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Biomass Potential, Carbon Stock and Carbon Sequestration of Urban Forest in Shimla City of Himachal Pradesh, India

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Abstract

The study was conducted during April–June month of 2022 at Shimla city of Himachal Pradesh, India under the facilities provided by Department of Environmental Sciences, HPU, Shimla to determine the carbon storage potential by urban forests in Shimla city, Himachal Pradesh. The biomass production and carbon sequestration of the urban forest across two altitude ranges (B_1 and B_2) and four aspects (A_1, A_2, A_3, and A_4) showed significant variation due to the aspects and altitudinal gradient. The results revealed the maximum biomass (625.61 t ha^{-1}) was accumulated in A_1, whereas in case of altitudinal range maximum biomass (530.98 t ha^{-1}) in B_2 (2100–2500 m). Vegetation carbon density of moist-temperate forest ecosystem followed the order; A_1>A_2>A_3 and A_4 aspect, whereas in case of altitudinal ranges the trend was B_2>B_1. Similar trend was also seen in respect of biomass carbon stock at different aspect and altitudinal range. Maximum soil organic carbon density was recorded in aspect (22.73 t ha^{-1}), which was found to be significantly higher than all other. In case of the altitudinal range the trend was B_1 (19.66 t ha^{-1}) >B_2 (17.06 t ha^{-1}). There were 5 pre-dominant tree species identified in study area as *Quercus leucotrichophora, Rhododendron arboretum, Cedrus deodara, Pinus roxburghii and Quercus floribunda which contributed in biomass production and carbon storage potential.* For species contribution in biomass, *Quercus leucotricophora* has maximum contribution (742.48 t ha^{-1}) among all other and similar observations in case of total carbon stock and total CO_2 sequestrated, which were seen maximum in *Quercus leucotricophora* (371.24 t ha^{-1}) and (1362.1650 t ha^{-1}).

Keywords: Biomass potential, carbon stock, carbon sequestration

1. Introduction

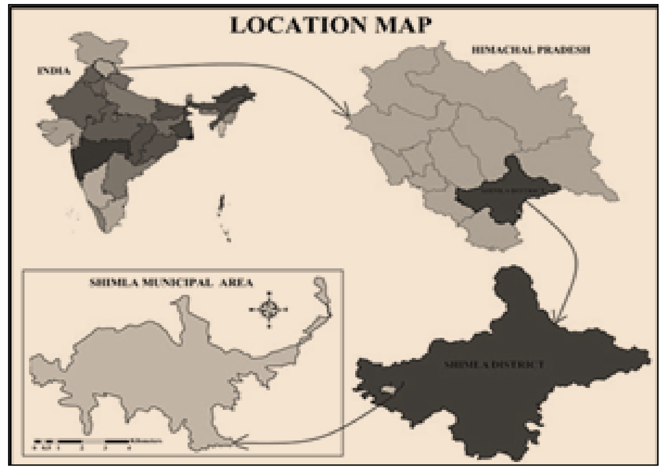
The literature has recognized several ecosystem services and profits of urban forests that ranges from ecological to social services. The urban trees on social front have been found to increase mental health, decrease hospitalizations, decrease rate of sickness, urban trees make available wildlife habitat, water mitigation, shade and decreased soil erosion problem. These increasing benefits are quickly becoming a central attention, for example rural forests are cut down because more people migrate to expanding cities. So, the ecosystem and human society continuing threatened by climate and biodiversity crises threaten ecosystems and human society (Pecl et al., 2017). There is one of the major services which is significantly have great attention is the carbon storage capacity of urban forests. In 2019 a recent study conducted by the US Department of Agriculture (USDA) and the US Forest Service (USFS) described that, all trees including urban trees, were collectively the largest carbon sink in terms of terrestrial carbon storage (Domke et al., 2021). In 2019, they counterweight >11% of total GHGs emissions. The theme of carbon storage has become more imperative with the United Nations IPCC (Intergovernmental Panel on Climate Change) 2022 report, issued calamitous need GHGs emission (Portner et al., 2022). Forest ecosystem is one of the most significant parts of terrestrial ecosystems and the major carbon pool, occupying an integral position in global carbon cycle of terrestrial ecosystems (Crowther et al., 2015; Olagunju et al., 2015; Kuuluvainen and Gauthier, 2018; Zhao et al., 2019; Cook et al., 2020; Friedlingstein et al., 2020). The total forest area of the world was nearby 4 billion hectares which corresponding to around 31% of the total land area (Anonymous, 2016). In the current period of global warming, interrelated climate indicators make available a comprehensive interpretation of climate change and the surging threats to the Sustainable Development Goals (SDGs) disturbing the environmental, social, and economic systems. The growing anthropogenic human impacts during the past coupled with industrialization has given rise to in the constantly increasing GHG production, mainly carbon dioxide (CO_2) due to the burning of fossil fuels (Zandalinas et al., 2021; Malhi et al., 2021). Based on analysis from NOAA's Global Monitoring Lab, global average atmospheric carbon dioxide was 414.72 parts million^{-1} ("ppm" for short) in 2021, setting a new record high despite the continued economic drag from the COVID-19 pandemic. In fact, the jump of 2.58 ppm over 2021 amounts tied for 5th-highest annual increase in NOAA's 63-year record (Gamon, 2023; Gao et al., 2023).

