

**INTER COMPARTMENTAL VARIATIONS IN FLORISTIC
COMPOSITION, BIOMASS PRODUCTIVITY AND SOIL
PHYSICO-CHEMICAL CHARACTERISTICS OF
SAL FOREST IN HIMACHAL PRADESH**

Thesis

by

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(F-2018-31-D)**

submitted to



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The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE-II

This is to certify that the thesis entitled, “**Inter compartmental variations in floristic composition, biomass productivity and physico-chemical characteristics of Sal forests in Himachal Pradesh**” submitted by **Ms. Aditi Sharma (F-2018-31-D)** daughter of Mr. Pawan Dev Sharma to Dr Yashwant Singh Parmar University of Horticulture and Forestry, (Nauni) Solan (HP)-173230 India in partial fulfillment of the requirements for the degree of **Doctor of Philosophy (FORESTRY)** in the discipline of **Silviculture** has been approved by the Advisory Committee after an oral examination of the student in collaboration with an External Examiner.


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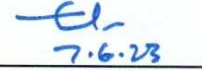
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ABBREVIATIONS USED

a m s l	:	above mean sea level
AGB	:	Above Ground Biomass
B	:	Boron
BA	:	Basal Area
BD	:	Bulk Density
BGB	:	Below Ground Biomass
C	:	Carbon
C.D. 0.05	:	Critical difference at P = 0.05
cm	:	Centimeter
°C	:	Degree Celsius
CO ₂	:	Carbon dioxide
Cu	:	Copper
DBH	:	Diameter at Breast Height
E	:	East
e.g.	:	Exempli gratia
ECD	:	Ecosystem Carbon Density
<i>et al</i>	:	Et alii
Fe	:	Iron
FSI	:	Forest Survey of India
g	:	gram
GHG	:	Green House Gas
GHGs	:	Green House Gases
H P	:	Himachal Pradesh
ha	:	Hectare (10,000 m ²)
HB	:	Herb Biomass
HT	:	Average height
i.e.	:	Id est
IPCC	:	Intergovernmental Panel on Climate Change
IVI	:	Importance Value Index
K	:	Potassium
Kg	:	Kilogram
m	:	Meter
Mg ha ⁻¹	:	Mega gram per hectare
Mg C ha ⁻¹	:	Megagram Carbon per hectare

Mg ha ⁻¹ yr ⁻¹	:	Megagram per hectare per year
mm	:	mili meter
N	:	North
N ha ⁻¹	:	Number per hectare
NE	:	North East
NW	:	North West
°C	:	Degree Celsius
P	:	Phosphorus
pH	:	pouviour of hydrogen
pp.	:	Pages
%	:	Percent
R/S	:	Root: Shoot ratio
\bar{R}^2	:	Adjusted R squared
RF	:	Reserve forest
S	:	Sulphur
SB	:	Shrub Biomass
SOC	:	Soil Organic Carbon
SQI	:	Soil Quality Index
Sp	:	Species
SQ	:	Site Quality
TB	:	Tree Biomass
TC	:	Tree Carbon
D	:	Tree density
V	:	Volume
<i>Viz</i>	:	<i>Videlicet</i>
Yr	:	Year
Zn	:	Zinc

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Chapter-1

INTRODUCTION

Vegetation is an assemblage of plants that grow together in a specific location and are distinguished by either their component species or the combination of structural and functional characteristics that define vegetation's phenotypic characteristics (Goldsmith *et al.*, 1986). The magnitude of changes in forest stands is studied through phyto-sociological attributes, mainly by density and total basal cover, which are the foremost basis of study for any vegetation type (Mishra *et al.*, 2000). The ecological characteristics of sites, species richness, diversity, distribution, abundance and regeneration status of species significantly influence the composition of forest communities (Pandita *et al.*, 2019). The stand structure represented in terms of diameter class distribution gives vital information on the reproductive capability of the forest stand (Joshi and Chandra, 2020; Sinha *et al.*, 2018). Furthermore, an examination of species diversity indices shows the stability and sustainability of forest communities (Sarkar and Devi, 2014). Each species within a community exhibits a high degree of structural and functional individualism, as well as varying ecological amplitude and modality (Singh and Joshi, 1979). Hence, the floristic composition and phyto-sociological attributes can be used to compare one community to another from season to season and year to year (Singh, 1976).

Biomass is defined as the total amount of above-ground biomass in trees expressed as oven-dry tons per unit area that reduces the concentration from atmospheric concentration of carbon dioxide (Chavan and Rasal, 2012). Quantitative information on biomass helps to estimate energy accumulation within forest ecosystems and serves as an ecological indicator for sustainability by assessing forest productivity, nutrient cycling, carbon pools and carbon sequestration in biomass components (Chave *et al.*, 2005). The forest ecosystem is the most important carbon sink because it produces vast carbon pools that are stored as vegetative biomass in wood, leaves, litter, and roots including carbon storage in the soil (Brown and Lugo, 1982).

Forests can operate as either a carbon sink or a carbon source, depending on their succession stage and disturbance or management intervention (Masera *et al.*, 2003; Lorenzo and Lal *et al.*, 2010). Carbon sequestration, the capture of atmospheric carbon dioxide and its storage in terrestrial ecosystems in the form of living biomass for a very long period of time,

such that it is not quickly re-emitted back into the atmosphere (Lal *et al.*, 2004; Malhi *et al.*, 2009 and Pan *et al.*, 2011). Forest ecosystems are particularly situated in the global climate change scenario because they serve as a repository of biodiversity and a carbon sink in their biomass and soil (Gibbs *et al.*, 2007 and Fahey *et al.*, 2010). Carbon sequestration in biomass is currently regarded as the most promising method of mitigating the greenhouse effect (Kimble *et al.*, 2002). As a result, carbon storage as biomass in forest ecosystems has become increasingly relevant in global climate change studies (Usuga *et al.*, 2010; Gren and Zeleke, 2016; Nonini and Fiala, 2019). The Kyoto Protocol explicitly considered afforestation, reforestation and forest regeneration for carbon sequestration accounting in order to reduce greenhouse gas emissions and counterbalance deforestation (IPCC, 2007).

The regeneration status of a forest indicates its health and vitality and a healthy forest ensures good future regeneration. The presence of different age groups of seedlings, saplings and tree determines the forest's regenerating and productive character (Chauhan *et al.*, 2008). The majority of the regeneration stock in Sal-dominated mixed forests typically comes from seed and root suckers re-sprouting. Sal seeds germinate at a rate of more than 90% and if they do not receive rain within a week due to a delay in the onset of monsoon, which usually begins in mid-June or insufficient moisture, the seed loses viability (Gautam and Devoe, 2006). The 'die back' of Sal seedlings caused by a variety of factors environmental conditions, such as light, temperature, frost, soil quality, drought, soil moisture availability and drainage system affect the regeneration of Sal Forest and lead to mortality (Mishra *et al.*, 2000). Although Sal seeds germinate profusely, seedling establishment and conversion to trees are very low. *Shorea robusta* has a high seedling mortality rate (Chauhan *et al.*, 2010). Sal is a light-demanding species and complete overhead light is required in most cases from the earliest stages of development (Champion and Seth, 1968). The opening of the canopy in a forest stand promotes regeneration and the growth of understory seedlings and saplings (Troup, 1986 and Gautam, 1990).

The physiochemical characteristics of forest soils change in location and time due to differences in terrain, climate, physical weathering processes, plant cover, microbiological activity and a variety of other biotic and abiotic factors. The nature of the soil profile, pH and nutrient cycling between soils and plants are important dimensions in determining the quality of a forest site. Plants are the primary source of soil organic matter, which influences soil physicochemical properties such as texture, pH, water retention capacity and nutrient availability (Johnston, 1986). Sal grows on a wide range of soil types, except in the very

sandy and gravelly soils immediately adjoining rivers and in waterlogged areas (Jackson, 1973). It prefers slightly acidic to neutral sandy loam (pH=5.1-6.8) and may develop on alluvial to lateritic soils (Tewari, 1995). Primary production is usually regulated by the availability of nutrients. On better sites, mineral nutrition appears to be an important factor in sal forest productivity or where the rate of stem timber production is greater; the nutrient requirements are much higher. On poor sites, nutrient status is lower and a higher proportion of the uptake goes into the production of foliage (Kaul *et al.*, 1966). Deficiencies of nitrogen, phosphorus and magnesium affects height growth. Deficiencies of calcium and magnesium produce a shorter taproot and sparse lateral roots while nitrogen and potassium-deficient seedlings had thin and long tap roots. Good sal regeneration is highly influenced by nitrogen, phosphorus, potassium, and soil pH (Bhatta, 2016). The composition of the forest stand and ground cover, the pace of tree development, the strength of natural reproduction and other silvicultural important elements are influenced by forest soils (Bhatnagar, 1965).

A forest compartment is a section of a forest with homogenous growth conditions and tree species. It may also be called a stand compartment. Compartments are marked on forestry maps and forest management plans are made according to their growing conditions. A compartment is kept as far as possible homogenous throughout its extent with regard to the composition of growing stock, soil and aspect. The area of the compartment depends mainly on the intensity of management. In forest areas that are worked intensively; the area of the compartment is usually small and sometimes it is maybe around 10 to 20 ha. However, in forests managed extensively, the area of the compartment may go up to 1000 ha or even more. Other factors such as topographic and site variation may affect the area of the compartment. During the preparation of the working plan, a compartment is inspected and if necessary, it is further divided into sub compartments. Sub-compartment is usually identified as a unit of treatment. The compartment is divided into sub compartments mainly based on vegetation, growing stock and site conditions. In areas of management sub-compartment forms the unit of silvicultural and utilization treatments.

Sal (*Shorea robusta* Gaertn. f.) is a dominant tree species with a slow to a moderate growth rate that is valued for its heavy, thick and durable wood in India's tropical moist and dry deciduous forests. It frequently develops a mono-specific canopy, which requires complete overhead light from the start of its establishment (Kayastha, 1985). Its geographical range stretches from the southern Himalayan slopes and lower foothills to plains, river slopes and valleys in India, Nepal, Bangladesh, Bhutan, and South China, between 75° and 95° E

longitudes and 20° to 32° N latitude (Sapkota, 2009). In India, forests cover nearly 21.71 per cent of the country's total geographical area (FSI, 2021) and Sal forest accounts for around 13.3 per cent of India's total forest area. It stretches up to the Assam valley (including Meghalaya and Tripura) in the east to the foothills of north-west Bengal, Uttar Pradesh, Uttarakhand and Paonta Sahib in Himachal Pradesh in the Himalayan foothill region. Sal forest is relatively rich in ground flora diversity. In sal forests, there are generally four separate layers: *Shorea robusta* and *Terminalia alata* in the top story, *Syzygium cumunii* in the middle story with *Mallotus philippensis* as a codominant tree species and *Ardisia solanacea*, *Clerodendron viscosum* and *Lantana camara* as understory associate species in shrub layer and *Pogostuimon benghalensis* in the herb layer. Apart from trees and shrubs, the ground flora of sal forests includes ferns, herbs, grasses, and liana species, the abundance of which varies amongst woods (Sharma and Bahuguna, 1989). It is one of the principal timber species of the country, which needs to be managed intensively on a sustained yield basis for achieving maximum productivity level. Knowing the extent of inter-compartmental variation or sub-compartmental variation in vegetation, growing stock and site condition will form the scientific base for developing a set of silvicultural treatments to enhance and maximize productivity of this species on a sustained basis. In Himachal Pradesh, the Sal Forest is present in the Paonta and Andreta village of district Kangra with a total area of around 306.97 km² (Sharma *et al.*, 2020). Champion and Seth (1968) categorized the forest types found in the division as: 3C/C2a Moist Shiwalik Sal Forests, 3C/C2b(i) Moist Bhabar Sal-Bhabhar-Dun Sal Forest, 5b/C1a Dry Shiwalik Sal Forests and 5b/C2 Northern Dry Mixed Deciduous Forests. Sal forests of compartments including the present study area are part of the 3C/C2b (i) Moist Bhabar Sal-Bhabhar-Dun Sal Forest.

