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Evaluation of carbon sequestration potential of *Salix* tree and shrub species in the cold desert conditions of Himachal Pradesh

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ABSTRACT

The present study was carried out at six sites in Lahaul and Spiti district of Himachal Pradesh. The density of *Salix alba* at Gue-1, Gue-2 and Lidang sites was found to be 407, 303 and 620 individuals per ha while for the shrub species it varied from 3 to 6 individuals per m^2 for *S fragilis*. The biomass, carbon density, soil carbon density and carbon sequestration potential of the species were evaluated. The biomass of the tree species varied from 24.27 tonnes per ha at Gue-2 site to 56.30 tonnes per ha at Lidang site. The biomass for the shrub species varied from 12.56 tonnes per ha at Lalung site to 38.82 tonnes per ha at Gulling; maximum soil carbon density of 44.60 tonnes per ha was recorded at Gulling and minimum 11.87 tonnes per ha at Lalung. Net carbon sequestration for *S alba* varied from 3.88 tonnes per ha per year at Gue-2 to 10.21 tonnes per ha per year at Lidang site, while for *S fragilis* it varied from 0.93 tonnes per ha per year at Lalung to 5.56 tonnes per ha per year at Gulling.

Keywords: Carbon density; carbon sequestration; biomass; *Salix alba*, *S fragilis*, *S wilhelmsiana*

INTRODUCTION

Willow species (*Salix alba* L *and S fragilis* L) play a vital role in the agroforestry systems of the cold desert region of Lahaul and Spiti district, Himachal Pradesh located in the northwestern Himalayas. Their unique ability to propagate through shoot cuttings and thrive in the harsh, arid conditions of cold deserts make them ecologically well-suited and socially-valued for forestry initiatives. These willow species are particularly effective in combating desertification, outperforming many other species in such challenging environments. In this region, willows serve as essential subsistence resources and hold significant socio-religious importance for local communities.

The anthropogenic activities in the recent past like industrialization, urbanization, habitat degradation etc have led to increase in the concentration of carbon dioxide in the environment triggering a series of major environmental changes. According to Fasihi et al (2019), global CO_2 emissions have continued to rise steadily in recent years, with emissions in 2019 increasing by 1.9 per cent compared to 2018 levels. The combustion of fossil fuels for power generation remains and transportation are the primary source of CO_2 emissions accounting for 65 per cent of share across key economic sectors in many developing nations. In contrast, the agricultural sector has been identified as the smallest contributor to emissions since 2018 (Lin and Xu 2018, Yoro and Daramola 2020). If the emission of anthropogenic greenhouse gases like CO_2 is not reduced, the earth's atmospheric temperature in coastal areas will increase by 2°C by 2050 and 4°C by 2100 and the interior temperature of the earth will also increase by 4°C by 2050 and 7°C by 2100 affecting food security and extreme climatic conditions like flood and draughts, change in composition of forests and shift in the tree line (Orimoloye et al 2019, Donat et al 2020, Yoro and Daramola 2020).

Forests can have varying impacts on the carbon cycle, ranging from net emitters to net carbon sinks, depending on their unique characteristics and regional settings. Forests serve as vital carbon sinks by absorbing CO_2 from the atmosphere and converting it into biomass through photosynthesis. The sequestered carbon accumulates in forest soils, biomass, deadwood and litter (Al Kafy et al 2023). Additionally, The Paris Agreement, a legally binding international treaty on climate change, adopted by 196 Parties during the UN Climate Change Conference (COP-21) in Paris, France on 12 December 2015 and enforced on 4 November 2016, provides a global framework for addressing this crisis. The agreement aims to limit the rise in global average temperatures to 'well below 2°C above pre-industrial levels' while pursuing efforts to cap the increase at 1.5°C. To achieve the 1.5°C target, greenhouse gas emissions must peak by 2025 at the latest and be reduced by 43 per cent by 2030 (Streck et al 2016).

