Estimation of forest carbon stocks in temperate and subtropical mountain systems of Pakistan: implications for REDD+ and climate change mitigation

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Abstract Forests are important carbon pools as they provide pathway to mitigate climate change. Quantification of forest carbon has gained momentum after Paris Agreement in 2015. This information is a prerequisite for REDD+ implementation and carbon trading. Temperate and subtropical mountain systems of Khyber Pakhtunkhwa province host about one third of Pakistan's 4.51 million ha forests. Present study estimated forest carbon stocks in the Khyber Pakhtunkhwa province of Pakistan. The data was collected from 449 sites in different forests across the province using a stratified cluster sampling technique. Total carbon stock in the forests of the province was estimated at 144.71 million tons with an average of 127.66 ± 9.32 t/ha. Aboveground carbon stock was 68.15 million tons accounting for 48% of the total forest carbon stock of the province. Further, belowground biomass and litter accounted for 10% and 1% respectively. The mean aboveground carbon stock was 59.98 ± 4.26 t/ha. The highest aboveground carbon stock was found in dry temperate forests (99.41 t/ha) followed by moist temperate (85.04 t/ha). Overall, temperate forests have aboveground carbon stock of 90.52 t/ha. Temperate and subtropical forests of Pakistan with high carbon densities have ample potential for reducing forest sector emissions. Therefore, forests of Khyber Pakhtunkhwa province having substantial carbon stocks must be conserved for climate change mitigation. Present study provides a framework for carbon stock assessments in other temperate and subtropical regions of the world.

Introduction

Climate change is the biggest global challenge of the modern industrial era. Excessive emissions of greenhouse gases (GHGs) due to burning of fossil fuels, clearance of land, and other human activities are the key causes of climate change. Average annual global temperature has increased by 0.85 °C during 1880–2012 and may reach to 4.8 °C by the end of twenty-first century if GHG emissions continue unabated (IPCC 2014). This unprecedented increase in global temperature will affect all biophysical and socioeconomic systems of the Earth (McCarthy et al. 2001). There is a pressing need to explore all possible ways that could potentially reduce GHG emissions into the atmosphere to mitigate the dangerous effects associated with climate change.

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Forests play a crucial role in climate change as a sink and source of carbon emissions. Forests sequester CO_2 from the atmosphere through photosynthesis and store carbon in the form of biomass and soil organic matter in forest ecosystem. Global forest ecosystems hold more than half of all terrestrial carbon stock (Smith et al. 1993) and account for 90% of the annual carbon flux between the atmosphere and the land surface (Streck and Scholz 2006). According to FAO (2006), this carbon is more than one trillion tons, twice the amount found in the atmosphere. Therefore, preventing this stored carbon from escaping into the atmosphere is vital for mitigating climate change and conserving the environment. On the other, forests also contribute substantially to global carbon emissions. They release about 1.6 billion tons carbon annually to the atmosphere. About 12% of GHG emissions are contributed by deforestation and degradation of forests (IPCC 2014; Pan et al. 2011). About 75% of these emissions occur in developing countries where forests are under tremendous pressure due to a variety of social and economic factors. This crucial role of forests in climate change makes it imperative to include forest-related climate actions in international agreements (Baker et al. 2010).

Agriculture, forestry, and other land use (AFOLU) are the second largest source of GHG emissions in the world after energy sector (IPCC 2014). Accurate data of forest carbon stocks and GHG emissions are required to determine potential of forests in climate change mitigation. However, there is considerable uncertainty in estimates of emissions arising from deforestation and land use changes due to unavailability of precise data on emission factors and activity data related to different forest areas of the world (FAO 1993; Dixon et al. 1994). Scientific studies suggest that forests sequester a large amount of carbon from the atmosphere (Mackey et al. 2008). Forests can not only sustain its own carbon stock but also have the potential to remove additional carbon from the atmosphere. However, the available information on carbon stock in different forest areas is incomplete or vague. Accurate and precise information about terrestrial carbon stocks and fluxes is essential for quantifying regional contributions to terrestrial sources and sinks.

Most of Pakistan's natural forests are found in the province of Khyber Pakhtunkhwa, situated in the north west of the country. About one third of the country's forest area and 40% of the country's natural forests are

located in the province (Govt. of Pakistan, 1992). The total forest area of the province has been estimated at 1.504 million ha (Bukhari et al. 2012) which constitute 20.3% of the total land surface of the province. A recent study has assessed forest cover of the province as 1.133 million ha (Ali 2017). Out of nine forest types of Pakistan, seven are present in Khyber Pakhtunkhwa which include subalpine forests, dry temperate forests, moist temperate forests, oak forests, subtropical pine forests, subtropical broad-leaved forests, and dry tropical thorn forests (Sheikh 1993).

Realizing the importance of forests for climate change mitigation under REDD+, the government of Khyber Pakhtunkhwa has started a subnational REDD+ programme in the province to protect and enhance its forest resources through shifting the focus of forest management from timber to carbon sequestration. A key step in this mechanism is estimating the amount of carbon stock in the forests and the rate at which carbon is sequestered by them at different spatial and temporal scales. Currently, landscape level data are not available to quantify carbon stock in different forest types of the province. There is a need to accurately quantify spatial and temporal changes in carbon stock to qualify for participation in REDD+ and other carbon trading schemes.