This major pool of carbon (C) has significant effect on atmospheric C concentration by releasing and sequestering processes. A key step in guiding such environmental targets is gaining a comprehensive understanding of the global distribution of existing forest carbon stocks, as well as the potential for carbon recapture if healthy ecosystems are allowed to recover (Bastin et al., 2019; Lewis et al., 2019). The enhancement of forest carbon stocks through effective organization has arisen as a pressing authoritative, given that forests establish the keystone of terrestrial carbon sinks (Cai et al., 2022), accounting for 80% of carbon in aboveground biomass and 40% in belowground biomass within terrestrial ecosystems, respectively (Yu et al., 2020). They play a pivotal role in responding to climate change and striving toward the objective of carbon neutrality. This study could be highly helpful for selecting the vegetation combination, to know the contributions of their urban forests toward carbon storage, and how this might change in the future based on management verdicts.

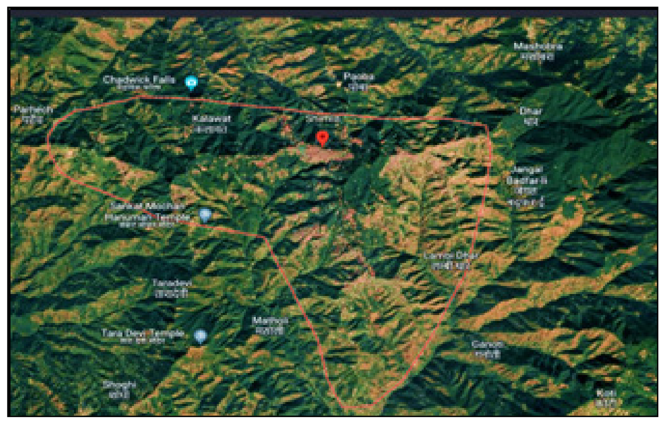
2. Materials and Methods

2.1. Study area and sampling

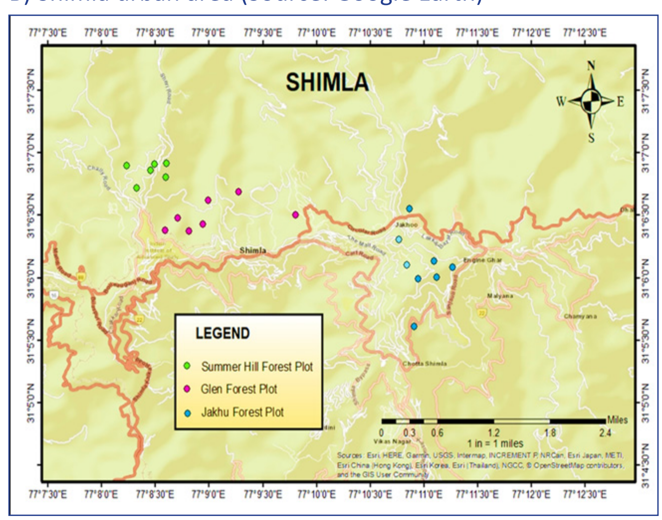
The experiment was conducted during April–June month of 2022 at Shimla city of Himachal Pradesh, India under the facilities provided by Department of Environmental Sciences, HPU, Shimla. The study area situated between 31.7'30" N and 77.12' 30" E in Shimla city (Figure 1) with an average altitude of 2,206 metres above mean sea level which is surrounded in the North by Kullu and Mandi, in the East by Kinnaur, South by Uttrakhand, and West by Sirmaur. Shimla City has seven main hills which are Inverarm Hill, Observatory Hill, Prospect Hill, Summer Hill, Bantony Hill, Elysium Hill and Jakhu Hill. The highest point in city is the Jakhu hill, which is at a height of 2,454 metres (8,051 ft). The climate is predominantly cool during winters, and moderately warm during summer. The average temperature during summer is 19˚ and 28˚C, and in winter 1˚ and 10˚C. The forests of study area have vegetation of temperate nature mainly comprising of the following forest types (Champion and Seth, 1968) as group 9: Subtropical Forests [C1b: Chir pine forest (*Pinus roxburghii*] and group 12: Himalayan Moist Temperate Forests [C1a: Ban oak forest (*Quercus leucotrichophora*), C1b: Mohru Oak Forest (*Quercus dilatata*) and C1c: Moist Deodar Forest (*Cedrus deodara*). For



A. Location Map (Source: ArcMap 10.5 software)



B) Shimla urban area (Source: Google Earth)



C) Map of Experimental plots (Source: ArcMap 10.5 software)