Potential of the *Salix* spp in biomass accumulation and sequestration of atmospheric CO_2 is well established (Shah et al 2015, Pietrzykowski et al 2021, Rytter et al 2015), however, its potential in cold desert conditions is not well studied. To address the gap, current study was carried out at six locations in Lahul and Spiti district, Himachal Pradesh to determine the biomass and above- and below-ground standing carbon density of willows.

MATERIAL and METHODS

The present investigations were carried out during the year 2020-21, 2021-22 and 2022-23 at Gue-1, Gue-2, Lidnag, Lalung, Gulling and Teling sites. Three quadrates of 30 m x 33 m (approximately 100 m^2) size were laid at each site to record the various observations. A holistic phyto-sociological status of the selected willow plantations was recorded to calculate the importance value index (IVI) at species level (Misra 1968). The data for all the parameters were recorded twice a year from each of the selected sites during both the years of investigations.

Observations recorded

Tree density: The tree density was quantified according to the procedure described by Curtis and McIntosh (1950):

$$\text{Density/ha} = \frac{\text{Total number of individuals of species in all sampling units}}{\text{Total number of sampling units studied}}$$

Volume: Form factor and volume were calculated as per procedure followed by Pressler (1865) and Bitlerlich (1984):

$$f = 2h_l/3h$$

where f = Form factor, h_l = Height at which diameter is half of dbh (m), h = Total height (m)

The volume (V) of trees was calculated as under:

$$V\,(m^3) = f \times h \times g$$

where f = Form factor, h = Total height (m), r = Radius (cm), g = лr2 or л (dbh/2)2

Wood specific gravity: The specific gravity of wood was determined by using the maximum moisture method prescribed by Smith (1954):

$$G = \frac{1}{\frac{Mn-Mo}{Mo}+\frac{1}{Gso}}$$

where G = Specific gravity based on gross volume, Mn = Weight of saturated sample (g), M = Weight of oven-dried sample (g), Gso = Average density of wood (g/cm^3)

Stem wood biomass: Stem wood biomass was calculated as under:

$$\text{Stem wood biomass} = \text{Volume} \times \text{Specific gravity}$$

Branch biomass: Five representative sample trees in each diameter class were used to record the total number of branches. These branches were categorized (on the basis of basal diameter) into three groups viz small, medium and large. Five branches from each category were randomly removed from each sample tree and their fresh weight was determined separately. After recording the fresh weight, these samples were taken to the laboratory and oven-dried at 65 ± 5°C for a period of 72 hours or till the weight became constant (Chapman 1964).

Leaf biomass: Five branches (from each category) of three sample trees in each diameter class were selected for determination of leaf biomass. The fresh weight of leaf samples was recorded just after removing them from the branch to minimize the loss of weight. The leaf samples were placed in separate paper bags and oven-dried at 65 ± 5°C for 72 hours or till the weight became constant (Chapman 1964).

Root biomass: The root biomass per ha was determined by bush greenhouse field measurement procedure (Dury et al 2002) which recommends taking the estimate of above-ground biomass per ha and multiplying it with default root-shoot ratio of 0.25 for hardwood species.

$$\text{Below-ground biomass (/ha)} = \text{Above-ground biomass (/ha)} \times 0.25$$

Total tree biomass: The total tree biomass was determined as sum of stem, branch, leaf and root biomass.

Standing carbon density: The standing carbon density (above- and below-ground) of *S alba* was determined by using tissue specific carbon content as measured by ash content method prescribed by Negi et al (2003):

$$\text{Carbon (\%)} = 100 - \{\text{Ash weight} + \text{molecular weight of } O_2 \text{ (53.3) in } C_6H_{12}O_6\}$$

The carbon density (tonnes/ha or kg/tree) was calculated as per method followed by Hu (2006):

$$Cb = \alpha M$$

where Cb = Carbon density (above- and below-ground), α = Average carbon content (above- and below-ground biomass), M = Total biomass (tonnes/ha or kg/tree)