Hitherto no detailed study has been carried out on these lines; therefore, the present investigations entitled “**Inter compartmental variations in floristic composition, biomass productivity and soil physico-chemical characteristics of Sal forest in Himachal Pradesh**” were carried out with the below objectives:

1. Assessment of inter-compartmental variation in floristic composition and regeneration status in sal forest ecosystems;
2. To study the variation in biomass and site quality under different compartments of sal forest ecosystems;
3. To establish the relationship between physico-chemical characteristics and site quality of sal forest ecosystems.

Chapter-2

REVIEW OF LITERATURE

The pertinent literature related to the present investigations entitled “**Inter compartmental variations in floristic composition, biomass productivity and soil physico-chemical characteristics of Sal forest in Himachal Pradesh**” has been reviewed under the following major headings:

2.1 Floristic composition and regeneration status.

2.2 Biomass productivity and carbon stock.

2.3 Physico-chemical characteristics.

2.1 FLORISTIC COMPOSITION AND REGENERATION STATUS

Floristic composition refers to the measure of species diversity in any community. Its study form one of the fundamental prerequisites to classifying the flora into different vegetation type. The nature of a community at any place is determined by the species that grow and develop in such an environment. Forest regeneration makes a significant contribution to the sustainable and balanced growth of forest ecosystem. It provides the base for forest protection and rehabilitation, increased carbon sequestration, and restoration of native biodiversity.

Odum (1969) defines species diversity as "the richness of species as well as the balanced distribution of species. Floristic composition, stratification and other vegetation characteristics vary with season and year. The species diversity reflects the gene pool and adaptation potential of the community and distribution of individuals among the species in a particular habitat and the importance of quantitative information, like floristic richness, diversity, evenness and dominance of the vegetation (Odum, 1971; Ilorkar and Khatri, 2003). It is also affected by the biotic and abiotic components of the area liable to the change and the net result of the interaction in a new community.

Giril *et al.* (1999) investigated the vegetation composition and regeneration of tree species in Terai *Shorea* Forest (TSF) and *Shorea-Terminalia* Forest (STF) in Nepal's Royal Bardia National Park's southwestern region. The top canopy of forests was dominated by

Shorea robusta and *Terminalia alata*. TSF had a higher basal area and total density. In TSF, *Shorea robusta* had the maximum density and basal area, whereas, in STF, *Terminalia alata* had the maximum density and basal area. In the TSF and STF, respectively, 9 and 21 tree species displayed seedling and sapling stages. There were no seedlings or saplings in 17 tree species in TSF and 19 in STF. *Shorea robusta* had the most seedlings (13166.66 ha⁻¹) in the TSF, followed by *Lagerstroemia parviflora* (666.66 ha⁻¹). A similar trend was observed for saplings. In STF, *Shorea robusta* had the highest number of seedlings (9204.54 ha⁻¹) and saplings (321 ha⁻¹) followed by *Mallotus philippensis* (seedlings: 1590.9 ha⁻¹; saplings: 184 ha⁻¹).

Pandey and Shukla (2003) assessed the plant diversity, regeneration pattern and the status of species conservation of Sal (*Shorea robusta*) forest in Sohagibarawa Wildlife Sanctuary, Gorakhpur. 208 species representing 165 genera and 72 families were recorded within 24 ha of sal stands. *Shorea robusta* was the most frequent species. After *Shorea robusta*, the next most frequent species were *Mallotus philippensis* and *Ichnocarpus frutescens*, followed by *Clerodendrum infortunatum* and *Desmodium gangeticum*. In general, the sal stands showed a high Shannon index of species diversity ($H' 53.96$). Simpson's index was quite low (50.06). Among the four different growth forms, the species richness was maximum for trees (93) followed by shrubs (50), lianas (34) and perennial herbs (31). The mean density of individuals having >30 cm girth was only 404 ha⁻¹, while that for tree species having 30 cm girth was 20413 ha⁻¹.

Kumar *et al.* (2006) studied the plant and soil diversities in a sub-tropical forest of the Garhwal Himalaya. The highest density of the tree layer (380 trees ha⁻¹) was documented in the southern aspect. Whereas, the lowest density (260 trees ha⁻¹) is in the western aspect. In the shrub layer, the highest density (1790 shrubs ha⁻¹) was recorded in the eastern aspect and the lowest (970 shrubs ha⁻¹) in the western aspect. The range of values of total density and total basal cover of saplings were 200 to 550 saplings ha⁻¹ and 0.78 to 1.43 m² ha⁻¹, respectively. The values of similarity among the aspects and different layers ranged from 25.0 to 66.67 per cent, 22.22 to 57.14 per cent, 28.57 to 57.14 per cent and 57.14 per cent to 72.72 per cent for trees, saplings, seedlings and shrubs, respectively. The range of diversity was 0.846 to 1.710 (trees), 1.943 to 2.847 (shrubs), 1.10 to 1.520 (saplings) and 0.496 to 1.435 (seedlings).

Chauhan *et al.* (2008) compared regeneration, tree diversity and floristic diversity of natural and planted tropical deciduous forests dominated by *Shorea robusta* and *Tectona grandis*, *Acacia catechu* and *Syzygium cuminii*, respectively in Katarniaghat Wildlife Sanctuary, Uttar Pradesh. Species diversity as well as species evenness was higher in natural forests than in planted forests. Natural forest sites also had a higher mature tree, pole, sapling and seedling densities compared with planted forests. Dominant families in both forest types are Fabaceae, Euphorbiaceae, Verbenaceae, Rubiaceae and Caesalpiniaceae (five species each), followed by Moraceae, Mimosaceae and Combretaceae. Of the 126 species found in both sites, 32.5 per cent showed good regeneration, 19.8 per cent fair, 24.6 per cent poor and 11.1 per cent lacked regeneration. The remaining 11.9 per cent of species were present only as seedlings. Species richness and diversity differed between natural and planted forests and the regeneration of some important tree species also varied because of variations in their microclimate and edaphic characteristics.

Sapkota *et al.* (2009) investigated the spatial distribution, advanced regeneration and stand structure of five *Shorea robusta*-dominated forests subject to disturbances of different intensities. A total of 67 tree species were recorded in the forest plots, 41 species in least disturbed forests, and 10 species in heavily disturbed forests. A total of 5320 individuals out of which 3254 individuals were advanced regeneration and poles and 1966 were mature trees with >1.5 cm dbh. Significant variations in the mean stem density of advanced regeneration/poles ($F [4,620] = 27.95$; $p < 0.0001$), adult trees ($F [4,620] = 25.66$; $p < 0.0001$) and total population ($F [4,620] = 21.40$; $p < 0.0001$) were observed among forests. A strong inverse relationship was found between the overall stand density and diameter class in the least disturbed and moderately disturbed forests. Little or no regeneration in the least and most heavily disturbed forests showed for socio-economically important tree species. *Shorea robusta* showed a change in its advanced regeneration/pole density across the disturbance gradient.

Basyal *et al.* (2011) studied regeneration of *Shorea robusta* in tropical forest of Palpa district, central Nepal. The major tree species at the study site was *Shorea robusta*. It had the highest importance value index among the 26 tree species (99.93). Frequency of *Shorea robusta* was 87.5 per cent. *Terminalia alata* was codominant species in the forest. The total tree density in the forest ranged from 3.13 N ha⁻¹ to 209.37 N ha⁻¹. The total basal area of all tree species was 63.86 m² ha⁻¹. In the case of saplings, the total density was 3437.5 N ha⁻¹,

with *Shorea robusta* was found higher (2250 N ha⁻¹). Likewise, it had 4375 N ha⁻¹ seedlings, 2562.5 sapling N ha⁻¹, and 209.37 N ha⁻¹ saplings.

Deka *et al.* (2012) in Assam observed the community characteristics of naturally regenerated sal forest. Altogether, 71 plant species were recorded from the selected sal forest. The herbaceous layer of the forest was the most species-rich (30 species) layer followed by tree and shrub species. *Shorea robusta* has contributed about 90 per cent of the total stand density (2559 individual ha⁻¹) of the forest and it contributed to the highest basal area of 26.08 m² ha⁻¹. Among the total basal area of *Shorea robusta*, the highest basal area (10.44m² ha⁻¹) was recorded in the 30-45 cm girth class followed by 45-60 cm (6.63 m² ha⁻¹) and 15-30 cm (3.98 m² ha⁻¹) girth class. Hence, the girth class distribution confirmed a reverse J-shaped distribution with higher density in lower girth classes and a sharp decline thereafter. The total density of shrubs and herbs was recorded as 2 individuals m⁻² and 63 individuals m⁻², respectively. Among shrubs, *Chromolaena odorata* was the dominant species with the highest IVI (36.48) having a density (of 5560 individuals ha⁻¹) followed by *Cledodendron viscosum* with an IVI (33.22) with a density of 4506 individuals ha⁻¹ and *Flemingia strobilifera* with IVI (32.47) and density 4826 individuals ha⁻¹. Based on the dominance, *Shorea robusta* showed the highest dominance followed by *Zizyphus rugosus*. The diversity index for tree, shrub and herb species was recorded as 1.43, 2.30 and 3.28, respectively. The dominance index showed a reverse trend to that of the diversity index. About 84per cent of the plant species showed contagious distribution, however, none of the species exhibited regular distribution. The forest is heterogeneous in composition with high dominance of Sal and is under regenerating stage.

Chaubey and Sharma (2013) reported the regeneration potential of *Shorea robusta* and its associates in Satpura Tiger Reserve, Madhya Pradesh. The results indicated that the average number of regenerations of sal seedlings ha⁻¹ was 6372 ha⁻¹, which was quite adequate. The distribution pattern of individuals of *Shorea robusta* was uninterrupted, which is a healthy sign of establishment.

Dutta and Devi (2013) performed a quantitative analysis of plant diversity and community structure in the Doboka reserve forest of Assam's tropical wet deciduous Sal forest. A total of 89 plant species were identified (34 trees, 15 shrubs, 25 herbs, and 15 climbers) from 77 genera and 45 families. *Shorea robusta* had the highest IVI (125.3) followed by *Dillenia pentagyna* (27.24) and *Careya arborea* (23.12). The tree stand density

and basal area were 422 individual ha⁻¹ and 88.87 m² ha⁻¹, respectively. Tree density was found to be higher in the lower girth class, i.e., 30-60 cm. The Shannon-Wiener diversity index ranged between 2.02 to 2.43.

Mandal and Joshi (2014) compared the vegetation dynamics and plant diversity from the dry deciduous forests of Doon Valley. Species richness, regeneration, soil conditions and change in community composition of these forests were studied and change was noticed with *Shorea robusta* as the main dominant species and *Mallotus philippensis*, *Syzygium cuminii* and *Ehretia laevis* as codominant tree species in all communities. The highest species richness and diversity rates increased with the decrease in tree density and basal area. The high IVI recorded in Thano (>150) indicated that *Shorea robusta* forest was progressing toward the culmination stage, whereas the lower IVI values (100 and 150) in the other two sites (Selaqui Jhajra and Asarori) signified the heavy disturbance of these sites and further establishment of alien invasive species such as *Cassia tora*, *Cassia occidentalis*, *Lantana camara*, *Urena lobata*, *Ipomoea carnea*, *Sida acuta* and *Solanum torvum*. IVI values for shrubs ranged between 8.35 and 27.33, with *Murraya koenigii*, *Lantana camara* and *Clerodendrum viscosum* being the most dominant species in the Selaqui Jhajra range. A 100 per cent frequency was recorded for *Shorea robusta*. *Terminalia alata*, *Bauhinia variegata*, *Flacourtia indica*, *Ehretia laevis* and *Cordia dichotoma* had a frequency of 20 per cent in this range, however, a 10 per cent frequency was observed for two tree species. IVI (16.59) value with 90 per cent frequency and highest density (3.50 individual m²) were recorded for *Vernonica cinerea*. An analysis of the diversity status of herbs at various study sites showed that diversity (species richness) ranged from 27 species (Thano range) to 49 species (Asarori range). The concentration of dominance (Cd) ranged from 0.03 (for Asarori range) to 0.04 (Thano range and Selaqui Jhajra range). The results revealed that diversity (species richness) for the herb layer was highest at the Thano range (24). Asarori range and Selaqui Jhajra had the same diversity (21). The diversity (species richness) for tree species was highest (15) at the Asarori range. Selaqui Jhajra and Thano, meanwhile, had the diversity of 14 and 08, respectively.