Figure 1(A, B & C): Map of study area

the assessment of the above ground biomass and associated carbon sequestration the experiment was conducted in RBD (Random Block design) with 8 treatments and 3 replications (Table 1 and 2). The study area was divided into two altitudinal ranges i.e. B_1 1800–2200 m a.s.l and B_2 2200–2600 m a.s.l whereas the selected aspects were A_1 Northern Aspect, A_2

Table 1: Week wise meteorological data during the experiment

Month	Week	Maximum temperature (°C)	Minimum temperature (°C)	Relative humidity (%)	Precipitation (in cm)
April	1st week	34.41	17.18	23.93	0
April	2nd week	36.27	20.06	22.23	0
April	3rd week	35.19	20.34	22.29	0
April	4th week	36.63	21.34	20.99	0
May	1st week	35.84	22.26	30.26	0.40
May	2nd week	37.73	22.77	27.49	0.001
May	3rd week	38.81	24.14	18.84	0.83
May	4th week	35.15	22.16	35.95	0.59

Table 2: Details of layout

Design	RBD (Random block design)
Treatments	8 {2 (altitudinal ranges)×4 (aspects)}
Replication	3
Total plots	24 (Treatment×Replication)
Plot size	
For trees	0.1 hac
For shrubs	5×5 m^2
For herbs	1×1 m^2

Western Aspect, A_3 Southern Aspect and A_4 Eastern Aspect.

2.2. Biomass estimation

The biomass of the tree has been calculated by non-destructive methods for different parts of the plant i.e. stem, branches, and leaves. All the trees falling within a sample plot were enumerated for their diameter by using calliper at breast height (DBH) and heigh from base to tip of the trees and form height was measured with the help of Spiegel Relaskop (using Ravi multimeter) and measuring tape in case of standing trees. The form factor calculated by (Bitterlich, 1984) formula and then volumes were converted to biomass using the specific gravity values of each species (Table 4). The AGB of trees was assessed by using local species specific volume equations and specific gravity for each tree species. The volume was multiplied by species specific gravity to obtain the biomass.

Form factor (f)=(2 hl)/3 h

Here, h_1=height where diameter is half of DBH

h=Total height of the tree

Volume (V)=f×h×g

Here, f=Form Factor of the tree

h=Total height of the tree

g=basal area

Where,

g =π{dbh/2}^{2} or πr^2

Specific gravity has been calculated by the following formula given by (Smith, 1954):

In case where, the values were not available stem cores will be used to find the specific gravity which will be used to determine the stem biomass using the maximum moisture technique.

$Gf=1/(M_n-M_o/M_o)+(1/GS_o)$

Here,

G_f=Specific gravity based on gross volume

M_n=Weight of saturated volume sample

M_o=Weight of oven- dried sample

GS_o=Average density of wood substances equal to 1.53

Estimation of wood weight by using the formula, mass per unit volume.

In case where calculation of the form factor was not feasible Volume equation for the calculation of volume were used. The Stem biomass (t ha^{-1}) was calculated by:

Stem biomass (t ha^{-1})=Specific gravity of stem wood×volume of the stem

The AGB (above ground biomass) was calculated by the formula:

AGB (t ha^{-1})=Stem biomass×Biomass expansion factor (BEF)

BGB (t h^{-1})=AGB×Root-shoot ratio

The total biomass of tree has been calculated by addition of AGB and BGB of trees. The quadrate size of 5×5 m^2 used for the estimation of shrub biomass. All the shrubs falling into the boundaries of the quadrate enumerated. To estimate grass biomass 1×1 m^2 quadrate has been used. To calculate the grass biomass, grass present within the given quadrate has been cut at the ground level and weighed. The vegetation biomass was calculated by addition of total tree biomass, shrub biomass and herbage biomass. The parameters related to carbon stock were vegetation carbon density (Eq. 1), surface leaf litter and twig carbon density, ecosystem carbon Density (Eq. 2), Co_2 Sequestration by Vegetation, Co_2 Sequestration by Ecosystem also calculated. To estimate surface litter quadrates of 1×1 m^2 has been used. The samples collected weighed, sub-sampled and oven-dried (655°C) to constant weight. Then, it was subsampled and oven-dried to a constant weight. Thereafter, the carbon present in the grass will be calculated by multiplying it with the factor of 0.5 (Anonymous, 2003) (Table 3 and 4).

Vegetation carbon density (t ha^{-1})=Tree biomass+Shrub Biomass +Herb and Grass carbon ....(1)

Ecosystem carbon density (t ha^{-1}) = Soil carbon density + Plant carbon density ....(2)

2.3. Soil nutrient analysis

The composite samples of soil were collected at depth of 0–15 and 15–30 cm from plots. The collected samples were placed in ziplock bags with suitable tags and transported to the laboratory, stored properly for subsequent analysis. The collected soil samples were dried in an oven at 45°C for 24 hrs, then passed oven-dried soil through different sieves to obtain soil texture (Piper, 1966). Soil organic carbon (%) was estimated by rapid titration method as suggested by (Walkley and Black, 1934). Bulk desnity of soil is measured by Excavation method (volume replacement) as it is best method for soils that have a high proportion of coarse fragments, such as those in forests. The soil carbon (t ha^{-1}) is calculated by the following formula:

Table 3: Specific gravity and volume equation for biomass estimation of sample trees

Sl. No.	Sample tree	Specific gravity	Reported value	Volume Equation
1.	*Pinus roxburghii*	0.72±0.11	0.491**, 0.61***	$V=0.034529+0.284662\times D^2H$ ($R^2=0.9478$)
2.	*Cedrus deodara*	0.87±0.32	0.468**, 0.57****	$V=0.167174-1.735312\times D+12.039017\times D^2$ ($R^2=0.2664$)
3.	*Rhododendron arboreum*	0.59±0.02	0.512**, 0.628*	$V=0.06007-0.21874\sqrt{D}+3.63428D^2$ ($R^2=0.91132$)
4.	*Quercus floribunda*	0.76±0.01	-	$V/D^2=0.1358/D^2$ $1.84908/D+10.8234-0.6276$
5.	*Quercus leucotrichophora*	0.72±0.14	0.826**, 0.865*	$V=0.06007-0.21874\sqrt{D}+3.63428D^2$ ($R^2=0.91132$)

*: (Sheikh, 2011). **: (Rajput, 1985), ***: (Bhatt, 1992), ****: (Zobal and Jett, 1985)

Table 4: Root shoot ratio of sample trees

Sample trees	Root shoot ratio	References
Pinus roxburghii	0.21	Anonymous (2003)
Pinus wallichiana	0.27	Anonymous (2003)
Cedrus deodara	0.27	Anonymous (2003)
Quercus semicarpifolia	0.39	Anonymous (2003)
Rhododendron arboreum	0.25	Anonymous (2003)
Quercus leucotrichophora	0.39	Anonymous (2003)

Soil carbon (t ha^{-1})=Soil bulk density (g cm^{-3})×Soil depth (cm) ×Carbon

The data obtained under field and laboratory were subjected to statistical analysis as per the procedure suggested by (Gomez and Gomez, 1984).

3. Results and Discussion

3.1. Biomass production levels and biomass carbon density of different aspects (A) and altitudinal ranges (B)

The biomass production as categorized into above ground, below ground and total biomass was presented in the Table 5. All the components of biomass viz., stem, above, below and total biomass of trees, shrubs and herb/grass was significantly influenced due to aspect effect in Shimla City which was part of moist temperate Western Himalayan ecosystem. In the selected study area which is part of moist temperate western Himalayan ecosystem, tree above ground biomass (AGB) production was found to be maximum under Northern aspect (456.49 t ha^{-1}) followed by Western, Eastern and Southern aspect respectively (Table 5). The tree below ground biomass (BGB) followed the same trend as that of above ground biomass (AGB) as maximum below ground biomass (149.48 t ha^{-1}) was found in Northern aspect Western>Eastern and then Southern aspect. The total tree biomass was maximum (622.607 t ha^{-1}) in Northern aspect, which followed more or less same trend as that recorded in respect of above and below ground biomass (Table 5). The minimum total tree biomass was found in Southern aspect (293.57 t ha^{-1}). The shrub biomass production was found to be maximum under Western aspect (1.425 t ha^{-1}) which was followed by Eastern, Southern and Northern aspect respectively. In the moist temperate western Himalayan ecosystem, Western aspect exhibited significantly higher values of shrub biomass than all other aspects. The herb and grass biomass (Table 5) production was found to be maximum under Southern aspect (3.561 t ha^{-1}), which was followed by Eastern, Western and Northern aspect, respectively. It has been observed that biomass components viz., above ground biomass (AGB), below ground biomass (BGB) and total tree biomass produced by particular aspect was influenced by the age/diameter of the components, type

Table 5: Altitudinal and aspects effect on biomass estimation parameters (t ha^{-1})

		B_1	B_2	Mean
SB	A_1	238.60	331.06	284.83
	A_2	126.40	130.48	128.44
	A_3	166.94	169.76	168.35
	A_4	184.43	258.19	221.32
	Mean	179.09	222.37	
AGB	A_1	391.030	521.950	456.490
	A_2	223.750	240.010	231.870
	A_3	266.430	282.800	274.610
	A_4	308.610	475.270	391.940
	Mean	297.530	380.010	
BGB	A_1	120.450	178.440	149.480
	A_2	94.230	72.500	83.360
	A_3	87.180	99.000	93.090
	A_4	109.470	176.210	142.840
	Mean	102.830	131.540	
TTB	A_1	511.480	733.730	622.607
	A_2	245.820	341.330	293.570
	A_3	353.610	381.810	367.710
	A_4	418.070	651.483	534.780
	Mean	382.250	527.090	
SB	A_1	1.010	0.895	0.952
	A_2	0.806	1.230	1.018
	A_3	1.354	1.415	1.385
	A_4	1.090	1.759	1.425
	Mean	1.065	1.325	
H+G	A_1	1.660	2.437	2.049
	A_2	4.114	3.008	3.561
	A_3	4.602	1.806	3.204
	A_4	1.789	3.038	2.413
	Mean	3.041	2.572	
VB	A_1	514.150	737.060	625.610
	A_2	250.740	345.560	298.150
	A_3	359.560	385.030	372.300
	A_4	420.950	656.280	538.620
	Mean	386.350	530.980	