The elemental carbon removed from the atmosphere (CO_2) was calculated as per the procedure followed by Dury et al (2002):

$$CO_2e = C \times 3.67$$

Net carbon sequestration: Net carbon sequestration (CS tonnes/ha) was calculated as per the procedure prescribed by Dury et al (2002):

$$CS = \text{Change in TR} + \text{Change in L} + \text{Change in S}$$

where TR = Annual change in shoot and root biomass (above- and below-ground), L = Annual change in litter biomass, S = Annual change in soil organic carbon

Shrubs: The shrub characteristics were studied by laying out sub-plots of size 3 m x 3 m in each sample plot. Density of shrubs was calculated by counting plants of different species in each sub-plot. Stratified sampling of each shrub species was done by grouping them into three categories by visual appearance viz large, medium and small on the basis of size and number of stems in each of them. In each category, number of plants was counted. Basal area of stem was determined by Vernier calipers.

Shrub biomass: Shrub samples were collected and brought to laboratory. The diameter of all the tillers was measured at base, with the help of calipers according to the method given by Chaturvedi and Khanna (1982). The length of tiller was measured with the help of measuring tape. They were segregated into leaves, branches and stem portion, washed and oven-dried at 70°C for 72 hours till the constant dry weight was obtained. Each sample was weighed to determine above-ground biomass (stem + branch + leaves) of each species. Below-ground biomass estimation was done by extracting roots of sample plants (shrubs). These were washed thoroughly and weighed to determine their fresh weight. The root samples for each species were brought to laboratory, packed in paper bags and dried at 70 ± 5°C for 72 hours to determine their dry weight. Total biomass of a shrub species was calculated by adding its above- and below-ground biomass.

RESULTS

***Salix* tree biomass:** The average density of *S alba* plantations was found to be 443 trees per hectare across the three selected locations. Maximum tree density of 620 trees per hectare was recorded at the Lidang site. The minimum density of 303 was recorded at Gue-2 (Table 1, Fig 1).

Shrub biomass: The density of the shrub species varied at different locations. The maximum density of 6.0 individuals per m^2 was found at Gulling followed

Table 1. Tree density (/ha) of *S alba* under different diameter classes at selected locations

Diameter class (cm)	Density (trees/ha) at different sites			
	Gue-1	Gue-2	Lidang	Mean
<10	17	13	30	20
10-15	47	143	170	120
15-20	127	83	140	117
20-25	153	23	143	107
25-30	63	40	50	51
30-35	0	0	47	16
>35	0	0	40	13
Total	407	303	620	443