Nag and Gupta (2014) studied the population structure and regeneration of Sal by laying 34 quadrats in three differently managed forests of 3 Wildlife Sanctuaries: Ballavpur (protected, artificially created), Illambazar (natural, disturbed) and Garhjungle (natural, sacred). For 595 trees, mean tree density and basal area were highest in Garhjungle (2233.3 N ha⁻¹ and 13.89 m² ha⁻¹) and lowest in Ballavpur (1441.7 N ha⁻¹ and 12.89 m² ha⁻¹). The

density of regenerating individuals (seedling and sapling) was highest in Garhjungle (4266.7 N ha⁻¹) and lowest in Illambazar (2710 N ha⁻¹). The seedling density was highest in Ballavpur (1016.7 N ha⁻¹). The diameter class distribution of the tree species revealed that the highest number of individuals were concentrated in the lower diameter classes indicating a young and expanding population of *Shorea robusta* in all three forests indicating good overall regeneration.

The diversity and composition of tree species of secondary Dipterocarpus hill forests in Chunati Wildlife Sanctuary of Chittagong, Bangladesh were studied by Mamun *et al.* (2015). A total of 993 individual trees of 99 species belonging to 73 genera and 36 families were recorded from the forests of Chunati. The forest had diverse floristic resources as indicated by Shannon Wiener's diversity index (3.35), Margalef's richness index (14.20) and Simpson's dominance index (0.09). The total basal area of tree species was 12.47 m² ha⁻¹, whereas *Dipterocarpus turbinatus* showed the highest basal area (2.62 m² ha⁻¹) followed by *Acacia auriculiformis* (1.39 m² ha⁻¹). IVI was found maximum (40.11) for *Acacia auriculiformis* followed by *Tectona grandis* (16.46) plantation species. On the other hand, IVI was highest for *Dipterocarpus turbinatus* (25.10) followed by *Ficus hispida* (19.76) for natural species.

Kumar and Saikia (2020) studied the regeneration status of *Shorea robusta* and its four dominant associated tree species (*Diospyros melanoxylon*, *Buchanania cochinchinensis*, *Madhuca longifolia*, and *Butea monosperma*) in Sal forests of Ranchi, Eastern India. Out of the 103 recorded tree species, 50 species (48.54 %) had shown the total absence of regeneration, while 23 species each (22.33 %) showed poor and good regeneration, and rest 07 species (6.80 %) showed fair regeneration in the studied Sal forests stand. On the other hand, the maximum studied Sal forest stands (42.39 %) had shown fair regeneration of *Shorea robusta* followed by good regenerating forests (36.96 %), and 17.39 per cent forests showed no regeneration. The total seedling density of *Shorea robusta* was 22,071 N ha⁻¹. However, the recorded tree density (416 N ha⁻¹) of *Shorea robusta*, density (N ha⁻¹) of seedlings ranged from 54–22,071 N ha⁻¹, for saplings 4–1239 N ha⁻¹, and adults ranged from 0.02–416 N ha⁻¹ of tree species were significantly varied among the Sal forests.

Nag and Gupta (2020) assessed the population structure and regeneration status of nine selected tree species in eight tropical dry deciduous forests in West Bengal's lateritic zone. Highest number of species was recorded at Ballavpur (8) and lowest at Garh Joypur

(1). The overall structure of the eight forests comprises of 15.82 per cent seedlings, 59.35 per cent saplings and 24.82 per cent adult trees. Garh Joypur forest had the largest percentage of trees (61.02 %) and Ganpur forest had the lowest (10.78 %). Several species' seedling, sapling, and tree densities varied dramatically among locations. Regeneration was better in the Ganpur forest, which had the highest seedling density (3290 N ha⁻¹) and sapling density (15900 N ha⁻¹), followed by the Aduriya forest, which had the seedling density (2780 N ha⁻¹), sapling density (9720 N ha⁻¹) and the lowest seedling density (260 N ha⁻¹) and sapling density (940 N ha⁻¹) was found at Garh Panchakot.

Sharma *et al.* (2020) investigated the status of regeneration on a community-managed hill forest. In the study area, the total number of seedlings, saplings and trees of all species were 12,589, 2643 and 1979 N ha⁻¹, respectively. The total number of Sal seedlings, saplings, and trees was 8352, 1876, and 1320 N ha⁻¹, respectively. Similarly, the total number of sal seedlings (4384 N ha⁻¹), saplings (1043N ha⁻¹) and trees (804 N ha⁻¹) in site A was greater than the total number of sal seedlings (3968 N ha⁻¹), saplings (833 N ha⁻¹) and trees (516 N ha⁻¹) in site B.

Biswas *et al.* (2021) conducted a study to assess biodiversity and estimate the carbon stock of two dry deciduous forest ranges in Bihar, India. The Banka and Bounsi ranges had a total distribution of 18,888 [14,893 <10 cm (diameter at breast height) dbh] and 2,855 (1,783 <10 cm dbh) individuals with basal areas of 181,035.00 cm² and 32,743.76 cm², respectively. *Shorea robusta* had the highest IVI in both ranges, with values of IVI 56.27 and 55.88. The species diversity index and dominance index, which were 1.89 and 1.017 in Banka and 1.99 and 5.60 in Bounsi, showed the presence of biotic pressure. Decreased dbh and tree height resulted in a lowered growing stock volume of 59,140.40 cm³ ha⁻¹ (Banka) and 71,306.37 cm³ ha⁻¹ (Bounsi). The total biomass of the two ranges was 78.875 and 93.011 kg ha⁻¹. Total C stock at Banka and Bounsi ranges was 39.44 and 46.51 kg ha⁻¹, respectively where the highest C stock is recorded for *Shorea robusta* in both the ranges (Banka 7.65 kg ha⁻¹; Bounsi 9.40 kg ha⁻¹) C sequestration potential was about 194.25 t CO₂ (Banka) and 45.9 t CO₂ (Bounsi). A positive correlation was found between the volume, total biomass, and basal area of tree species and C stock.

Kongkham *et al.* (2021) assessed the community structure and regeneration status in four different sites viz. Shuduwala, Manduwala, Bhawala and Tilwari of Shivalik Sal forests in Dehradun Forest of Uttarakhand. Sal tree density was maximum in the Manduwala (226.66

trees ha⁻¹). *Shorea robusta* had the highest IVI value (203.63) in the Tilwari site, followed by *Mallotus phillippinsis* (46.74). Species richness (Margalef index) varied between 1.15 and 22.56 in different study sites. The tree density of *Shorea robusta* was recorded as higher as compared to seedlings and saplings in all the sites. Maximum seedlings and saplings were reported in Shuduwala (93.30 N ha⁻¹, 60 N ha⁻¹). Whereas, Manduwala and Bhawala had identical values of 53.30 and 36.70 N ha⁻¹ for seedlings and saplings, respectively.

2.2 BIOMASS PRODUCTIVITY AND CARBON STOCK

An estimation of the biomass carbon stock is beneficial in determining the effect of disturbances on productivity, nutrient cycling and stability of forest stands. Tree above ground biomass (AGB) distribution and carbon storage in different dbh classes were compared between natural semi-evergreen forests and sal plantation forests in the humid tropical region of northeast India by Baishya *et al.* (2009). The natural forest had a lower AGB (323.9 Mg ha⁻¹) than the plantation forest (406.4 Mg ha⁻¹). About 49 per cent of the AGB was present in > 60 cm dbh trees in the natural forest against 24 per cent in the plantation forest. The carbon storage was highest in 60-80 cm and 40-60 cm dbh classes in the natural forest and plantation forest, respectively. The differential AGB and carbon distribution pattern had been related to past disturbance history and the age of the forests. Although both the forests had the potential for carbon sequestration due to the presence of a large number of trees belonging to small dbh classes, the plantation forest had an edge over the natural forest because of better silvicultural practices.

Devi and Yadava (2009) analyzed the aboveground biomass dynamics and net primary productivity to assess the productive potential of Dipterocarpus forest in Manipur, Northeast India. Two forest stands (stand I and II) were earmarked randomly in the study site for the evaluation of biomass in the different girth classes of tree species by harvest method. The total biomass was 22.50 t ha⁻¹ and 18.27 t ha⁻¹ in forest stand I and II, respectively. The total aboveground production was recorded to be 9282.73, 848.80 and 294.44 kg⁻¹ ha⁻¹a⁻¹ for *D. tuberculatus*, *A. peniculata* and *W. wallichii*, respectively in the stand I. In forest stand II, total aboveground net production of *D. tuberculatus* and *A. peniculata* was recorded to be 7506.68 kg⁻¹ ha⁻¹a⁻¹ and 1354.37 kg⁻¹ ha⁻¹a⁻¹, respectively; stem 32.64 per cent, branch 31.73 per cent and leaf 35.63 per cent of the total aboveground net production. The total biomass for the tree species recorded in the different components was in the order of bol>leaf>branch

for *D. tuberculatus*. The total forest aboveground biomass was 21.92 t ha⁻¹, which accounted for 68.51 per cent trees, shrub 28.96 per cent and herbs 2.5 per cent in the stand I. In forest stand II, total aboveground biomass was 18.28 t ha⁻¹. Out of the total aboveground net primary production, the bole production accounted for 31.80 per cent, branch 29.60 per cent and leaf 38.60 per cent in the stand I. In stand II, the bole production accounted for 32.64 per cent, branch 31.73 per cent and leaf 35.63 per cent of the total aboveground net production. Hence, the values of production efficiency and the biomass accumulation ratio indicated that the forest is at the succession stage with high productive potential.

Pande and Patra (2010) compared the biomass and productivity of sal forest and miscellaneous forests (MF) of Satpura plateau (Madhya Pradesh) India. These forest types were divided into four sites namely open miscellaneous (OMF, site-I), closed miscellaneous (CMF, site-II), open sal (OSF, site-III) and closed sal (CSF, site-IV). The per cent allocation of above-ground tree biomass followed the order: 85.08 (II) < 85.51 (I) < 81.31 (III) < 78.09 (IV). The higher above ground tree biomass was produced by MF than by SF. OMF produced 9.5 per cent less biomass than the CMF whereas; OSF had 39.91 per cent less biomass than the CSF. The contribution of above ground biomass of shrubs percentage was as follows: 8.3 (IV) < 32.72 (I) < 33.77 (III) < 52.63 (II). The per cent contribution of root biomass was higher for closed sites as compared with open sites. The Root: Shoot ratio ranged between 0.169-0.249. NPP tree (kg ha⁻¹yr⁻¹) was highest for the site –IV (38094.79), followed by III (33384.29), II (12374.89) and I (9736.52). NPP shrub followed the order: 204 (IV) > 109 (III) > 79.80 (I) > 52.69 (II), while for NPP herb, the order of importance was, 109.50 (IV) > 73.27 (I) > (II), 71.75 (III) > 55.71 (II). NPP total was highest for closed forest stands than for the open ones. NEP was higher for SF than MF. Disturbances in open forests not only reduced the stand biomass of tree species, dominant species in particular but also declined tree productivity. So, a gap-filling plantation inside the forest was suggested to improve the productivity of open forests.

Chavan and Rasal (2012) carried out biomass estimation of 4099 trees of *Eucalyptus* spp. was calculated by a non-destructive approach. Above ground biomass (AGB) was calculated by multiplying the volume by wood density. The BGB has been evaluated by multiplying AGB taking 0.26 as the root-to-shoot ratio. The total standing biomass and total carbon sequestered of *Eucalyptus* spp. were estimated at 641.35 t ha⁻¹ and 320.67 t ha⁻¹, respectively.