SB: Stem biomass; AGB: Above ground biomass; BGB: Below ground biomass; TTb: Total tree biomass; SB: Shrub biomass; H+G: Herb and grass biomass; VB: Vegetation biomass

of the forest vegetation grown therein; structure nature and number of woody components and soil type, etc. According to Singh et al. (2019), Salve and Bhardwaj (2020), Sharma et al. (2022) and Panwar et al. (2022), the differences in productivity of aspect may also be due to differences in soil conditions, phenology of dominant species, better root net working as well as efficient and economical use of limited resources for maintaining higher photosynthetic activities, leaf area index, better light interception and water use efficiency. Goggs et al. (2022), Goswami et al. (2014), Gupta et al. (2017) and Rajput et al. (2017) have almost same findings as the average total biomass recorded in the present investigation of forest ecosystem (625.61 t ha^{-1}) was on the higher side than temperate and boreal forest ecosystems (326.0 t ha^{-1}) of the world.

The same results were recorded for the biomass being highest in Northern aspect in moist temperate Himalayan ecosystem (Singh et al., 2017). The biomass carbon density on a particular aspect to a great extent depends upon its age, structure, functional component and its number and intensity of management. It was observed that the maximum vegetation (321.80 t ha^{-1}) carbon density was exhibited by Northern aspect and followed the trend; Western, Eastern and Southern aspect respectively (Figure 3 A). The vegetation carbon storage (321.80 t ha^{-1}) as recorded in our Himalayan temperate forest ecosystem is more than the value reported by Gupta et al. (2017) for Himalayan forest i.e. 190 t ha^{-1} and Singh et al. (2015) for wet temperate Himalayan forest ecosystem (185.0 t ha^{-1}). The carbon density values were also higher than the world average value of 160.0 t ha^{-1} as given by Goswami et al. (2017). The higher carbon density of this forest can again be owned to forest department of given to the area, which does not allow the removal of biomass from the area. However, it has been found less than the findings reported by Singh et al. (2017) for moist temperate Western Himalayan ecosystem (512.86 t ha^{-1}).

The data in Table 5 revealed that all the components of biomass viz., above, below and total biomass of trees, shrubs and herb/grass was significantly influenced due to altitudinal effect also. In study area, B_2 (2100–2500 m) exhibited significantly higher values of above, below and total tree biomass than all other altitudinal range. The data presented in Table 5 revealed that tree below ground biomass (BGB) followed the same trend as that of above ground biomass. Maximum tree below ground biomass (102.83 t ha^{-1}) was found in B_2 (2100–2500 m). It has been observed that total tree biomass (TTB) in study area was maximum (527.09 t ha^{-1}) in B_2 (2100–2500 m). The shrub biomass (Table 5) production was found to be maximum (1.675 t ha^{-1}) under B_2 (2100–2500 m). The altitudinal range B_1 (1700–2100 m) exhibited significantly higher values of herb and grass biomass than other altitudinal range. The level of organic carbon at B_2 altitudinal range may have favoured more biomass production. Similar, views were also expressed by Cairns (1997), Kanime et al. (2013), Anjana (2016) and Chaturvedi et al. (2016). The variation in the above ground biomass (AGB) level at different altitude can be explained on the basis of age of the woody species, soil organic carbon (%) and human population density. It was observed from Table 5, that the major contributor of biomass at the different altitudinal ranges are woody perennial and with the increasing altitudinal ranges the average age of the tree species also increased. This may be one of the major reasons for biomass variation at different altitudinal ranges. Secondly, the organic matter (% C) also decreased significantly as we moved from lower to upper altitudinal ranges. Higher level of organic carbon at B_2 altitudinal range may have favoured more biomass production. Similar, views were also expressed by Lal and Lodhiyal (2016) and Lal (2000). The data in Table 5 revealed that the maximum biomass carbon density has been seen in B_2 (2100–2500 m) range which is 265.49 t ha^{-1}. It was observed that interaction effect between aspect and altitudinal range exercised significant influence on the biomass production and carbon density in study area. There were various treatment combinations of aspect (A) and altitudinal range (B) in moist temperate western Himalayan ecosystem showed the highest value of biomass production (737.06 t ha^{-1}) and biomass carbon density (368.53 t ha^{-1}) in A_1B_2 treatment combinations in comparison to all other treatments. The differences in productivity of aspects and altitudinal ranges may also be due to differences in soil conditions, phenology of dominant species Parveen et al. (2016), better root net working as well as efficient and economical use of limited resources for maintaining higher photosynthetic activities, leaf area index, better light interception and water use efficiency Pant and Tewari (2013). The average total biomass as recorded in our case in the forest ecosystem (1433.0 t ha^{-1}) is on the higher side than temperate and boreal forest ecosystems (326.0 t ha^{-1}) of the world. The higher average total biomass of our temperate forest ecosystem can be ascribed to protection offered to the vegetation under the Indian forest Act (1927) of the area being a protected forest.