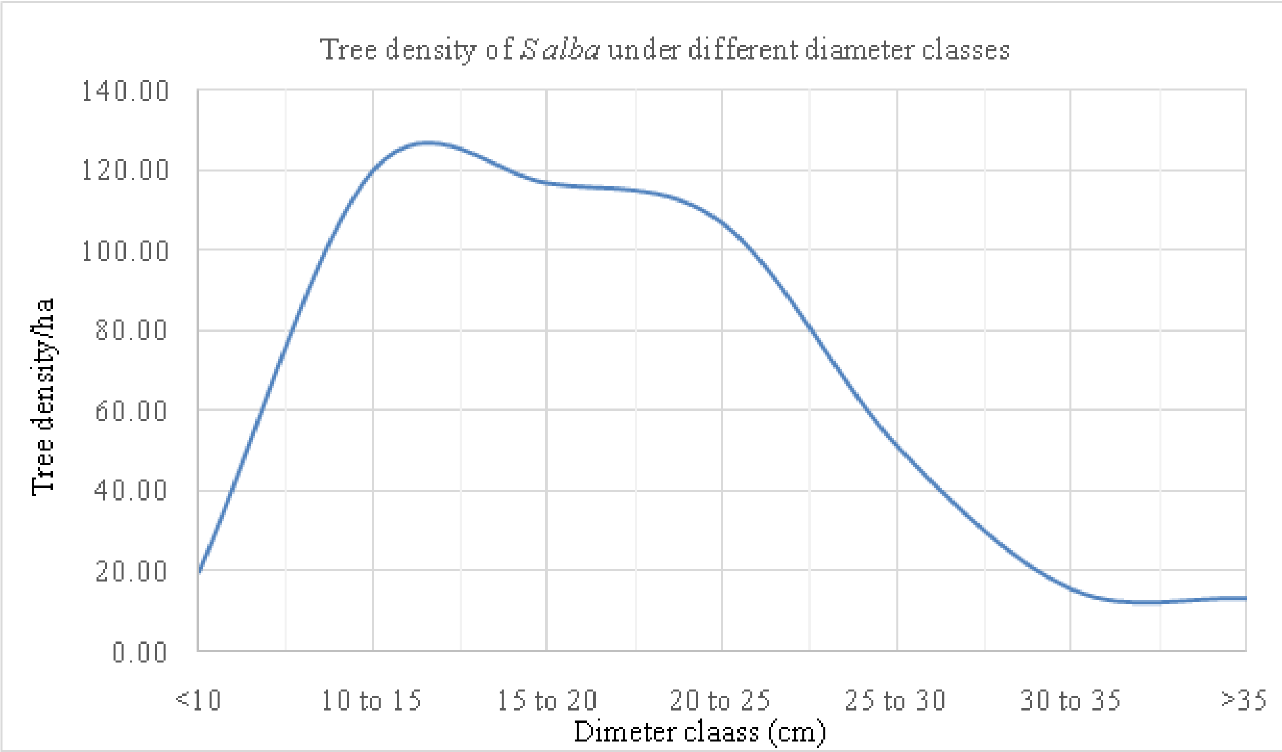

Fig 1. Tree density of *S alba* under different diameter classes

Table 2. Density of *Salix* shrub species at selected sites

Site	Species	Density (individuals/m^2)
Gulling	*S fragilis*	6.0
Teling	*S fragilis*	4.0
	S wilhelmsiana	3.0
Lalung	*S fragilis*	3.0
Mean		4.0

by Teling (4.0 individuals/m^2) and Lalung site (3.0 individuals/m^2) (Table 2).

Biomass, total carbon density and CO_2 sequestration by *Salix* spp

The biomass of the *S alba* plantations varied at selected locations. Maximum biomass of 56.30 tonnes per ha was found at Lidang followed by Gue-1 (39.84 tonnes/ha) and Gue-2 (24.27 tonnes/ha). Consequently, the plant carbon density also varied at different locations; with maximum of 25.38 tonnes per ha at Lidang and minimum at Gue-2 (11.22 tonnes/ha) (Table 3).

Furthermore, maximum soil carbon density (SCD) of 44.12 tonnes per ha was observed at Gue-1 followed by Lidang (43.07 tonnes/ha), while minimum (28.53 tonnes/ha) was observed at Gue-2. Thus total carbon density was found maximum (68.45 tonnes/ha) at Lidang sequestering 251.21 CO_2e tonnes/ha and the minimum at Gue-2 (39.75 tonnes/ha) sequestering 145.88 CO_2e tonnes/ha.

Maximum biomass of *Salix* shrub species (38.82 tonnes/ha) was found at Gulling followed by Teling (16.30 tonnes/ha) and the minimum (12.56 tonnes/ha) at Lalung. Similarly, the average plant carbon density (10.07 tonnes/ha) was observed at three selected locations, with maximum carbon density at Gulling (17.33 tonnes/ha) followed by Teling (7.27 tonnes/ha) and Lalung (5.61 tonnes/ha). Maximum soil carbon density was observed at Gulling (44.60 tonnes/ha) and minimum at Lalung (11.87 tonnes/ha). Thus maximum total carbon density of 61.93 tonnes per ha was observed at Gulling sequestering 227.30 CO_2e tonnes per ha and the minimum at Lalung (17.47 tonnes/ha) sequestering 64.13 CO_2e tonnes/ha.

The *Salix* tree species sequestered an average of 7.03 tonnes per ha per year carbon across selected locations. The maximum net carbon sequestration of 10.21 tonnes per ha per year was observed at Lidang and minimum of 3.88 tonnes per ha per year was observed at Gue-2 (Table 4).