Rabha (2014) studied the Species richness biomass and Carbon stock in pure Sal forests and excluding *Shorea robusta*, only one individual of *Albizia procera* was encountered. Average density and basal area were recorded at 830 ± 33.6 tree ha^{-1} and 26.29 ± 1.0 m^2 ha^{-1} . In the present study, the average basal area was recorded at 26.29 ± 10 m^2 ha^{-1} , respectively. The mean AGB and C were recorded at 239.45 ± 12.8 Mg ha^{-1} and 119.73 ± 6.4 Mg ha^{-1} , respectively.. The lowermost two dbh classes possessed 97 per cent density, pointing out the mass regeneration nature of Sal forests and 91.6 per cent AGC indicated the potential of carbon sequestration of that stand.

Shahid and Joshi (2015) conducted the study in the three forest ranges of Dehra Dun Forest Division of Doon Valley, Western Himalaya, India. Volumetric equations were used to evaluate the biomass and the carbon status in the moist deciduous forest. The carbon stocks varied between 169.20 Mg ha^{-1} and 219.08 Mg ha^{-1} and the biomass ranged from 338.40 Mg ha^{-1} to 438.17 Mg ha^{-1} in different study sites.

A study was conducted in a Sal-dominated moist tropical forest of Sunsari District, eastern Nepal to determine the biomass and carbon stocks of trees, shrubs, herbs and fine roots by Gautam and Mandal (2016). Total biomass for the undisturbed forest stand (US) was 960.4 Mg ha^{-1} (equivalent to 452.06 Mg C ha^{-1}), while for the disturbed forest stand (DS) it was 449.1 Mg ha^{-1} (equivalent to 211.33 Mg C ha^{-1}). Biomass and NPP of trees and shrubs were estimated by using allometric equations and herbaceous biomass was estimated by harvest method. Fine root biomass was determined from soil monolith. The C stock in vegetation was calculated by multiplying C concentration to dry weight. Total stand biomass (Mg ha^{-1}) in undisturbed forest stand (US) was 960.4 while in disturbed forest stand (DS) it was 449.1. The biomass (Mg ha^{-1}) of trees, shrubs and herbs in the US was 948.0, 4.4 and 1.4, respectively, while in DS they were 438.4, 6.1 and 1.2, respectively. Total NPP (Mg $\text{ha}^{-1}\text{yr}^{-1}$) was 26.58 (equivalent to 12.26 Mg C $\text{ha}^{-1}\text{yr}^{-1}$) in the US and 14.91 (6.88 Mg C $\text{ha}^{-1}\text{yr}^{-1}$) in DS. Total C input into the soil through litter and root turnover was 6.78 and 3.35 Mg $\text{ha}^{-1}\text{yr}^{-1}$ in US and DS, respectively. Among the different life forms: trees, shrubs, and herbs comprised 72 per cent, 2 per cent, and 6 per cent of NPP in the US and 67 per cent, 5 per cent and 9 per cent in DS, respectively; while resting 20 per cent of NPP in the US and 19 per cent in DS were contributed by stand fine root. The contribution in NPP by different components of trees was in the order leaf > bole > twig > coarse root > branch, in both stands.

Aboveground biomass and carbon stock assessment in Indian tropical deciduous forest and its relationship with stand structural attributes were investigated by Behera *et al.* (2017). The relationship between PFT microclimate, structural attributes and diversity vs. AGB were studied with a total of 22, 22 and 6 tree species found in dry mixed (DM), sal mixed (SM), teak plantation (TP) and plant functional types (PFTs), respectively. Shannon's diversity index was highest (2.46) in DM, whereas Simpson's dominance index was maximum (0.85) in TP. AGB (Mg ha^{-1}) ranged from 290.82–455.99 among all PFTs. AGBC (Mg ha^{-1}) ranged between 207.52–220.34, 215.58–228.87, and 125.94–141.18 in DM, SM and TP, respectively. AGB observed a strong positive correlation between tree density and cover. PCA revealed humidity and air temperature as the major microclimatic variables, leading to higher AGB.

Banik *et al.* (2018) in Tripura investigated tree composition, stand characteristics, biomass allocation pattern and carbon storage variability in Sal forests under two forest management regimes (Sal Forest and Sal plantation). The results revealed that Sal plantation possessed maximum AGB ($179.88 \pm 29.43 \text{ Mg ha}^{-1}$) in girth class 121-150 cm followed by $110.53 \pm 1.82 \text{ Mg ha}^{-1}$ in girth class 31-60 cm recorded in Sal Forest. Also, higher species richness (29 species), stand density of $1060.00 \pm 11.12 \text{ stems ha}^{-1}$ and diversity index (1.90 ± 0.08) in Sal Forest and lower species richness (4 species), stand density of $230.00 \pm 37.22 \text{ stems ha}^{-1}$ and diversity index (0.38 ± 0.15) in Sal plantation. The total basal cover ($33.02 \pm 4.87 \text{ m}^2 \text{ ha}^{-1}$) and dominance (0.76 ± 0.08) were found higher in the Sal plantation than in the Sal Forest ($22.53 \pm 0.38 \text{ m}^2 \text{ ha}^{-1}$ and 0.23 ± 0.02 , respectively). The total vegetation carbon density was recorded higher in the Sal plantation ($219.68 \pm 19.65 \text{ Mg ha}^{-1}$) than in the Sal Forest ($167.64 \pm 16.73 \text{ Mg ha}^{-1}$). The carbon density estimates acquired in the study suggested that the Sal plantation in Tripura has the potential to store a large amount of atmospheric carbon despite very low species diversity.

Subedi (2018) estimated the timber volume of Sal and selected model for total over bark stem volume as $\ln V = - 8.04674 + 2.26641 \ln \text{DBH}$ with R^2 of 0.92 and standard error of 0.18. Similarly, the selected models for over bark volume up to 10 and 20 cm top diameter have R^2 of 0.82 and 0.79 and standard errors of 0.35 and 0.42, respectively.

Paudel *et al.* (2020) developed carbon stock models based on DBH and total height. Regression model with natural logarithm of DBH^2 and total tree height (i.e. log transformed

polynomial equation) was best fitted for estimation of carbon stock per tree in different crown cover class with adjusted $R^2 > 0.99$.

Raj and Jhariya (2021) evaluated vegetation statistics along with carbon dynamics, sequestration, storage, mitigation, and carbon flux in Sal-dominated mixed tropical forests in Chhattisgarh, India, that used a compartment model approach. In different SQ, the density (individuals/ha) and basal area ($m^2 ha^{-1}$) ranged from 710 to 1010 and 33.5-46.8 in a tree, 2000-2500 and 0.32-0.33 in a sapling, and 9750-14500 and 17.96-21.43 in the seedling. In varying SQ, total biomass ranged from 182.27 to 375.84 $t ha^{-1}$. The total carbon content of trees ranged from 79.86 to 163.63 $t ha^{-1}$. The amount of carbon in the above ground and below ground sections of trees at various sites was 72.32-143.36 $t ha^{-1}$ and 7.54-20.27 $t ha^{-1}$, respectively. On various SQ, total aboveground tree C sequestration levels ranged from 5.12 to 11.68 $t C ha^{-1} yr^{-1}$. Different regression models based on carbon stock and net fluxes were generated to evaluate the different SQ. According to models, the forest produced 14.63, 10.81, 8.19, and 6.83 $t ha^{-1} yr^{-1}$ of C input through net primary production (NPP) in SQ-I, SQ-II, SQ-III, and SQ-IV, respectively, which is depleted as 3.55, 3.12, 2.77, and 2.33 $t/ha/yr$. as total C input in the soil. Furthermore, 1.77 (SQ-I), 1.60 (SQ-II), 1.46 (SQ-III), and 1.30 (SQ-IV) $t ha^{-1} yr^{-1}$ of C were transferred from the foliage to the litter compartment.

2.3 PHYSICO-CHEMICAL CHARACTERISTICS AND FERTILITY INDICES OF SOIL

Primary production is generally influenced by the availability of nutrients which in turn depends on the amount of organic matter present in the soil, and its rate of decomposition and mineralization.

Paudel and Sah (2003) studied the physicochemical properties of soils of two different types of forests (pure *Shorea robusta* and mixed *Shorea robusta*) in tropical sal (*Shorea robusta* Gaertn.) forests in eastern Nepal. Soil samples were collected from both types of forest and analyzed for texture, pH, organic matter, humus content, water holding capacity, nitrogen, phosphorous and potassium. In both the pure and mixed forest, soil was sandy loam (60.12 per cent and 50.58 per cent sand, 28.59 per cent and 35.24 per cent silt and 11.12 and 22.41 per cent clay, respectively). The pH value was lower in pure forest (4.33) than in the mixed forest (5.26), and so were phosphorus and water holding capacity. The higher values of humus carbon, organic matter, nitrogen and potassium (7.34 per cent, 2.42 per cent, 0.117 per cent, 267.73 $kg ha^{-1}$, respectively) were found in pure forest. The higher levels of soil

nutrients in the pure forest were due partly to reduction in the loss of top soil and partly to the increased supply of nutrients in the form of leaf litter and biomass from the larger number of sal trees and their saplings.

Hoque *et al.* (2008) analyzed the seasonal variation of edaphic features and available nutrients in soils of Madhupur Sal Forest in Bangladesh. The percentage of soil moisture content was found to vary from one stand to another in different seasons. The overall mean moisture content was 5.26 per cent to 7.78 per cent in top soil layer and subsoil layer (January-February). Moisture content was 10.94 per cent and 10.83 per cent, 23.82 per cent and 22.11 per cent in March- April and 20.87 per cent and 20.60 per cent in May-June, respectively. In the months of November- December, soil moisture came down to 10.49 per cent in top soil layer and 11.61 per cent in subsoil layer. Seasonal variation of pH was observed in different stands ranged from 4.60 to 6.28. Seasonal fluctuation of the electrical conductivity of soil was observed in different seasons. Highest value (207.90 micromhos cm^{-1} : May-June) and lowest value (34.65 micromhos cm^{-1} : September-October), (40.04 micromhos/cm: November and December). An increasing trend of sodium accumulation was found in both top and sub-soil layers at all the stands. The concentration of potassium also showed a decreasing tendency in both layers. It was a common phenomenon to all the stands condition that the percentage of organic matter content was higher in top soil layer than sub soil layer. In the months of March-April (dry season), the average mean value of organic matter was 1.71 per cent in top soil and 1.36 per cent in sub soil layer in March-April. In the months of September-October (wet season), the average mean value of organic matter content was 1.94 per cent in top soil and 1.51 per cent in sub soil layer. As a whole, the organic matter content was highest in wet season and was lowest in dry season. The variation of CEC in soils was found to range between 7.60 to 14.00 me/100 g. CEC was a bit higher in top soil than sub soil layer. Bad soil aeration and inadequate moisture are chiefly responsible for unsatisfactory regeneration and dying back of sal seedlings was reported.

Kunwar *et al.* (2008) analyzed soil characteristics of *Shorea robusta* and *Castanopsis hystrix* forests and slash and burn habitats of Arun Valley, Eastern Nepal. Sandy loam soil texture was common in *Castanopsis hystrix* forests while loam-sandy loam was observed in *Shorea robusta* forests. Concentration of Nitrogen (0.281 -0.438 %) was high in slash and burn site whereas the value (0.112–0.127 %) was lower in *Shorea robusta* forest site. Soil was slightly acidic (pH 5.78 ± 1.28) and fertile (OM 11.67 ± 7.42) in all the sites. The soil texture was sandy loam (sand, silt and clay, 49-61 per cent, 27-37 per cent and 6-19 per cent, respectively). The percentage of

sand and silt increases at higher altitude sites. Concentration of all chemical components of soil decreased with increase in altitude excepting that of Phosphorus, which showed the significant reverse trend. Concentration of Nitrogen (0.281-0.438 %) was high in SB site where as low in SR site (0.112–0.127 %). Similarly, the concentration of Phosphorus (97.62–225.00) kg ha⁻¹ was high in SR site and low (61.51–70.36) kg ha⁻¹ in CH site. The CH site was richer in bearing the concentration of Potassium (352.80–471.75) kg ha⁻¹.