3.2. Physico-chemical properties of soil in different aspects and altitudinal ranges

The data presented in the Tables 6 showed that the bulk density (g cm^{-3}) varied significantly under different aspect, altitudinal ranges and soil layers. The bulk density in moist Temperate Western Himalayan ecosystem of Shimla City in Himachal Pradesh followed the trend: Northern aspect< Eastern aspect<Western aspect<Southern aspect (Table 6). Thus, the findings clearly indicated that aspects which are lower in vegetation density and organic matter have higher bulk density and it declined as the density of vegetation and organic matter increased. The high value of bulk density in the soils can also be ascribed to lower soil organic carbon content in these systems. These findings are in agreement with the findings of Chaturvedi et al. (2016). The (OC) organic carbon (%) varied significantly under aspect, altitudinal ranges and soil layers in the experiment. In selected study area, maximum soil organic carbon (1.45%) was found in Northern aspect, which differed significantly from all other aspect and followed the trend; Western, Eastern and Southern aspect respectively in the descending order shown in table no. 6. The findings showed the significantly increase organic carbon contents in soils under Northern aspect may attributed to more leaf litter deposition cool climate and more biomass density (Adhikari et al., 2020). Low soil organic carbon under Southern aspect may be attributed due to lower vegetation density. It is crystal clear from the data presented in the Table 6 that organic carbon varied significantly under aspect, altitudinal ranges and soil layers in the experiment. In study area, maximum soil organic carbon (1.45%) was found in Northern aspect which differed significantly from all other aspect and followed the trend; Western, Eastern and Southern aspect respectively in the descending order. The significant increase in organic carbon content in soils on the northern aspect can be attributed to greater leaf litter deposition due to a cooler climate and higher biomass density, as noted by Goswami et al. (2014), Singh et al. (2015), Gupta et al. (2017), Rajput et al. (2017), and Singh et al. (2019) (Table 6). The low soil organic carbon under Southern aspect may be attributed due to lower vegetation density. It has been observed that soil organic carbon density was determined by multiplying organic carbon with soil weight for a particular depth. It is evident from the data presented in the Table 6 that soil organic carbon

Table 6: Aspects and altitudinal gradient effect on soil physiological properties

		B_1	B_2	Mean
BD (g cm^{-3})	A_1	0.82	0.78	0.8
	A_2	1.06	1	1.03
	A_3	0.88	0.82	0.85
	A_4	1.1	1.07	1.08
	Mean	0.97	0.92	
SOC (%)	A_1	1.53	1.37	1.45
	A_2	1.17	1.1	1.13
	A_3	1.27	1.2	1.23
	A_4	1.48	1.31	1.4
	Mean	1.36	1.24	
SCD (t ha^{-1})	A_1	18.85	16	17.42
	A_2	18.62	16.56	17.6
	A_3	16.66	14.74	15.7
	A_4	24.5	20.96	22.73
	Mean	19.66	17.06	

BD: Bulk density; SOC: Soil organic carbon; SCD: Soil carbon density was significantly influenced by aspect and altitudinal ranges. The maximum soil organic carbon density in Shimla City was recorded in Western aspect (22.73 t ha^{-1}) which was found to be significantly higher than all other. It can be owed to more leaf litter accumulation in the western aspect vis-à-vis other aspect, followed by steady decomposition and mineralization. The abundant leaf litter biomass returns to soil, combined with decay of roots contribute to the improvement of organic matter under complex land use systems (Singh, 1994; Zobel and Jett, 1985; Subramaniyan et al., 2017; Sharma et al., 2016). The low amounts of soil organic carbon density under Eastern aspect can be ascribed to lower surface litter and less vegetation density. Bulk density showed a decreasing trend with increasing altitudinal ranges (Table 6). This can be owed to decreasing trend of soil organic matter with increasing temperature and decomposition rate with increasing altitude. As it is known that, soil organic matter decreased with the increasing altitude because of higher decomposition rate with increasing altitude. The findings of Gupta et al. (2017) recommended an increase in soil carbon density along altitude but minimum at higher altitude which is in line with present findings. The reduction of bulk density of soil due to increase in soil organic carbon has been amply reported in literature (Aguilar et al., 2020; Prasadan and Jithila, 2018; Rawat, 2020). In present study, we found that the organic carbon decreased with increasing attitudinal range (Table 6), which can be owed to continuous accumulation of the leaf-litter and slower decomposition rate at the lower attitude than at higher ones. Slower decomposition means less mineralization and hence losses of organic carbon through erosion will be lower at higher altitude and hence more carbon content concentrations. In the present study, it has been found that the organic carbon density decreased with increasing attitudinal range (Table 6), which can be owed to continuous accumulation of leaf-litter and slower decomposition rate at the lower attitude than at higher ones in moist temperate western Himalayan ecosystem the soil is of forest origin. In addition to it, the rate of mineralization is slower because of rapid fall in temperature and humidity with increasing altitudinal gradient hence more soil organic content and soil organic carbon density was found significantly higher at lower altitudinal range. In the three ways interaction effects between aspects, altitudinal range and soil layer (Table 6), maximum bulk density (1.10 g cm^{-3}) was recorded in the A_4B_1 western aspect, which was found to be significantly higher than all other treatment combinations. From table 6 it can be seen that soil maximum soil organic carbon (1.53%) was recorded in A_1B_1 combination and minimum (1.10%) in A_2B_2 combination. It is mainly because of presence of high number of *Quercus leucotrichophora* which is a broad leave tree and whose leaves decomposes easily to add to organic matter of soil. From table 6 it can be seen that maximum soil organic carbon density (25.50 t ha^{-1}) was recorded in A_4B_1 combination and minimum (14.74 t ha^{-1}) in A_3B_2 combination. It is mainly because of presence of high number of *Quercus leucotrichophora* which is a broad leave tree and whose leaves decomposes easily to add to organic matter of soil.