Some fragmented studies have been conducted on vegetation types, timber inventory, species diversity, and composition of the dominant forest types of Khyber Pakhtunkhwa, but studies related to carbon stocks in different forest types of this region are still lacking. Present study was the first ever attempt to estimate forest carbon stocks at provincial level covering all forest types and forest areas across the province. The main objective of the study was to estimate total carbon stock in the forests of Khyber Pakhtunkhwa and quantify carbon densities in different forest types of the province.

Material and methods

Study area

The focus of the study was the province of Khyber Pakhtunkhwa, situated in the north west of Pakistan between 31° 15′ and 36° 57′ North latitude and 69° 5′ and 74° 7′ East longitude, which is the most forested province of Pakistan (Fig. 1). Total area of the province is 7.452 million ha constituting 9.36% of the total area
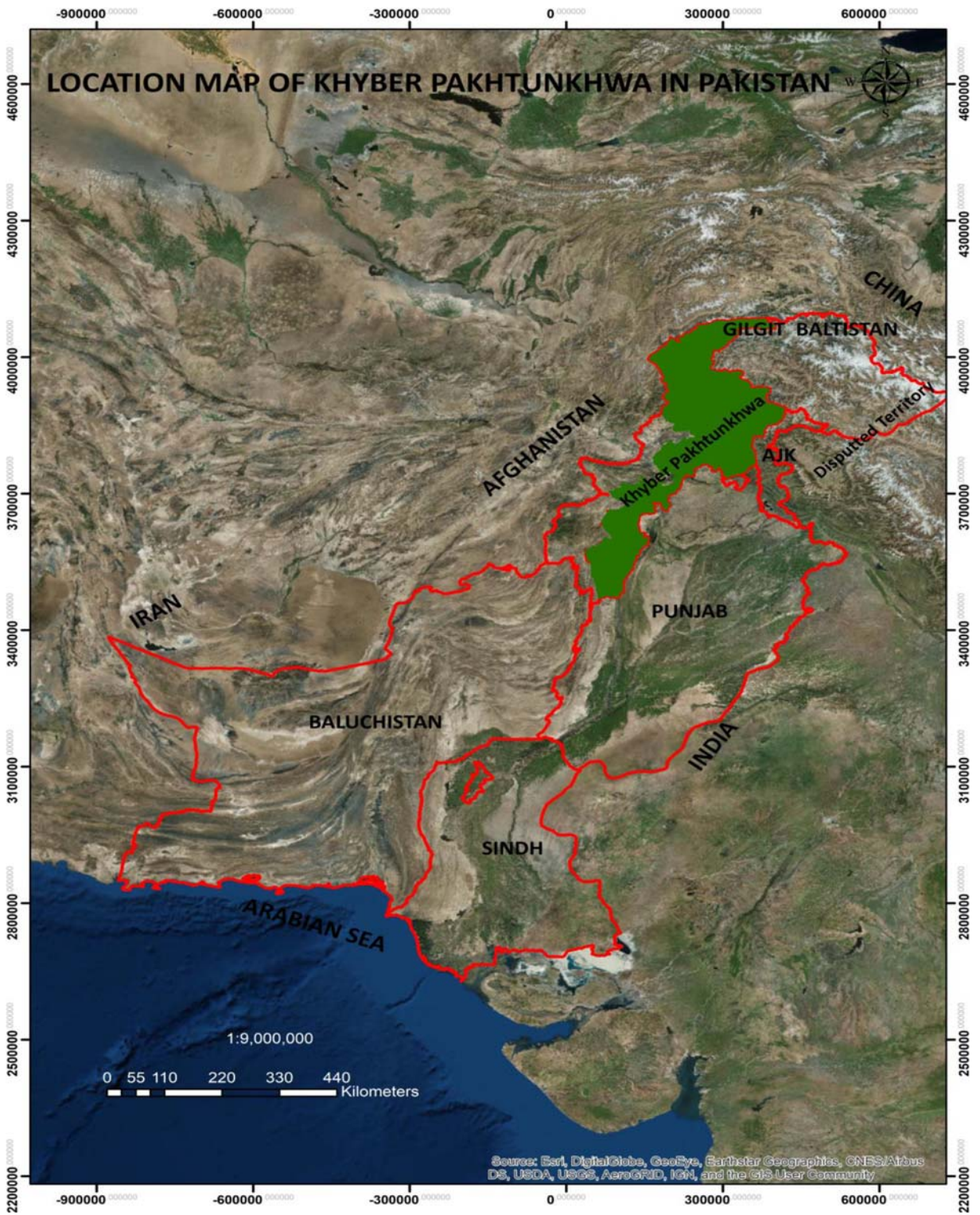
Fig. 1 Location of the study area (green colored): Khyber Pakhtunkhwa Province in North West Pakistan

of Pakistan. Agriculture, rangelands, and forestry are the major land uses in the province with 30%, 26%, and 20% shares in the total area, respectively (Bukhari et al. 2012). The actual forest cover of the province is 1.133 million ha (Ali 2017) with 30.523 million human population (Govt. of Pakistan 2017).