Sheikh and Kumar (2010) compared the soils of two forest types i.e., oak (*Quercus leucotrichophora* A. Camus) and pine (*Pinus roxburghii* Sargent) for physico-chemical properties. The collected soil samples from both the forests were analysed for texture, water holding capacity, pH, potassium, phosphorus and nitrogen. The results showed that the higher percent of moisture and water holding capacity was in oak forest and lower in pine forest. The forest types indicated that the soil of oak forest was acidic and slightly acidic to pine forest. The average SOC in oak forest was 2.19 per cent followed by 1.63 per cent in pine. The nitrogen for oak and pine forests was 0.15 and 0.19 per cent, respectively. The available phosphorus in oak forest was higher (17.99 kg ha⁻¹) than in pine forest (16.88 kg ha⁻¹). The exchangeable potassium was 188.92 kg ha⁻¹ in oak forest and 166.43 kg ha⁻¹ in pine forest. The total nutrients generated by soils, as an ecosystem service in oak and pine forests were calculated for market costs. The maximum contribution among the nutrients was of potassium followed by phosphorus and nitrogen in both the forests.

Joshi and Pant (2014) analyzed the physico-chemical properties of soils in Tarai region of Kumaun Himalaya near Kashipur (Uttarakhand) in 2 sites viz: Site I (Jurkha Forest) is mixed deciduous and plantation forest of *Eucalyptus hybrid* L. Herit., *Tectona grandis* L.f. and Site II, (Gulzarpur Forest) is mixed deciduous forest of *Acacia catechu* Willd., *Bombax ceiba* L., *Butea monosperma* (Lamk). Thub., *Dalbergia sisso* Roxb., *Ficus racemosa* L., *Mallotus philippenensis* Muell. Arg., soil texture varied from silty clay loam to sandy loam. The average moisture contents in soil in site I was 14.29 per cent. In site II, the average moisture contents in soil were 16.09 per cent at site II. In site I, average water holding capacity was 36.27 per cent and in site II, it was 33.73 per cent. The average value of soil pH ranged from 6.97±0.45 in site I and site II, respectively. Soil organic carbon under two sites: in site I, the average amount of organic carbon was 0.36 per cent. In site II, it was 0.48 per cent. The average value of total nitrogen was 0.00308 per cent, and 0.00475 per cent in site II. In site I, the average value of available potassium was 89.36 kg ha⁻¹ and in site II, the average value was 96.89 kg ha⁻¹. Average value of available phosphorus was 5.38 kg ha⁻¹ in

site I however, in site II; it was 4.88 kg ha⁻¹. In site I, the average value of available potassium was 89.36 kg ha⁻¹ and the average value was 96.89 kg ha⁻¹ in site II.

Mandal and Joshi (2014) studied the soil conditions and change in community composition of these forests with *Shorea robusta* as the main dominant species in the dry deciduous forests (Asarori, Jhajra and Selaqui forests) of Doon Valley. The percentage of sand ranged between 55.44 per cent and 69.87 per cent; silt between 10.12 per cent and 26.11 per cent ; and clay between 18.45 per cent and 20.01 per cent . Bulk density ranged between 1.25 g cm⁻³ and 1.43 g cm⁻³, and it was comparatively higher in Asarori forest. Soil porosity ranged between 42.97 per cent and 44.22 per cent, and the higher values were observed in Jhajra and Selaqui forests. Soil moisture content was also comparatively higher in the Jhajra and Selaqui forests, and the overall range was between 12.03 per cent and 15.04 per cent in all sites. The pH of the soil was found to be acidic in all sites, ranging between 5.69 and 6.21. The carbon content ranged between 1.67 per cent and 1.87 per cent, the nitrogen content ranged between 0.12 per cent and 0.13 per cent, the available phosphorus ranged between 22.98 ppm and 24.7 ppm, and the C/N ratio ranged between 12.85 and 14.92.

Bhattarai and Mandal (2016) studied the physico-chemical properties of forest soil and reported the variation in altitude, vegetation cover and microbial activities in Tarai Sal Forest (TSF) and Hill Sal Forest (HSF), of eastern Nepal. Both forests had sandy loam type of soil texture. Soil moisture was higher in TSF. It was maximum in the rainy season in both forests. Water holding capacity was slightly higher in TSF. Bulk density was higher in TSF and it increased with soil depth in both forests. The pH value was slightly higher in HSF than TSF however, the value increased in lower soil depth in both forest stands. In the upper soil layer (0-15 cm), soil organic carbon (SOC) was higher in HSF (2.09 per cent) than TSF (1.6 per cent). Similarly, total nitrogen (TN) was also higher in HSF (0.173 per cent) than in TSF (0.129 per cent) while total phosphorus (TP) was more or less same in both forest stands. Potassium (K) a soil extractable nutrient also showed higher value in HSF (312.13 µg g⁻¹) than TSF (238.47 µg g⁻¹). The values of SOC, TN, TP and K decreased in lower depth (15-30cm) in both forest stands.

Singh *et al.* (2019) estimated the physico-chemical properties of Sal (*Shorea robusta*) forests in foothills of Garhwal Himalaya, Uttarakhand, India. Different sites viz. Khalanga, Vikasnagar, Raiwala, Byasi and Dugadda were selected in Tehri Garhwal, Pauri Garhwal and Dehradun districts of Uttarakhand. Soil physicochemical characteristics revealed that sites

were highly supplemented by soil nutrients. The maximum soil organic matter (3.65 per cent), soil moisture (10.92 per cent) and available nitrogen ($139.23 \text{ kg ha}^{-1}$) were observed in Khalanga site, whereas maximum available phosphorus ($115.51 \text{ kg ha}^{-1}$), pH (5.6) and electrical conductivity (0.12 dSm^{-1}) were recorded in Vikasnagar site. The minimum organic matter (1.59 per cent), soil moisture (7.45 per cent), soil organic carbon (0.92 per cent), available electrical conductivity (0.09 dSm^{-1}), available nitrogen (87.1 kg ha^{-1}), available phosphorus ($101.31 \text{ kg ha}^{-1}$) was found in Dugadda site whereas, minimum pH (5.3) was observed in Byasi site.

The Physico-chemical studies of soil in the Sal Forest of the Hazaribag district, Jharkhand, India, were conducted by Kumara *et al.* (2021). The soil pH was slightly acidic which was found to be in the range of 6.05-6.40. The moisture content, water-holding capacity, organic carbon, organic matter, and total nitrogen of soil samples were determined to be between 7.20 per cent and 13.20 per cent, 55.90 per cent and 77.70 per cent, 1.32 per cent and 2.40 per cent, 2.65 per cent and 4.05 per cent, and 0.17 per cent and 0.34 correspondingly. P, Na, K in mg/L was found to be in the range of 0.54 mg/L-0.92 mg/L, 2.5 mg/L-5.3 mg/L, 8.7 mg/L-15.14 mg/L and Ca in meq/100 g was found to be 6.3 meq/100 g-7.4 meq/100 g, respectively.

Kongkham *et al.* (2021) investigated soil physico-chemical properties in four different sites, viz., Shuduwala, Manduwala, Bhawala, and Tilwari of Shivalik foothills Dehradun Forest Region of Uttarakhand. Soil bulk density ranged from 1.23 g/cm^3 to 1.50 g/cm^3 at various sites. Bhawala sites had the highest bulk density recorded. Soil moisture ranged from 9.71 per cent to 13.70 per cent at 0-15 cm and from 3.90 per cent to 17.56 per cent at 16-30 cm. The pH of various sites ranged from 5.40 to 6.18. Soil organic carbon (%) ranged from 0.75 to 2.06. The higher value of soil available Nitrogen at various sites ranged from 204.77 to 291.45. The values of Phosphorus recorded in all the sites were between 14.55 to 34.92.

Poudel and Devkota (2021) evaluated the soil physico-chemical properties of community-managed *Shorea robusta* (Sal) forests in Tanahun district, Gandaki Province, Nepal. The soil of both forests was acidic in nature. The mean soil pH of the MCF forest was 5.22, while that of LCF was 5.02. The mean soil nitrogen (N) content in MCF forest was 0.19 per cent whereas; in LCF forest was 0.16 per cent. The average organic carbon (OC) content in the soil of the LCF forests was 2.89 compared to 3.46 in the MCF forest. The

average available phosphorus and potassium in the soil of LCF forest were 71.0 and 67.5, respectively. Similarly, the average available phosphorus and potassium in the soil of MCF forest were 113.64 and 80.5, respectively.

Kumara and Kumar (2022) studied the physic-chemical characterization of soil on the growth of selected Sal forest in Hazaribag, Chatra, Koderma, and Ranchi districts of Jharkhand in India. Ten samples each were collected from Hazaribag, Chatra, Koderma, and Ranchi Sal forests of Jharkhand for the study of soil properties. The soil samples were collected from eight different quadrates in order to determine soil quality index viz., soil texture, MC, WHC, OC, OM, pH, N, P, Na, K, and Ca. The soil pH was found to be slightly acidic having a range of 5.40–5.99. Moisture content, water-holding capacity, organic carbon, organic matter and available nitrogen of soil samples were found to be in the range of 3.70–11.30 per cent , 35.27–57.59 per cent , 0.46–0.97 per cent , 1.36–3.54 per cent , 207–314 kg ha⁻¹, respectively. P, Na, K was found to be in the range of 2.96-7.19 kg ha⁻¹, 2.73-5.34, 154.56- 471.38 kg ha⁻¹ and Ca in mg kg⁻¹ was found to be 1712- 3144, respectively.

Chapter-3

MATERIALS AND METHODS

The present investigations entitled “**Inter compartmental variations in floristic composition, biomass productivity and soil physico-chemical characteristics of Sal forest in Himachal Pradesh**” were conducted during the year 2019-2021. Field investigation was conducted in different compartments selected/approved under Experimental Silvicultural Green Felling in the Paonta Forest Range of the Paonta Forest Division in Himachal Pradesh. Laboratory research was conducted at the Department of Silviculture and Agroforestry, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.). This chapter provides details of experimental sites, materials utilized and procedures employed during the research period. The sampling designs, data collecting techniques and analytic methods used in these investigations are provided in this chapter, which assisted in drawing the following conclusions discussed as below:

3.1 SITE DESCRIPTION

After reviewing the literature from the Paonta Forest Division's working plan, seven compartments were selected/approved under “Experimental Silvicultural Green Felling” under Sal working circle in the Paonta Forest Range. The detail of compartments under study are given below:

Description of the compartments under study:

1. **Rajban C₆**: This compartment is situated above Chaudi cultivation to the North West of Paonta road and South of Choudi Khali. It has an undulating, slightly flat to hilly terrain with a southern aspect. The soil texture is clayey to clayey loam with adequate drainage.
2. **Rajban C₇**: This compartment is situated between Rajban Khali and Dhangwali Khali to the south of the newly blazed block line. The topography is relatively flat to hilly with a southern aspect. The compartment has clayey loam type of soil texture.
3. **Rajban C₁₀**: This compartment is situated in between Baggar Khala and Haaldu Khala and to the south of the block line. It has a gentle to moderate slope with a southern aspect. The soil texture is clayey loam with good drainage.

4. **Kukron C₁₄**: This compartment is situated in between compartment 13 and below the sub-compartment cut line. It is a hilly area with a gentle main land slope near khalas and a southern aspect. The soil texture is clayey loam to sandy loam.
5. **Kukron C₁₅**: This compartment is situated along Jammu khala and below block line. It is a hilly tract with a gentle main land slope near Khalas. The topography is undulating, relatively flat to hilly with a southern aspect. The soil texture is clayey loam.
6. **Gorakhpur C₇**: The slope is a flat plain with a southern aspect. The soil texture is clayey loam.
7. **Lai C₂₈**: This compartment is situated south of Mehrar-Rajban road and west of Khara Ka Khala and East of Satiwala Khala. It has gentle slope with Southern aspect. The soil texture is loam to clayey loam.

Table 1 Details of compartments under sal working circle of Paonta Forest Division, Himachal Pradesh.