3.3. Carbon stock and CO_2 sequestration of different aspects and altitude gradient

According to the experimental findings observed in Figure 2A, revealed that the Northern aspect has the highest vegetation carbon density (321.80 t ha^{-1}), which is shown to be significantly greater than the Western, Eastern, and Southern perspectives, respectively, in descending order. As far as altitudinal range is concerned, the highest vegetation carbon density of the two, at 265.49 t ha^{-1}, is found in B_2 (2100–2500 metres above mean sea level). A pattern in the variance of vegetation carbon density has been seen when altitude is taken into account, and this pattern clearly suggests that vegetation carbon density rises as altitude increases. In the Northern aspect vegetation carbon density was high because of higher optimum growing condition like moisture and temperature, etc. The similar findings trends have been seen in the work of Singh et al. (2015, 2019) shown in figure 2A. According to the experimental findings observed in figure 2B, maximum surface leaf litter+twigs carbon density (3.93 t ha^{-1}) was recorded in the Northern aspect followed by Eastern aspect (3.34 t ha^{-1}), Western aspect (3.25 t ha^{-1}) and Southern aspect (2.17 t ha^{-1}) respectively in descending order. The minimum surface leaf litter+twigs carbon density (2.17 t ha^{-1}) was recorded in Southern aspect which was found to be significantly different from one another. In the average effect of altitudinal ranges, maximum surface leaf litter+twigs carbon density (3.26 t ha^{-1}) at B_2, which is significantly highest surface leaf litter+twigs carbon density than other altitudinal range (Figure 2B).

The data in Figure 2C revealed that significantly maximum ecosystem carbon density (343.15 t ha^{-1}) was recorded in the Northern aspect followed by Western aspect (295.29 t ha^{-1}), Eastern aspect (205.19 t ha^{-1}) and Southern aspect (168.85 t ha^{-1}), respectively in descending order. Minimum ecosystem carbon density (168.85 t ha^{-1}) was recorded in Southern aspect which was found to be significantly different from one another. The data also revealed that the vegetational density has been found maximum at altitudinal range B_2 i.e. 2100–2500 m above mean sea level (265.49 t ha^{-1}) (Figure 2C). The variation in the ecosystem carbon density on different aspect can be owed to prevailing environmental conditions on these aspects. The maximum ecosystem carbon density (388.52 t ha^{-1}) was recorded at A_1B_2 treatment combination, which was significantly different from all other aspect and altitudinal range and no certain trend followed. The main reason behind is comparatively higher vegetation biomass on the treatment combination. The figure 2D presented that Northern aspect has the highest vegetation CO_2 sequestration (1147.99 t ha^{-1}), which is shown to be significantly greater than the Western, Eastern, and Southern perspectives, respectively, in descending order. It is shown that the southern side has the lowest vegetation CO_2 sequestration (547.11 t ha^{-1}). As far as altitudinal range is concerned, the highest vegetation carbon density of the two, at 974.36 t ha^{-1}, is found in B_2 (2100–2500 metres above mean sea level). A pattern in the variance of vegetation CO_2 sequestration has been seen when altitude is taken into account, and this pattern clearly suggests that vegetation carbon density rises as altitude increases (Figure 2D). In the interaction between altitude and aspect, the B_2 (2100–2500 m) range at Northern aspect) has the largest vegetation CO_2 sequestration (1352.51 t ha^{-1}). Southern B_2 (2100–2500 m) has lowest vegetation CO_2 sequestration at about 460.11 t ha^{-1}. According to the experimental findings observed in Figure no. 2E, the Northern aspect has the highest ecosystem CO_2 sequestration (1226.38 t ha^{-1}), which is shown to be significantly greater than the Western, Eastern, and Southern perspectives, respectively, in descending order. It is shown that the southern side has the lowest ecosystem CO_2 sequestration (619.65 t ha^{-1}) (Figure 2E). As far as altitudinal range is concerned, the uppermost ecosystem CO_2 sequestration of the two, at 1048.94 t ha^{-1}, is found in B_2 (2100–2500 metres above mean sea level). A pattern in the variance of ecosystem CO_2 sequestration has been seen when altitude is taken into account, and this pattern clearly suggests that ecosystem CO_2 sequestration rises as altitude increases. In the interaction between altitude and aspect, the B_2 (2100–2500 m) range at Northern aspect) has the largest ecosystem CO_2 sequestration (1425.87 t ha^{-1}). Southern B_2 (2100–2500 m) has lowest ecosystem CO_2 sequestration at about 536.19 t ha^{-1}.