Khyber Pakhtunkhwa (KP) has diverse ecological conditions mainly arising from sharp altitudinal variations, ranging from 250 m above mean sea level in Dera Ismail Khan in the south to 7708 m in Tirich Mir (Chitral district) in the north. The province experiences a wide range of temperature conditions from a lowest of − 14 °C in the north to the highest of 51 °C in the south. The province receives varied precipitation for as low as 130 mm per annum in the southern districts to around 3200 mm in the northern parts (Sarfaraz et al. 2016). These heterogeneous climatic conditions bestow the province with numerous forest types. About 90% of the total forest area of the province is located in the temperate and subtropical mountain systems in Hazara and Malakand regions. Out of the total forest area of the province, 70% is in temperate zone and 30% in subtropical zone (Ali 2017).

Sampling design

Stratified cluster sampling technique was used to collect representative data. Stratification was realized using the existing forest type maps of Khyber Pakhtunkhwa prepared by Pakistan Forest Institute Peshawar (Ali 2017). These maps have been prepared from Spot-5 satellite imageries (2.5 m resolution) through segmentation using object-based image analysis (OBIA) technique with semiautomated classification. The definition adopted for this classification was based on the definition of forest given by FAO which include minimum area 0.5 ha; minimum canopy cover 10%; and minimum tree height 2 m at maturity.

Forest area was stratified into different forest types based on climatic conditions and floristic composition i.e., subalpine, dry temperate conifer, dry temperate oak, moist temperate, subtropical pine, subtropical broadleaved evergreen forests, and dry tropical thorn forests (Sheikh 1993). As these forests occur on well-defined altitudinal ranges, it was easy to stratify these forests using digital elevation model (DEM) and expert opinion of foresters familiar with the area. Cluster sampling involves the division of sample plot into several subsamples which are distributed according to the specific spatial patterns. The whole sampling unit is called primary sampling unit (PSU) and the subplots are called secondary sampling units (SSUs). This sampling design is actually based on a two-stage sampling design. In the first stage, the center of square shaped primary sampling unit (PSU) is marked on a geo-referenced forest cover map. In the second stage, four SSUs are laid out in the field on the corners of the PSU at 200 × 200 m (Govt. of NWFP 2000). In this way, one PSU comprises one SSU in the center and four SSUs at the corners (Fig. 2). The sampling units were randomly distributed among strata. Nested circular plot approach was used for measurement of trees, shrubs and litter. The outermost circular plot with radius of 17.84 m (or 8.92 m in case of dense forest or high hill forest) was established for measurement of trees. The second circular plot with radius of 5.64 m was used for measurement of shrubs and saplings; and the inner most plot with radius of 0.56 m was used for measurement of litter and soil (Fig. 3). Nested circular shape plots were preferred for the field inventory due to its easiness in establishing, particularly in sloppy terrains and to reduce the problem of edge effect associated with rectangular plots (Ali 2020).

The coordinates of the centers of sample plots were recorded and uploaded into GPS sets for navigation in the field. Beside forest cover maps, general topographic sheets were also used to locate the actual position of the sampling units in the field.

Sample size

Sample size was determined for each stratum based on variations in forest, topographic, and climatic conditions. Based on the results of the Provincial Forest Resource Inventory (Govt. of NWFP 2000), it was found that the coefficients of variation (CV) for open, medium-dense, and dense forest are 65%, 36%, and 41% respectively. The objective of the inventory was to achieve a standard error of less than ± 10%. Sample sizes for three strata were estimated using Eq. 1.

$$N = \frac{(CV)^2 \times t^2}{E^2} \qquad (1)$$

where N is the number of required sample plots; CV is the coefficient of variation; t is the student t-test value (1.96 at 95% confidence level); and E is the allowable error.

Fig. 2 Spatial arrangement of secondary sampling units (SSUs) within a primary sampling unit (PSU)
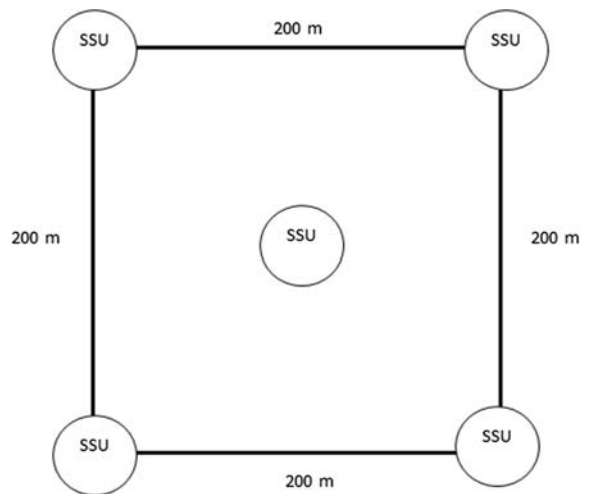
The required PSUs for different strata were calculated by putting values in Eq.1 as mentioned below:

For open forest $N_o = \frac{(65)^2 \times 1.96^2}{10^2} = 162$

For medium-dense forest $N_M = \frac{(36)^2 \times 1.96^2}{10^2} = 50$

For dense forest $N_D = \frac{(41)^2 \times 1.96^2}{10^2} = 64$

Total PSUs $N_T = N_o + N_M + N_D = 276$

A total of 276 PSUs were required for obtaining the desired percision of ± 10%. It was found during the course of inventory that the variation is quite high. Therefore, sample size was increased to 449 to achieve better accuracy. The PSUs were randomly assigned to strata based on proportionate allocation using GIS software for randomization. As more than 90% of the Khyber Pakhtunkhwa's forest cover is concentrated in the northern part, most of the sample plots were laid out in this area. The distribution of PSUs in different forest types is given in Table 1 and shown in Fig. 4.