Forest class	Forest type	Compartments		Site quality	Silviculture system
Reserve Forest (RF)	3C/C2b(i) : Moist Bhabhar Sal-Bhabhar-Dun Sal Forest	R18 C ₁	Rajban C ₆	II	Sal Conversion Working Circle, PB I with Sal overlapping.
		R18 C ₂	Rajban C ₇	II	Sal Conversion Working Circle, PB I with Sal overlapping.
		R18 C ₃	Rajban C ₁₀	III	Sal Conversion Working Circle, PB I with Sal overlapping.
		R23 C ₄	Kukron C ₁₄	II	Sal Conversion Working Circle, PB I with Sal overlapping.
		R23 C ₅	Kukron C ₁₅	II	Sal Conversion Working Circle, PB I with Sal overlapping.
		R19 C ₆	Gorakhpur C ₇	II	Sal Conversion Working Circle, PB I with Sal overlapping.
		R25 C ₇	Lai C ₂₈	III	Sal Conversion Working Circle, PB I with Sal overlapping.

(Working Plan Paonta Forest Division, 2019-20)

The scientific forest management of Forests in Paonta Division started in 1895 with Chintamani Joshi/R. Bhattacharya Working Plan (1895-1915). This Working Plan did not provide any silviculture system but only standardized the extraction of tress and some control regarding the felling. The period of Working Plan was for 20 years. In Vineet Working Plan (1998-99 to 2012-13), the Sal Working Circle generally covered all the Sal forest of the area.

The main criteria for allotment to this was the presumption that Sal regeneration can be obtained there. The poor sal forest which was allotted in Chauhan's Working Plan under Protection cum Afforestation Working Circle were also included in Sal Working Circle. The density and quality of Sal crop varied from site to site. This was due to biotic pressure on each forest. The result indicated that Sal constituted 69 per cent by number and 84 per cent by volume. Sain came next as 4 per cent and 8 per cent, respectively. The site quality varied II and III according to compartments. The density varied from 0.3 to 0.9 with an average of 0.7 (Table 2).

Natural regeneration was also very poor due to poor viability of Seed. The Sal forest were bifurcated into two Categories:

Type A: It included Sal Forest having predominant mature sal trees. Coppice regeneration was deficient. Such forest have been specially mentioned as Type A.

Type B: It included the area where regeneration is mainly from coppice. It was supplemented by artificial planting. All the areas not categorised type A were presumed as Type B.

Table 2 Working Plan for the entire management period of Paonta Forest Division

Sr. No.	Working Plan	Period
1	Chintamani Joshi / R. Bhattacharya Working Plan	1895 - 1915
2	The Period without working Plan	1916-1932
3	Sewal's Working plan	1933-34 to 1952-53
4	Sharma and Tikku's Working Plan	1953-54 to 1962-63
5	Period without working Plan	1963-68
6	Arya's Working Plan	1968-69 to 1977-78
7	Period without working Plan	1978-82
8	Chauhan's Working Plan	1982-83 to 1991-92
9	Period without working Plan	1992-98
10	Vineet Working Plan	1998-99 to 2012-13

However, green felling has been banned vide orders of the Hon'ble Supreme Court of India dated 12th December 1996 and February 2000 and reinitiated on experimental basis in the selected forest compartments vide the Hon'ble Supreme court order of 2018 through which area of 76.01 ha. for the year 2018-2019 and area of 120.12 ha. for the year of 2019-2020 has been earmarked for silvicultural felling of Sal. Therefore, seven compartments viz.,

Rajban C₆, Rajban C₇, Rajban C₁₀, Gorakhpur C₇, Kukron C₁₄, Kukron C₁₅ and Lai C₂₈ in Sal Working Circle of Paonta Forest Division of Himachal Pradesh, India were selected for the Working Plan, which is extended working plan for the period 2018-19 to 2019-20. One felling series have been formed with rotation period of 120 years with regeneration period of 30 years under irregular shelterwood system keeping in view the rate of growth and market favourable size, the exploitable diameter was fixed as 40 cm DBH has been proposed. The detailed description of each compartment is tabulated in Table 1 and 3.

Table 3 Proposed felling sequence in different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh.

Felling in PB I			
Year of felling	Compartment No. in which Silvicultural felling proposed	Area of Forest (area in ha)	Type of felling
2018-19	R-18 Rajban (Comptt. 6)	30.96	Seeding felling
	R-18 Rajban (Comptt. 7)	19.87	Seeding felling
	R-18 Rajban (Comptt. 10)	30.18	Seeding felling
	R23 Kukron (Comptt. 14)	45.00	Seeding felling
	Total area for Silvicultural Felling (126.01 ha)		
2019-20	R-25 Lai (Comptt. 28)	22.56	Seeding felling
	R-23 Kukron (Comptt. 15)	70.12	Seeding felling
	Total area for Silvicultural Felling (92.68 ha)		
Felling in PB IV			
Year of felling	Compartment No. in which Silvicultural felling proposed	Area of Forest (area in ha)	Type of felling
2018-19	R-19 Gorakhpur(Comptt. 7)	50.00	Final felling
2019-20	R-19 Gorakhpur (Comptt. 7)	50.00	Final felling
	Total area for Silvicultural Felling (100 ha)		

3.1 STUDY AREA

3.1.1 Location

The research was conducted in the Paonta Forest Division of the Sirmour district of Himachal Pradesh. The area is located between 30° 22' 37" and 30° 41' 36" North latitude and 77° 7' 19" and 77° 49' 48" East latitude at elevations ranging from 300 to 400 m above mean sea level. In the north, the area is surrounded by the Nahan and Renuka ji Forest Divisions. Uttarakhand's Dehradun and Chakrata Forest Divisions confine the east. The south is bounded by the Haryana district of Yamuna Nagar, while the west is surrounded by the Haryana district of Ambala. Most of the tract is plain. The slope is generally gentle to moderate. The valley is thickly populated and supports one of the best Sal forests of the outer

Himalayas. The three well defined ranges running almost parallel form the most striking geographical feature of the area, they are the “Shiwalik hills “and the “Kamraoo-Bharli Dhar” and the “Dharti dhar”.

3.1.2 Geology, Rock and Soil

It is divided broadly into two distinct formations:

- a) Sub Himalayan formation
- b) Himalayan formation.
- b) Himalayan Formation**

This consist of Shiwalik Hills

i) Shiwalik Hills:

The major part of division is Shiwalik formation and is the outer most part of Himalayas adjoining the plains.

It is formed of alternating bed of hard clay, sand stone, conglomerate and sand. These alternating titled bands can be seen at many places in vertical section of the hills formed by denudation and sliding landmasses. Soil is poor in humus, shallow and inter bedded with boulders. Naked vertical edged hillocks are the common sight in this tract. Good quality sal forests are found from Dhaula Kuan to Behral on the Northern aspect towards Gorakhpur, Rajban Malgi in Paonta Sahib.

3.1.3 Climatic parameters

The climate is mainly Sub tropical. All the seasons are well marked i.e., summer, monsoon and winter season. The months of May & June are extremely hot. Temperature rises up to 45⁰ C. Monsoon starts from last week of June and continues up to mid September. Sometime pre monsoon occurs in the month of May-June also. Most of the rains received during monsoon. Average rainfall varies from 1270 mm to 1900 mm. During winters, rain are received in the last week of December. In the valley, the frost is of common occurrence but damage is not high. The tender Seedlings in nursery need special attention during winter season.

3.1.4 Vegetation

The dominant species found in the compartments under study was *Shorea robusta*. Other associated species were *Terminalia tomentosa*, *Mallotus philippenensis*, *Cordia dictoma*, *Bauhinia variegata*, *Syzygium cuminii*, *Acacia catechu*, *Callicarpa macrophylla*, *Ficus palmate* and *Cassia fistula*. While, there is a heavy undergrowth of *Ardisia solanacea*, *Lantana camara*, *Murraya koenigii*, *Carissa carandas*, *Clerodendron infortunatum* and *Phyllodium longipes*. The forest types found in the division are as: 3C/C2a Moist Shiwalik Sal Forests, 3C/C2b(i) Moist Bhabar Sal-Bhabhar-Dun Sal Forest, 5b/C1a Dry Shiwalik Sal Forests and 5b/C2 Northern Dry Mixed Deciduous Forests.

Experiment I: Assessment of inter compartmental variation in floristic composition under Sal forest.

Treatments (7 compartments)

- T₁ - Rajban C₆
- T₂ - Rajban C₇
- T₃ - Gorakhpur C₇
- T₄ - Rajban C₁₀
- T₅ - Kukron C₁₄
- T₆ - Kukron C₁₅
- T₇ - Lai C₂₈

Sample plot size

Trees	:	31.62m × 31.62m
Shrubs	:	5m×5m
Herbs	:	1m×1m
Regeneration	:	2m×2m
Replications	:	4
Design	:	One-way ANOVA

Experiment II: Assessment of stand characteristics, biomass, carbon density and site quality of different compartments of Sal forest.

Experiment III: Studies on natural regeneration status through seeds and coppice shoots under different compartments of Sal forest.

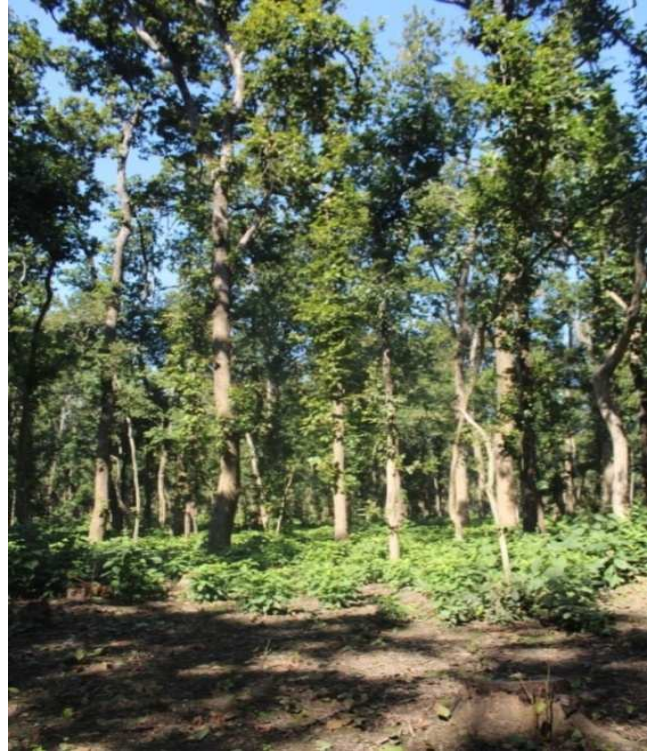


Plate 1: *Shorea robusta* Forest (3C/C2b (i): Moist Bhabhar Sal- Bhabhar- Dun Sal Forest)

Experiment IV: Estimation of physico-chemical characteristics under different compartments of Sal forest.