Figure 2: Diagrammatic representations of aspect and altitudinal gradient effects on: A: Vegetation carbon Density; B: Surface leaf litter+twigs carbon density; C: Ecosystem carbon density; D) Vegetation CO_2 sequestration; E: Ecosystem CO_2 sequestration

3.4. *Comparison of biomass and biomass carbon density of different tree species*

A comparison has been drawn between different dominant tree species and AGB, BGB, Total biomass, Total carbon stock and CO_2 sequestration in the Shimla City (Figure 3). The maximum AGB of *Quercus leucotricophora* which is 65.15% of total tree biomass followed by *Cedrus deodara* which is 22.52% of total tree biomass. The *Rhododendron arboreum* follows with 6.75% whereas, the least contribution by *Quercus floribunda* with only 0.47% of total tree biomass. *Quercus leucotricophora* has the highest BGB overall, accounting for 80.34% of all tree biomass, followed by *Cedrus deodara* at 12.12%. With 4.32%, the *Rhododendron arboreum* comes in third, followed by *Pinus roxburghii* with 2.75%. *Quercus*

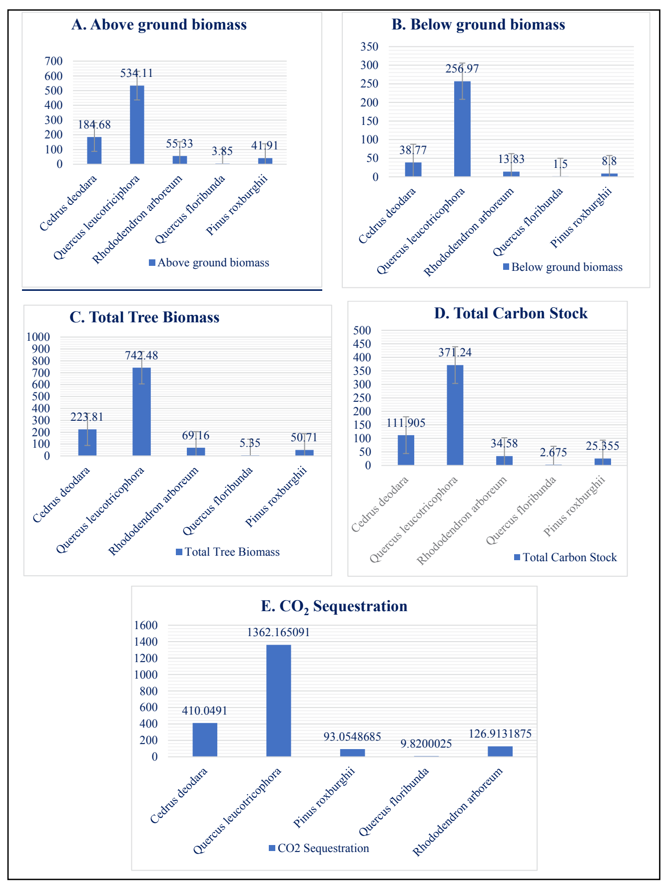


Figure 3: Comparisons of A: AGB; B: BGB; C: TTB; D: Total carbon stock; E: Carbon dioxide sequestration by local dominant tree species

floribunda makes the least contribution with 0.47%. *Quercus leucotricophora* has the uppermost BGB overall, accounting for 68.02% of all tree biomass, followed by *Cedrus deodara* at 20.50%. With 6.34%, the *Rhododendron arboreum* comes in third, followed by *Pinus roxburghii* with 24.45%. *Quercus floribunda* makes the least contribution with 0.49%. *Quercus leucotricophora* has the highest carbon stock overall, accounting for 68.04% of all tree biomass, followed by *Cedrus deodara* at 20.48%. With 6.34%, the *Rhododendron arboreum* comes in third, followed by *Pinus roxburghii* with 4.65%. *Quercus floribunda* makes the least contribution with 0.49% (Figure 3). *Quercus leucotricophora* has the highest CO_2 sequestration, accounting for 68.04% of all tree biomass, followed by *Cedrus deodara* at 20.48%. With 6.34%, the *Rhododendron arboreum* comes in third, followed by *Pinus roxburghii* with 4.65%. *Quercus floribunda* makes the least contribution with 0.49% (Figure 3).

4. Conclusion

The carbon storage potential of the experimental site was found to be considerably good due to an adequate number of trees. However, carbon sequestration could have been further enhanced by planting young tree species, preventing forest fires, and avoiding anthropogenic activities.

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