Data collection and analysis

Diameters at breast height (DBH) of all trees were measured with caliper at 1.37 m above ground on uphill side. However, for big size trees, diameter tape was used. Considering that measurement of tree height is a time-consuming and difficult task in forest inventory, it was decided to measure the height of every fifth tree in the sample plot. Tree height was measured with the help of Vertex Hypsometer VL5. These data were used for the development of diameter-height relations employing regression technique, considering height as dependent variable and diameter as independent variable. These relationships were used to estimate heights of all unmeasured trees. Aboveground biomass was calculated through locally developed allometric equations. In case local allometric equations were not available for some species, equations available in published scientific literature were used (Sakici et al. 2018). The allometric equations used for biomass calculation are given in Table 2.

All shrubs in the second circular plot (100 m^2) were cut and weighed on the spot. Representative samples were collected in bags and their fresh weights were recorded. The samples were brought to laboratory for analysis. The samples were dried in the oven at 105 °C until constant weight using a digital balance. Moisture content (MC%) was calculated by Eq. 2.
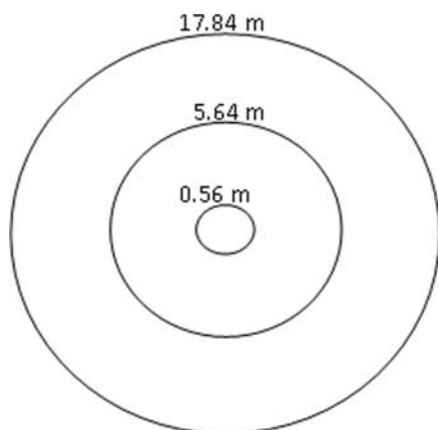
Fig. 3 Arrangement of nested circular sample plots with radius of each subplot

Table 1 Distribution of primary sampling units (PSUs) in different forest types

Forest type	Open forest	Medium forest	Dense forest	Total PSUs
Subalpine	10	8	12	30
Temperate (conifer)	48	44	118	210
Dry temperate (oak)	17	16	18	51
Subtropical pine	40	29	31	100
Subtropical broad-leaved evergreen	16	15	11	42
Dry tropical thorn	16	–	–	16
Total	147	112	190	449

Temperate (conifer) includes dry and moist temperate forest types

$$MC\% = \frac{(\text{Fresh weight of sample} - \text{dry weight of sample})}{\text{Dry weight of sample}} \times 100$$

$$(2)$$

Leaf, litter, herbs, and grasses in the innermost circular plot (1 m^2 area) were destructively sampled. The material was weighed on the spot and a well-mixed subsample of 100 g was collected for drying in the oven to determine the ratio of dry to fresh biomass.

Belowground biomass (BGB) was estimated using default values from IPCC guidelines. Plot level tree and shrub biomass estimates were converted to tons per hectare by multiplying with 10 and 100 respectively. For litter, the per hectare estimates were obtained by multiplying with 10,000. In all pools, biomass was converted to carbon stock by multiplying with 0.47 (IPCC 2006). Total carbon stocks for forest types were obtained by multiplying the average per hectare value with total area of the particular forest type. The collected data were statistically analyzed using software packages e.g., MS Excel and SPSS 16.

Results

Frequency of tree species

In total, 22,521 trees were tallied during the field inventory. The sampled trees comprised conifer and broad-leaved species. Kail (*Pinus wallichiana*) was the dominant species (29%) succeeded by deodar (*Cedrus deodara*) (18%) and chirpine (*Pinus roxburghii*) (13%). Fir (*Abies pindrow*) and spruce (*Picea smithiana*) have small proportion in total number of trees with 7% and 2% contributions respectively. Similarly, chilghoza pine (*Pinus gerardiana*) has also 2% share in total trees

count. Oak (*Quercus spp.*) was the dominant broad-leaved species (10%) recorded during the inventory. Phulai (*Acacia modesta*) constituted 4% and other tree species were 15% of the total tree stock (Fig. 5).

Diameter class distribution

Diameter class distribution of sampled trees measured during the study is shown in Fig. 6. It is evident that diameter class distribution follows a left-skewed trend indicating that most of the trees are young and hence in the category of immature diameter classes (Fig. 6). The relationship between stem density and diameter classes is best expressed by an exponential fashion indicating that stem density in the study area decreases with increasing diameter. In fact, this is brought about not only by natural thinning but also by removal of mature trees by the local people and forest department. The highest number of trees was distributed in diameter class 11–21 cm. Second and third larger diameter classes by tree count were < 11 and 21–30 cm respectively. These three classes are considered young or immature crop. Therefore, majority of the trees were immature in the province. The proportion of trees in diameter classes 61 cm and above was very low. These diameter classes are considered exploitable size for harvesting. Consequently, smaller numbers of trees are available for harvesting. This finding may be useful for taking any decision about the forest management particularly resumption of harvesting in the provincial forests.