Treatments (7 compartments)

- T₁ - Rajban C₆
- T₂ - Rajban C₇
- T₃ - Gorakhpur C₇
- T₄ - Rajban C₁₀
- T₅ - Kukron C₁₄
- T₆ - Kukron C₁₅
- T₇ - Lai C₂₈

Sample plot size:

- Trees : 31.62m × 31.62m
- Shrubs : 5m×5m
- Herbs : 1m×1m

Soil Depths

- L₁ : 0 to 20 cm
- L₂ : 21 to 40 cm

Treatment combinations : 14 [7(compartments) ×2 (soil layers)]

Replications : 4

Design : Two-way ANOVA

Soil analysis (Soil physical and chemical analysis)

- Humus depth (cm)
- Bulk density (g/cc)
- Organic carbon (%)
- EC
- pH
- Available nitrogen (kg ha⁻¹)
- Available phosphorous (kg ha⁻¹)
- Available potassium (kg ha⁻¹)
- Soil depth

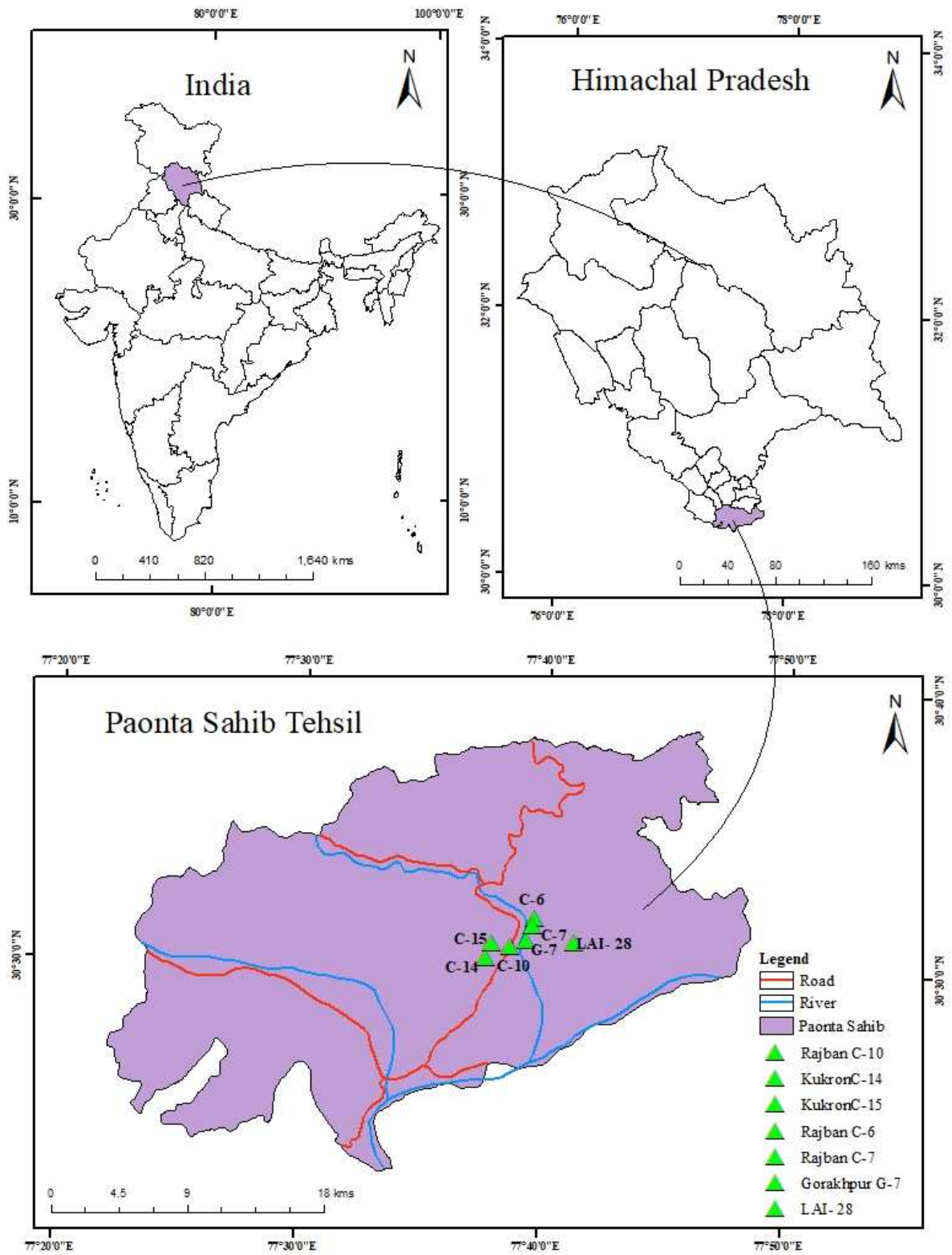


Fig. 1 Map of the study area

3.2 EXPERIMENTAL METHODOLOGY

3.2.1 Vegetation analysis

Tree

Four tree sample plots of 0.1 ha ($31.62 \times 31.62 \text{ m}^2$) (Fig. 2) were selected in each experimental compartment of the forest division under experimental felling for analyzing structural and functional parameters of tree vegetation. Density of trees was calculated by counting trees in each sample plot. Basal area of each tree in the sample plot was determined by tree caliper and height was measured by Spiegel Relaskop. Volume of standing trees was calculated by Pressler's formula (1865).

Shrubs

The shrub characteristics were studied by laying out sub-plots of size 5 m x 5 m in each sample plot (Fig. 2). 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., a) large b) medium and c) small; based on size and number of stems in each of them. In each category, numbers of plants were counted. Basal area of stem was determined by vernier calliper.

Herbs

Herbaceous vegetation in different compartments were studied at its peak growth in the month of September by harvesting quadrates of size 1 m x 1 m within each sample plot (Fig. 2). The vegetation from each quadrate was segregated species wise and identified. The help of herbarium in the university, experts, journals and research books was taken to identify them. The numbers of tillers in each herb species were counted to find out their density. Collar diameter of bundle of tillers of each herb species was measured to determine basal area of each species. Frequency of a species was determined by its presence in different quadrates sampled.

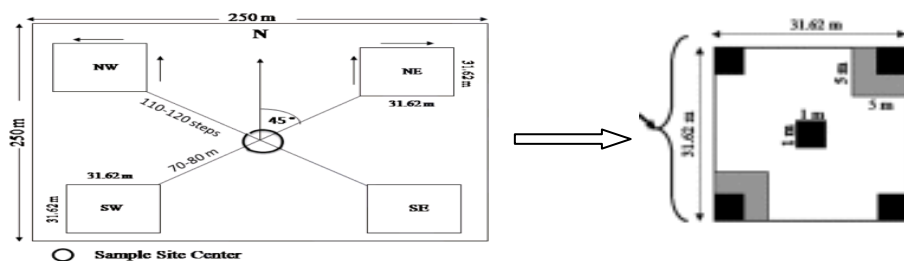


Fig. 2 Cluster sample plot design (2-stage sampling) for enumerating trees, shrubs and herbs sampling.

3.3.2 Density (N ha⁻¹)

It measured the total number of individuals per unit area and calculated as:

$$\text{Density (D)} = \frac{\text{Total number of individual}}{\text{Total number of quadrates studied}}$$

3.3.3 Basal area (cm²)

It measures the cross-section area of the stem and it is obtained by the following relationship with diameter/girth.

Where;

$$\text{Basal Area} = \frac{D^2}{4}$$

D = Diameter at breast height (1.37m)

3.3.4 Frequency (%)

It measures the degree of occurrence of a species in sampling units, thus it expresses the distribution of various species in the community.

$$\text{Percent frequency (\%)} = \frac{\text{Number of sampling units in which the species occurs}}{\text{Number of sampling units studied}} \times 100$$

3.3.5 Relative density, relative basal area and relative frequency

These parameters were obtained from per cent frequency, density and basal area by using the following relationship:

$$\text{Relative density (RD)} = \frac{\text{Number of individuals of the species}}{\text{Total number of individuals of all species}} \times 100$$

$$\text{Relative basal area (RBA)} = \frac{\text{Total basal area of individual species}}{\text{Total basal area of all species}} \times 100$$

$$\text{Relative frequency (RF)} = \frac{\text{Number of occurrence of individual species}}{\text{Number of occurrence of all species}} \times 100$$

3.3.6 Importance value index (IVI)

IVI is the sum total of relative density, relative basal area and relative frequency and was calculated for all herbs, shrubs and tree species separately at each study sites.

IVI = Relative basal area (RBA) + Relative density (RD) + Relative frequency (RF).

3.4 VEGETATION INDICES

Community diversity was assessed using non-parametric measures such as diversity indices, and these measures have gradually gained credibility (Magurran, 1988). Simpson diversity index (Simpson, 1949), Simpson concentration of dominance (Simpson, 1949), Margalef index of species richness (Margalef, 1958), the Importance Value Index (IVI) (Phillips, 1959), Shannon–Wiener diversity index (Shannon and Weaver, 1963), Pielou equitability (Pielou, 1966) and species richness index of Menheink (Whittaker, 1977), were computed for each particular forest type with the below mentioned formulae:

1. Shannon-Wiener Index of diversity (H') = $-\sum p_i \ln p_i$
2. Simpson's concentration of dominance index (C_d) = $\sum p_i^2$
3. Simpson's diversity index (D) = $1/C_d$
4. Margalef's Index of richness (MI) = $(S-1)/\ln N$
5. Pielou equitability (E_p) = $\frac{H'}{H'_{max}} = \frac{H'}{\ln S}$
6. Menheink index of species richness (MeI) = $\frac{S}{\sqrt{N}}$

3.5 BIOMASS ESTIMATION

3.5.1.1 Stem biomass ($Mg\ ha^{-1}$)

a) Diameter at breast height

The stem diameter over bark was measured (mean of two right angle measurements) at 1.37 m above ground level with the help of tree calliper according to method given by Chaturvedi and Khanna (1982).

b) Tree height

The height from base to tip of the trees was measured with the help of Spiegel Relaskop and expressed in meters according to method given by Chaturvedi and Khanna (1982).

c) Form factor

The form factor was calculated using the formula given by Pressler (1865) and Bitterlich (1984).

$$ff = \frac{2h_1}{3h}$$

Where;

- ff - Form factor
- h₁ - Height at which diameter is half of dbh, measured by Spiegel Relaskop.
- h - Total height of the tree measured by Spiegel Relaskop

d) Volume of standing trees

Volume of standing trees was calculated by Pressler's formula (1865) and expressed in cubic meters.

$$V = ff \times h \times g$$

Where;

- V - Volume
- Ff - Form factor
- h - Total height
- g - Basal area

e) Specific gravity

Specific gravity was determined from the available literature (Appendix-I). Where, the specific gravity values were not available in those case the stem cores were taken to find out specific gravity which was used further to determine the biomass of the stem using maximum moisture method (Smith, 1954). The wood in the form of disc (5-8 cm) was removed from two places (base and breast height) for the determination of specific gravity of wood. The weight of samples was taken at maximum moisture content. Then these samples were kept in oven at 102±1°C until a constant weight was obtained, dried samples were weighed and specific gravity of these samples was determined separately by applying the following formula:

$$G_f = \left[\frac{1}{\frac{(M_m - M_o)}{M_o} + \frac{1}{GS_o}} \right]$$

Where;

- G_r - Specific gravity of wood
- M_m - Constant weight of sample having maximum moisture content
- M_o - Oven dried constant weight of sample
- GS_o - Average density of wood, a constant having value of 1.53

The final value was determined by taking out the average of these samples (base and breast height). The final value was determined by taking out the average of these samples (Lower and upper).

Thus, the weight of wood (biomass) was estimated using the formula i.e. mass per unit volume

Stem Biomass = Average specific gravity of stem wood \times volume.

3.5.1.2 Above ground tree biomass ($Mg\ ha^{-1}$)

The total tree biomass was calculated by multiplying the stem biomass with the biomass expansion factor of the species (Appendix II).

3.5.1.3 Below ground tree biomass ($Mg\ ha^{-1}$)

Below ground biomass of trees was calculated by using the equation developed by Cairns *et al.* (1997).

$$BGB\ t\ ha^{-1} = \exp \{-1.059 + 0.884 \times \ln (AGB) + 0.284\}$$

3.5.1.4 Total biomass ($Mg\ ha^{-1}$)

Tree biomass was calculated by adding above ground tree biomass and below ground biomass.

3.5.1.5 Carbon Estimation

Carbon = Biomass \times 0.5 (IPCC default value)

3.5.1.6 Carbon density ($Mg\ ha^{-1}$)

Carbon density = Carbon in Mg per hectare.

3.5.1.7 Ecosystem carbon density [soil+plant ($Mg\ C\ ha^{-1}$)]

Total carbon was calculated by adding carbon density and plant carbon.

3.5.1.8 Carbon stock

Carbon density was multiplied by area of the compartment.

3.5.2 Shrub biomass

Each shrub samples were collected for studying the phyto-sociology and were brought to laboratory. They were segregated into leaves, branches and stem portion, washed and oven dried at 70°C for 72 hours until the constant dry weight was obtained. Each sample was weighed to determine aboveground biomass (stem + branch + leaves) of each species. Belowground biomass estimations were 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 aboveground and belowground shrub biomass.

3.5.3 Herbaceous biomass

The different species in each quadrat were packed in paper bags separately. Whole plants were uprooted with their root systems. In laboratory, these plants were segregated into shoot and root portion. The shoot portion was packed in paper bag and oven dried. The roots of different species were then washed in running water using fine mesh, packed in paper bags, oven dried at 70°C for 72 hours until constant dry weight is attained and weighed to determine their dry weight. Total biomass was calculated by adding above ground and below ground herb biomass of each species.