Table 3. Biomass, total carbon density and CO_2 sequestration by *S alba*, *S fragilis* and *S wilhelmsiana* at selected locations

Site	Species	Biomass (tonnes/ha) (A + B)	Plant carbon density (tonnes/ha) (A + B)	Soil carbon density (tonnes/ha)	Total carbon density (tons/ha)	Total CO_2 sequestration (CO_2e tonnes/ha)
Gue-1	*S alba*	39.84	17.96	44.12	62.08	227.83
Gue-2	*S alba*	24.27	11.22	28.53	39.75	145.88
Lidang	*S alba*	56.30	25.38	43.07	68.45	251.21
Mean		40.14	18.19	38.57	56.76	208.31
Gulling	*S fragilis*	38.82	17.33	44.60	61.93	227.30
Teling	*S fragilis* and *S wilhelmsiana*	16.30	7.27	28.81	36.08	132.42
Lalung	*S fragilis*	12.56	5.61	11.87	17.47	64.13
Mean		22.56	10.07	28.43	38.49	141.28

Table 4. Net carbon sequestration by *S alba*, *S fragilis* and *S wilhelmsiana* at selected locations

Site	Species	Current annual change in shoot and root biomass carbon (tonnes/ha/year)	Current annual change in soil biomass carbon (tonnes/ha/year)	Current annual change in litter organic carbon (tonnes/ha/year)	Net carbon sequestration (tonnes/ha/year)
Gue-1	*S alba*	1.32	5.00	0.69	7.01
Gue-2	*S alba*	0.61	2.84	0.42	3.88
Lidang	*S alba*	2.23	7.13	0.86	10.21
Mean		1.39	4.99	0.65	7.03
Gulling	*S fragilis*	2.27	2.95	0.33	5.56
Teling	*S fragilis* and *S wilhelmsiana*	0.33	1.56	0.17	2.05
Lalung	*S fragilis*	0.48	0.38	0.07	0.93
Mean		1.03	1.63	0.19	2.84

Data given in Table 4 show that net carbon sequestration by *Salix* shrub species across three selected sites sequestered average 2.84 tonnes per ha per year carbon. The maximum annual net carbon sequestration was observed at Gulling (5.56 tonnes/ha/year) and minimum (0.93 tonnes/ha/year) at Lalung.

DISCUSSION

The present study was conducted at six sites for the estimation of density, biomass and carbon stock of the *Salix* tree and shrub species in the cold desert region of the Lahaul and Spiti, Himachal Pradesh. The density of *S alba* varied from 303 to 620 individuals per ha and the biomass of the *S alba* plantations varied from 24.27 to 56.30 tonnes per ha. The findings of the study are in line with the study done be Rawat et al (2007) in cold desert region of Lahaul valley in Himachal Pradesh, wherein, it was reported that the highest density of *S fragilis* was at Hinsa (453 trees/ha) under agroforestry systems. Low density of *S fragilis* (20 individuals/ha) was observed at Jahlma and 6 individuals per ha at Hinsa in natural conditions.

The volume and the resultant biomass of a tree depends on its diameter, height and form. Therefore, greater the diameter, height and lesser the taper form of the tree, greater will be the volume of the tree and hence it results in greater biomass. The biomass production amongst the trees species varied from 24.27 to 56.30 tonnes per ha in the present study, which is in line with the study done by Rawat et al (2007). Kalita et al (2021) studied the effect of six different *Salix* verities on biomass and soil organic carbon and found that the average biomass of the verities varied widely from 3.9 to 19.8 tonnes per ha for the first harvest and 14.4 to 48.5 tonnes per ha for the 2nd to 5th harvest of the verities. SOC content was found to vary from 13.3 to 51.5 tonnes per ha, which also coincides with the present study. Contrary to it, a study conducted by Shah et al (2015), conducted in the four districts of Jammu and Kashmir, found that the average biomass production for *S alba* varied from 429.27 tonnes per ha at

Anantnag to 532.61 tonnes per ha at Bandipora. The maximum soil carbon density of 68.07 tonnes per ha was recorded at Bandipora followed by 67.93 tonnes per ha at Baramulla, 66.86 tonnes per ha at Ganderbal and 66.43 tonnes per ha at Anantnag. The variation from the present study can be attributed to the low tree density, ecological conditions of the cold desert region and soil conditions.