Stand structure

The results of the study showed that the forests of Khyber Pakhtunkhwa are generally young. Stand
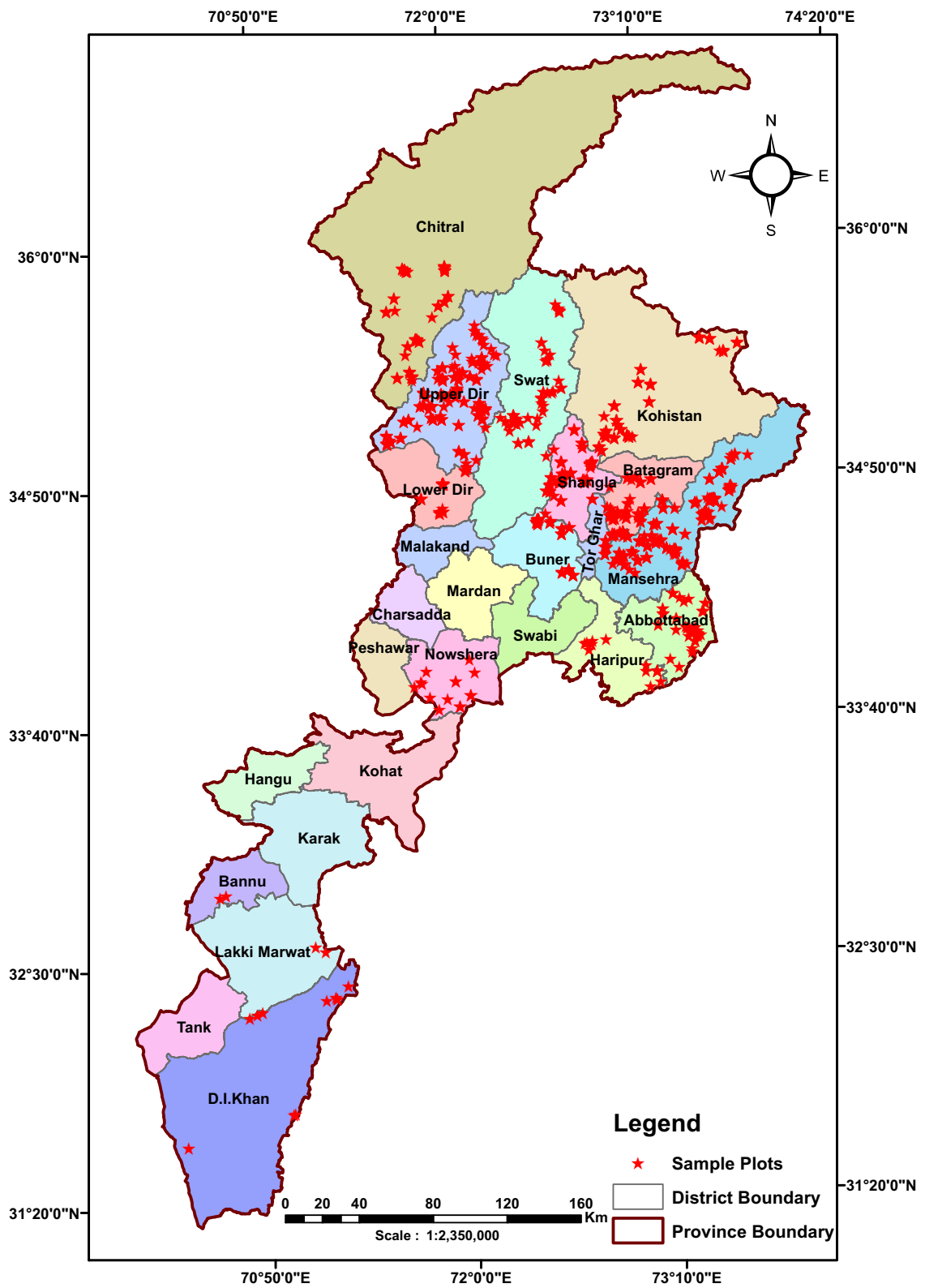
Fig. 4 Location of sample plots across the study area

Table 2 Allometric equations used for estimation of above-ground biomass

Species	Allometric equations	Source
Cedrus deodara (deodar)	$AGB = 0.0491(D^2H)^{0.9167}$	Ali (2019)
Pinus wallichiana (kail)	$AGB = 0.0594(D^2H)^{0.881}$	Ali (2019)
Pinus roxburghii (chirpine)	$AGB = 0.0224(D^2H)^{0.9767}$	Ali (2019)
Pinus gerardiana (chilghoza)	$AGB = 0.0253D^{2.6077}$	Ali (2015)
Abies pindrow (fir)	$AGB = 0.0452(D^2H)^{0.9029}$	Ali (2019)
Picea smithiana (spruce)	$AGB = 0.0821(D^2H)^{0.8363}$	Ali (2019)
Eucalyptus camaldulensis	$AGB = 0.023(D^2H)^{0.9985}$	Ali (2019)
Quercus ilex (oak)	$AGB = 0.8277(D^2H)^{0.6655}$	Ali (2015)
Other species	$AGB = 0.0112(D^2H)^{0.916}$	Chave et al. (2005)

