these forests have substantial amounts of soil organic carbon and their conservation is vital for climate change mitigation.

**Acknowledgements** This research is part of the doctoral dissertation of the first author at PMAS Arid Agriculture University, Rawalpindi, Pakistan (AAUR). The authors are extremely grateful to Prof. Dr. Sarwat N. Mirza, former Vice-Chancellor of PMAS Arid Agriculture University, Rawalpindi, for his valuable inputs and support during the study period. Thanks are also extended to the staff of Forest Mensuration Branch, Pakistan Forest Institute, Peshawar for their help in data collection in the field.

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