Biomass of *Salix* shrub species varied from 12.56 to 38.82 tonnes per ha and the average plant carbon density of 10.07 tonnes per ha was observed at three selected locations. The soil carbon density and total carbon density varied from 11.87 to 44.60 tonnes per ha and 17.47 to 61.93 tonnes per ha respectively. The findings of the study are in line with the findings of He et al (2021).

Soil organic carbon: The SOC variation may be attributed to the factors like climate, initial soil type, species, current forestry practices, pre-afforestation management, plantation age and land use history. In the present study, the value of SOC density varied from 28.53 to 44.12 tonnes per ha for the site having *Salix* tree species and 11.87 to 44.60 tonnes per ha for the shrub-rich sites which is in accordance with the findings of He et al (2021), Rytter et al (2015), Kalita et al (2021) and Verma and Kumar (2022). The study by Agostini et al (2015) varied in methodology and length of study period from the present study who reported that SOC accumulation rates ranged from 0.06 to 3.57 Mg per ha per year for *Salix* species. Verma and Kumar (2022) estimated the biomass and soil carbon stock in the alpine pasture of the Lahaul valley, Himachal Pradesh and found that the value of soil carbon stock ranged from 55.08 to 66.39 tonnes per ha for different sites for 0-30 cm soil depth.

The average net annual carbon sequestration by the *Salix* tree species was 7.03 tonnes per ha per year and by the shrub species was 2.84 tonnes per ha per year across the selected locations. The results of the present study are comparable to the study done by He et al (2021) in Tibetan Plateau alpine sandy land who reported that total carbon sequestration of plant components, litter and soil for three shrubs plantations was found to be 9.53, 6.77 and 4.50 tonnes per ha per m^2 per year in *S psammophila*, *S microstachya* and *S cheilophila* plantations respectively in the Tibetan Plateau alpine sandy land conditions. The findings are also in line with Rytter et al (2015).

CONCLUSION

Willows exhibit remarkable adaptability across diverse ecological zones. *S alba*, commonly found in lower altitudinal regions, is predominantly cultivated in agroforestry systems, while shrub species of willow grow naturally across the landscape. The productivity of *Salix* species varies significantly depending on ecological and soil conditions. Despite this variability, *S alba* and *S fragilis* demonstrated substantial potential for atmospheric carbon sequestration in cold desert regions, storing 56.76 tonnes per ha of carbon and sequestering 208.31 tonnes per ha of CO_2 equivalent.

The study quantified the biomass and carbon sequestration potential of *S alba* trees and *Salix* shrubs in the cold desert region of Lahaul and Spiti, Himachal Pradesh. *S alba* plantations exhibited significant variation in tree density and biomass across different locations, with Lidang showing the highest biomass and carbon density. *Salix* shrubs also demonstrated substantial biomass and carbon sequestration potential, with Gulling exhibiting the highest values. Both tree and shrub species contributed significantly to soil carbon density, with variations attributed to factors like climate, soil type and management practices. The average net annual carbon sequestration by *S alba* trees and *Salix* shrubs demonstratesed their effectiveness in mitigating atmospheric CO_2 in cold desert conditions. The results aligned with previous research indicating the potential of *Salix* species for biomass accumulation and carbon sequestration, although variations existed due to differences in ecological conditions and methodologies.

Overall, the study underscored the crucial role of *Salix* species in agroforestry systems of cold deserts, particularly in combating desertification and sequestering carbon. These species serve as valuable tools for climate change mitigation and provide essential subsistence resources for local communities. The data supports the use of these species in reforestation efforts within similar harsh environments.

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