**Fig. 5** Composition of growing stock by tree species in the study area
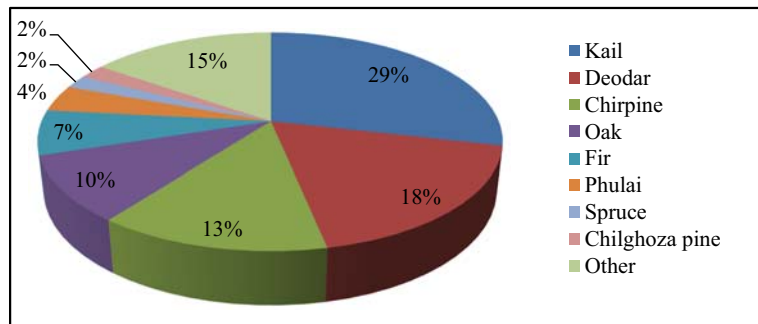
structure is given in Table 3. About 78.84% trees were in immature class succeeded by submature class with 17.25% sampled trees. On the other, only 3.90% of the sampled trees were mature. Accordingly, about 96% trees were not mature and hence not ready for harvesting at present. More trees in younger classes indicate high potential for carbon sequestration as growth rate is generally faster in early stages, and they can sequester a large amount of carbon dioxide compared with mature and old trees. Therefore, the forests of the province have high potential for REDD+ and carbon trading schemes.

Total carbon stock

The estimates of carbon stock in different pools by forest types are given in Table 4. Total carbon stock in the forests of Khyber Pakhtunkhwa was estimated at

Fig. 6 Diameter class distribution of sampled trees
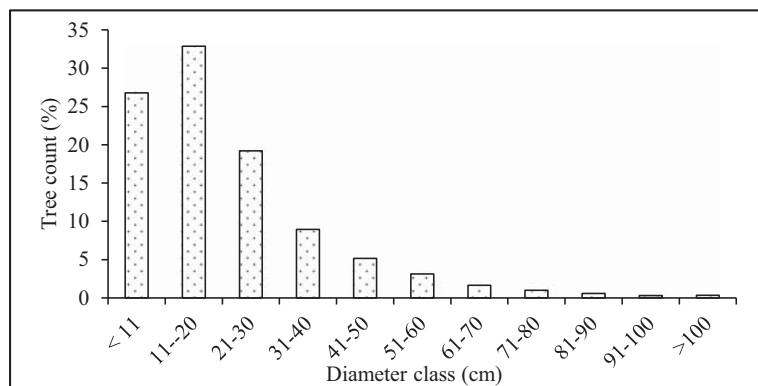
Table 3 Overall stand structure in the study area

Development stage	Tree count	Percentage
Young (< 30 cm)	17,757	78.84
Submature (30–60 cm)	3885	17.25
Mature (> 60 cm)	879	3.90
Total	22,521	100

Table 5 Distribution of carbon stock by pools

Pools	Carbon (%)
AGC	47
BGC	10
Shrub/sapling carbon	1
Litter carbon	1
Soil carbon	41
Total	100

AGC aboveground carbon and *BGC* belowground carbon

144.714 million tons. The highest amount of carbon stock was found in temperate forests (78.75%) followed by subtropical pine forests (6.96%). Subalpine and oak forests have 3.67% and 4.81% shares in the total carbon stock respectively, whereas subtropical broad-leaved forests have 5.76% share in the total stock. Dry tropical thorn forests have less than 1% share in the total carbon stock of Khyber Pakhtunkhwa. For the calculation of total carbon stock, the estimates of soil carbon were adopted from Ali et al. (2019).

It was further revealed that 47% of the total carbon stock is present in aboveground biomass, 10% in belowground biomass, about 1% in leaf/litter, and 41% in soil (Table 5). Dead wood is not a significant pool in Khyber Pakhtunkhwa's forests because it is frequently collected for firewood and, thus, not accumulated in the forests.

Aboveground carbon stock

The highest above carbon stock was found in temperate conifer forests as 99.41 ± 15.59 t/ha, followed by moist temperate as 85.04 ± 10.84 t/ha. Overall, temperate forests have aboveground carbon stock of 90.52 t/ha. In

subalpine forests and oak forests, the mean aboveground carbon stocks were 34.27 ± 6.51 t/ha and 34.58 ± 6.39 t/ha respectively. In subtropical pine forests, the aboveground carbon stock was calculated as 24.77 ± 3.97 t/ha. Similarly, in subtropical broad-leaved evergreen forests and dry tropical thorn forests, the aboveground carbon stocks were 4.52 ± 1.18 t/ha and 4.48 ± 1.32 t/ha respectively (Fig. 7). The results of one-way ANOVA showed that there were significant differences in the mean carbon stocks among different forest types ($F = 35.773$, $p = 0.000$) at 5% level of significance (Table 6).

Leaf/litter/grass carbon stock

Carbon was estimated in leaf/litter/grass biomass in 1 m^2 sample plots. It was found that carbon in this pool varies between 0.5 and 2 t/ha. In temperate and subtropical pine forests, it was estimated at 2 t/ha and for oak and subalpine forests, it was estimated at 1 t/ha. Similarly, for subtropical broad-leaved and dry tropical thorn forests, it was 0.5 t/ha (Table 7).

Table 4 Distribution of carbon stocks in different pools by forest types

Forest type	Forest area (m. ha)	AGC (m. tons)	BGC (m. tons)	Shrub/sapling carbon (m. tons)	Litter carbon (m. tons)	Soil carbon (m. tons)	Total carbon (m. tons)	Total carbon (%)
Subalpine	0.049	1.67	0.48	0.05	0.05	3.05	5.31	3.67
Temperate (conifer)	0.654	59.23	11.85	0.65	1.31	40.93	113.96	78.75
Dry temperate (oak)	0.077	2.68	0.80	0.04	0.08	3.36	6.96	4.81
Subtropical pine	0.144	3.58	0.93	0.04	0.29	5.24	10.07	6.96
Subtropical broad-leaved evergreen	0.207	0.99	0.26	0.21	0.10	6.79	8.34	5.76
Dry tropical thorn	0.002	0.01	0.00	0.00	0.00	0.06	0.07	0.05
Total	1.134	68.15	14.33	0.99	1.83	59.43	144.71	100

AGC aboveground carbon; *BGC* belowground carbon; and *m* million

Fig. 7 Aboveground carbon stocks in different forest types
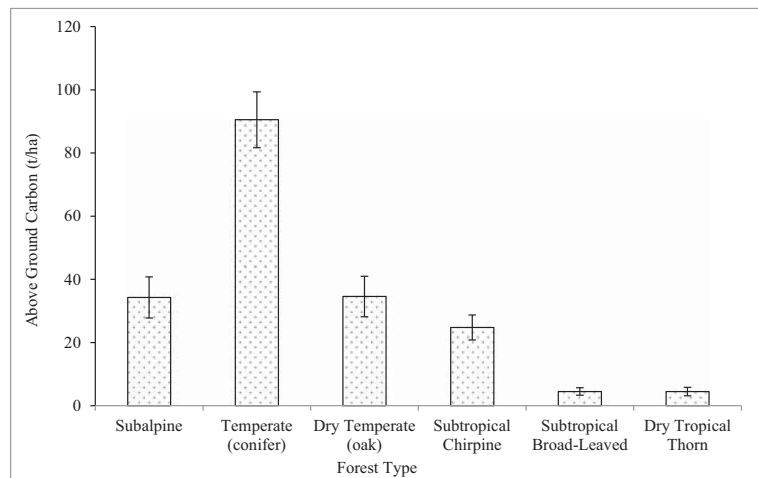
Belowground biomass carbon

Belowground biomass is the most difficult carbon pool to measure. It was derived from the aboveground biomass using the default values provided by IPCC (IPCC 2006; Cairns et al. 1997). The total carbon stock in belowground biomass of the forests of Khyber Pakhtunkhwa was estimated at 14.325 million tons. Estimates of belowground carbon in different forest types are presented in Table 8.

Dead wood biomass

Dead wood biomass was estimated for standing and fallen dead trees and coarse woody debris in the sample plots. The total carbon stock in dead wood was estimated at 0.1544 million tons which is only 0.1% of the total carbon stock in the forest ecosystems. It was found that dead wood is not a significant pool of carbon in the forests of Khyber Pakhtunkhwa as it is frequently collected by the local people for

fuelwood. The estimates of carbon stocks in dead wood are given in Table 9.

Discussion

Forests of Khyber Pakhtunkhwa have encountered ruthless deforestation and forest degradation in the past due to which mature trees have been mostly removed in the accessible areas. Consequently, carbon stocks have been decreased in most of the areas. Mean carbon stock in the forests of Khyber Pakhtunkhwa was estimated at 127.72 t/ha which is lower than the carbon stocks in Nepal's forests i.e., 153 t/ha (Oli and Shrestha 2009) and Indian Himalayan forests as 148 t/ha (Mahli et al. 1999). Mean carbon stock in temperate forests of Khyber Pakhtunkhwa was found to be 172 t/ha which is closer to the carbon stocks in temperate forests of Indian Kashmir as 112.5 to 205.7 t/ha (Dar and Sundarapandian 2015).

Carbon stocks in oak forest were estimated at 90 t/ha which is lower than the estimate of carbon in oak forests

Table 6 Analysis of variance (ANOVA) for aboveground carbon stock

	Sum of squares	df	Mean square	F	P significance
Between groups	566,803.297	6	94,467.216	35.773	0.000
Within groups	1,185,706.491	449	2640.772		
Total	1,752,509.788	455			

Level of significance (α) 0.05

Table 7 Estimates of carbon in leaf/litter/grass

Forest type	Carbon in leaf/litter (t/ha)	Area (m. ha)	Total carbon in leaf/litter (m. tons)
Subalpine	1	0.0488	0.0488
Temperate (conifer)	2	0.6543	1.3086
Dry temperate (oak)	1	0.0775	0.0775
Subtropical pine	2	0.1444	0.2888
Subtropical broad-leaved evergreen	0.5	0.2068	0.1034
Dry tropical thorn	0.5	0.0018	0.0009
Total		1.1336	1.8280

in Nepal as 142 t/ha (Jina et al. 2008). Lower carbon stocks in oak forests of the province are probably due to the severe degradation of these forests for fodder and fuelwood. Carbon stocks in subtropical pine forests were estimated at 69.74 t/ha which is closer to carbon stock in similar forest type in Nepal (62 t/ha) (Jina et al. 2008). Aboveground carbon stock in scrub forests (subtropical bread-leaved forests and dry tropical thorn forests) estimated at 4.5 t/ha is in conformity with estimates of carbon in scrub forests of Bodamalai hills located in India which was 5 t/ha (Arul 2015).

Soil is an important pool of carbon in the forest ecosystem and has been estimated for Khyber Pakhtunkhwa province by Ali et al. (2019). Results of the present study indicated that temperate forests (conifers) have the highest carbon density (t/ha) in main pools e.g., AGB and BGB, whereas highest soil carbon density was reported in subalpine forests (69.46 t/ha) followed by moist temperate forests i.e., 68.47 t/ha and dry temperate forest with 60.74 t/ha. Temperate forests as a whole have mean soil carbon of 62.55 t/ha (Ali

2020). This pool of carbon needs to be protected for climate change mitigation.

The Government of Pakistan is currently implementing a REDD+ Readiness Preparation Project with financial support of the Forest Carbon Partnership Facility of the World Bank which is aimed at development of national REDD+ Strategy, Forest Reference Emission Level (FREL) and Forest Reference Level (FRL) for Pakistan. The aboveground carbon stocks estimated in the present study can be used to develop local emission factors which are essential for estimating emissions and removals in forestry sector. Thus, current data will provide essential inputs for development of FREL/FRL for Pakistan. The results of the study also indicate that the forests of Khyber Pakhtunkhwa have high potential for climate change mitigation as they store a substantial amount of carbon in biomass and soil. It is further revealed that preventing the deforestation of temperate forests will have the largest per-unit-area-impact on reducing carbon emissions from deforestation.

Table 8 Belowground carbon in different forest types

Forest type	Root: shoot ratio	Belowground carbon (t/ha)	Area (m. ha)	Total carbon in belowground biomass (m. tons)
Subalpine	0.29	9.94	0.0488	0.4848
Temperate (conifer)	0.20	18.10	0.6543	11.8450
Dry temperate (oak)	0.30	10.37	0.0775	0.8039
Subtropical pine	0.26	6.44	0.1444	0.9301
Subtropical broad-leaved evergreen	0.26	1.24	0.2068	0.2569
Dry tropical thorn	0.56	2.51	0.0018	0.0045
Total			1.1336	14.3252

Table 9 Estimates of carbon in dead wood

Forest type	Carbon in dead wood (t/ha)	Area (m. ha)	Total carbon in leaf/litter (m. ton)
Subalpine	0.22	0.0488	0.0107
Temperate (conifer)	0.2	0.6543	0.1309
Dry temperate (oak)	0.01	0.0775	0.0008
Subtropical pine	0.04	0.1444	0.0058
Subtropical broad-leaved evergreen	0.03	0.2068	0.0062
Dry tropical thorn	0.04	0.0018	0.0001
Total		1.1336	0.1544

m million

Conclusions

The results of the study show that the forests of Khyber Pakhtunkhwa province are generally young. About 96% trees are immature and only 4% are mature. Higher numbers of trees in the younger category have very high potential for carbon sequestration as growth rate is generally faster in early stages of tree life. Therefore, these forests have higher capacity for carbon sequestration.

The total carbon stock in the forests of Khyber Pakhtunkhwa was estimated at 144.714 million tons with average of 127.66 ± 9.32 t/ha. Aboveground carbon stock is 68.15 million tons (60 t/ha) making 48% of the total carbon stock. Total soil organic carbon in the forests of KP is 59.42 million tons (52 t/ha) making 41% of the total carbon stock. The remaining carbon stock is in belowground biomass (10%) and litter (1%). Dead wood is not a significant pool in Khyber Pakhtunkhwa's forests because it is frequently collected for firewood and, thus, not accumulated in the forests. The highest amount of carbon stock is present in temperate forests (79%) followed by subtropical pine forests (7%). Subalpine and oak forests have 4% and 5% shares in the total carbon stock respectively, whereas subtropical broad-leaved forests have 6% share in the total stock. Dry tropical thorn forests have less than 1% share in the total carbon stock of Khyber Pakhtunkhwa.

The aboveground biomass is the most important pool of carbon in a forest ecosystem. The mean aboveground carbon stock in the forests of Khyber Pakhtunkhwa is estimated at 59.98 ± 4.26 t/ha. The highest aboveground carbon stock was found in dry temperate forests as 99.41 t/ha, followed by moist temperate as 85.04 t/ha. As a whole, temperate forests have aboveground carbon stock of 90.52 t/ha. In subalpine forests and oak forests, the mean aboveground carbon stocks were 34.27 t/ha and 34.58 t/ha respectively. In subtropical pine forests, the aboveground carbon stock was calculated as 24.77 t/ha. Similarly, in subtropical broad-leaved evergreen forests and dry tropical thorn forests, the aboveground carbon stocks are 4.52 t/ha and 4.48 t/ha respectively.

The forests of Khyber Pakhtunkhwa are mostly young and, therefore, have high potential for carbon sequestration and climate change mitigation under REDD+ and other carbon trading schemes. It is, therefore, recommended to manage these forests for carbon sequestration and climate change mitigation. Soil carbon is an important pool of carbon in the subalpine and temperate forests of the study area. Any activity involving soil disturbance, such as agricultural expansion or mining in this zone, will result in high amount of carbon emissions. It is, therefore, recommended to avoid such activities in these forest areas.

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