3.6 REGENERATION STUDIES

Within each demarcated sample plot of 31.62×31.62 m, the regeneration survey was carried out in a plot of size 2×2 m by recording the number of seedlings (<0.5 m) and sapling (0.5-2 m) of tree species. The main object of regeneration survey is to assess whether or not there is adequate regeneration in the forest area. The adequacy of regeneration was judged on the basis of number of established plants in a unit area. According to Chacko (1965), the desired numbers of established plants are 2500 N ha⁻¹ and the quadrat is considered fully stocked when it contained one established plant. For a detailed assessment of the status of regeneration following observations were made for each quadrat.

Recruits, un-established, established and per cent regeneration

1. The total number of recruits (r): which may be defined as current year seedlings.
2. The number of un-established regeneration (u): seedling other than recruits which has not established by not reaching established height of 2 m and four un-established plants were considered equivalent to one established plant.
3. The number of established regeneration (e): seedlings above 2 m height.

The recruits, un-established and established regeneration were computed using formulae given by Chacko (1965) as:

$$\text{Recruits (r)/ha} = \frac{2500 \times \text{Total number of individuals}}{\text{Total number of quadrates studied}}$$

$$\text{Un-established regeneration (u)/ha} = \frac{2500 \times \text{total number of un-established plants in sampling units}}{\text{Total number of recording units}}$$

$$\text{Established regeneration (e)/ha} = \frac{2500 \times \text{total number of un-established plants in sampling units}}{\text{Total number of recording units}}$$

$$\text{Weighted average height (cm)} = \frac{\text{Total ht. of un-established regeneration} + (\text{Number of established plants} \times \text{establishment height})}{\text{Total number of recording units}}$$

Based on above estimates, following indices were calculated:

$$\text{Established Index (I}_1\text{)} = \frac{\text{Weighted average height}}{\text{Establishment height}}$$

$$\text{Stocking Index (I}_2\text{)} = \frac{1}{2500} \times \frac{\text{Weighted average height}}{\text{Establishment height}} + \text{Established regeneration}$$

$$\text{Regeneration success (\%)} = \text{Stocking Index (I}_2\text{)} \times 100$$

$$\text{Established stocking per cent} = 100 (\text{I}_1 \times \text{I}_2)$$

3.7 PHYSICO-CHEMICAL ANALYSIS

The composite soil samples were collected from different layers viz., 0-20 cm and 20-40 cm for studying the soil physical analysis and depth-wise distribution of nutrient elements from each site. The composite soil samples were dried, ground with mortar and pestles and sieved with 2 mm mesh sieve before analysis. Details of methodologies employed for estimating different soil physico-chemical parameters are given in Table 4 as below:

Table 4 Methods applied for soil physico-chemical analysis

Particular	Method employed
Soil pH	1:2.5 soil: water suspension, with the help of digital pH meter (Jackson, 1973).
EC	1:2.5 soil: water suspension, with the help of digital conductivity bridge (Jackson, 1973).
Bulk density (g cm^{-3})	Soil core sampler
Organic carbon (%)	Walkely and Black method (1934)
Soil carbon density (t ha^{-1})	[Soil bulk density (g cm^{-3}) x Soil depth (cm) x Carbon] x 100 (Nelson and Sommers, 1996).
Labile soil carbon (%)	Difference in oxidizable organic C extracted between 18 N and 12 N H_2SO_4 (18 N–12 N H_2SO_4)
Non labile soil carbon (%)	Difference in organic C extracted with 24 N H_2SO_4 and TOC determined by CHN analyzer (TOC–24 N H_2SO_4).
Available nitrogen (kg ha^{-1})	Alkaline potassium permanganate method of Subbiah and Asija (1956).
Available phosphorus (kg ha^{-1})	Olsen method (Olsen <i>et al.</i> 1954).
Available potassium (kg ha^{-1})	Merwin and Peech method (Merwin and Peech, 1951).
Zinc (ppm)	DTPA method
Copper (ppm)	
Iron (ppm)	
Sulphur (cmol/kg)	
Boron (cmol/kg)	

3.8 STATISTICAL ANALYSIS

Descriptive statistics, scattered plots and histograms were made directly from a spreadsheet in window excel 2007. Analysis of variance and correlation coefficients were assessed by using Statistical Package for Social Sciences (SPSS) version 16.0 software PAST and R programming language version 4.2.0 software . The least significant difference at 5 per cent level (<0.05) was used for testing the significant differences among treatments.

Analytical Framework

3.8.1 Criteria for the selection of appropriate function

A function is supposed to be an appropriate one if the sign and magnitude of the estimated parameters are consistent with the theory.

Adjusted R^2 (Gujrati, 1998) calculated as under

$$\bar{R}^2 = 1 - \left(\frac{(1-R^2)(n-1)}{n-k-1} \right)$$

Where;

R	=	Sample R-square
n	=	Number of observations
k	=	Number of parameter

Adjusted R^2 is an appropriate tool to decide the selection of fundamental form. Usually, the function with higher adjusted R^2 is selected for the purpose.

A function with more significant explanatory variables is considered a better function compared to other functions.

3.8.2 Regression analysis

Based on the adjusted R^2 values different regression equations *viz.* linear, logarithmic, exponential, growth, quadratic and power were further developed for stem volume, total biomass and carbon (dependent variable) with DBH, tree height and density (independent variable).

3.8.3 Principal Component Analysis

It is a multivariate statistical technique to reduce the data with large number of correlated variables in to a substantially smaller set of new variables. A principal component analysis is concerned with explaining the variance- covariance structure of a set of variables through a few linear combinations of these variables. Its general objectives are:

1. Data reduction
2. Interpretation

It does not require the assumption of multivariate normality. It deals with the internal structure of the variables involved. Its aim is to sacrifice some information contained in the original variables in order to keep as few variables as possible, but the lost information is kept as minimum as possible.

The aim of principal component analysis is to ascertain new variables, called principal components, which carry most of the information present in original variables. Principal components are generally estimated from either the correlation matrix (R) or sample variance-covariance matrix (S). When the variables are measured in different units, scale effect can influence the composition of the derived components. In order to overcome such situation it is desirable to standardize the variable. Also correlation matrix should be used. The first few principal components usually account for most of the variation of the original variables and the variation described by following principal components is relatively little, it is often useful to retain only those first few principal component and drop all subsequent components from the analysis. It is so because the variable they express is largely random and is of no use in the analysis. Several thumb rules have been proposed for the number of principal components of the correlation matrix with eigen roots less than one. The principal component's with the variance less than one contains less information.

Various steps involved in worked out of principal components can be summarized as below:

- i. First of all Keyse-meyer-olkin measure for sampling adequacy is computed. If the value of KMO comes out to be more than 0.5 only then we should go for principal component analysis.
- ii. After that find the eigen value of variance-covariance matrix of correlation matrix.
- iii. Arrange eigen values in decreasing order. Let these values in decreasing order be $\lambda_1, \lambda_2, \dots, \lambda_p$, and corresponding variability be V_1, V_2, \dots, V_p , Where V_p is variability for λ_p .
- iv. Starting from first principal component, go on adding the variance or first few principal components whose value is more than unity. The variability described by them is of greater use. Discard the remaining principal components.
- v. From the eigen vectors of chosen principal components variables which load the respective principal components are found.

The output desired for interpretation and grouping should include:

- i. Eigen value and percentage of total variation explained by each principal component.
- ii. The eigen vector for each principal component.
- iii. The principal component scores
- iv. The correlation between original Standardized variable and the corresponding principal component scores (occasionally called loading)

RESULTS AND DISCUSSION

The results emerging out of the present investigations entitled “**Inter compartmental variations in floristic composition, biomass productivity and soil physico-chemical characteristics of Sal forest in Himachal Pradesh**” were carried out in seven compartments of Sal Working Circle in Paonta Forest Division of Himachal Pradesh. These compartments were assessed for their variation in floristic composition, population dynamics, carbon storage potential and natural regeneration status. All these compartments are the parts of the felling series in which felling were done in the years of 2018-2020. The floristic composition, carbon storage, soil nutrient and regeneration status assessed in years of 2018-2020 have been described in this chapter under the following major heads and sub heads:

- 4.1 Floristic composition**
- 4.2 Phyto-sociological studies**
- 4.3 Diversity indices**
- 4.4 Species-wise distribution**
- 4.5 Stand structure**
- 4.6 Biomass and carbon stock**
- 4.7 Regeneration status**
- 4.8 Soil physico-chemical properties**
- 4.9 Regression equations**
- 4.10 Correlation studies**
- 4.11 Principal component analysis**

Experiment 1: Assessment of intercompartmental variation in floristic composition under Sal forest.

4.1 FLORISTIC COMPOSITION

4.1.1 Diversity of trees, shrubs and herbs

The flora of different compartments in Sal Working Circle of Paonta Forest Division constituted a total of 33 genera, 34 species belonging to 26 families (Table 5). In Rajban C₆, 6 species of trees, 10 shrubs and 10 herbs representing 6 genera of trees, 10 shrubs and 10

herbs and 6 families of trees, 9 shrubs and 6 herbs were recorded. Similarly, 6 tree species, 10 shrub species and 10 herb species identified in Rajban C₇ belonged to 6 tree families, 9 shrub families and 6 herb families, as well as, 6 tree genera, 10 shrub genera and 10 herb genera. In Kukron C₁₄, there were 6 tree species from 6 families and 6 genera, 9 shrub species from 9 genera and 8 families and 9 herb species from 9 genera and 4 families. 7 tree species represented 7 genera and 17 families, 11 shrub species represented 10 genera and 9 families, whereas, 8 herb species belonged to 8 genera and 5 families were identified in Rajban C₁₀. In addition, 7 species of trees belonged to 7 families and 7 genera. 11 species of shrubs belonging to 10 genera and 9 families and 8 species of herbs representing 8 genera and 4 families were recorded in Kukron C₁₅. In Gorakhpur C₇, 6 species were reported, representing 6 genera and 6 families, 10 species of shrubs from 8 families and 9 genera and 8 species of herbs from 8 families and 4 genera. Lai C₂₈ included 9 tree species from 8 families and 9 genera, 8 shrub species from 8 genera and seven families and 9 herb species from 9 genera and 6 families, respectively.

Table 5 Floral distribution of vegetation under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Vegetation form											
	Trees			Shrubs			Herbs			Total		
	Species	Genus	Family	Species	Genus	Family	Species	Genus	Family	(Species)	(Genus)	(Family)
Rajban C ₆	6	6	6	10	10	9	10	10	6	26	26	21
Rajban C ₇	6	6	6	10	10	9	10	10	6	26	26	21
Rajban C ₁₄	6	6	6	9	9	8	9	9	4	24	24	18
Kukron C ₁₀	7	7	7	11	10	9	8	8	5	26	25	21
Kukron C ₁₅	7	7	7	11	11	10	8	8	4	26	26	21
Gorakhpur C ₇	6	6	6	10	9	8	8	8	4	24	23	18
Lai C ₂₈	9	9	8	9	8	7	9	9	6	27	26	21

Among different compartments under the present study, only a slight variation can be noticed in respect of number of species, genera and family of trees, shrubs and herbs. The number of tree species were maximum under the compartment Lai C₂₈. However, in shrub layer the representation of species, genera and families, in general lower than other compartments under investigation.



Plate 2 : View of Sal forest vegetation

Table 6 Presence/absence of tree, shrub and herb species among different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Trees										
Sr. No.	Scientific name	Family	Rajban C ₆	Rajban C ₇	Lai C ₂₈	Kukron C ₁₅	Rajban C ₁₀	Gorakhpur C ₇	Kukron C ₁₄	Total
1	<i>Shorea robusta</i>	Depterocarpaceae	+	+	+	+	+	+	+	7
2	<i>Syzygium cuminii</i>	Myrtaceae	+	+	+	+	+	+	+	7
3	<i>Cordia dichotoma</i>	Boraginaceae	+	+	+	+	+	+	+	7
4	<i>Mallotus philippinensis</i>	Euphorbiaceae	+	+	+	+	+	+	+	7
5	<i>Cassia fistula</i>	Caesalpiniaceae	+	+	-	-	-	+	+	4
6	<i>Bauhinia variegata</i>	Caesalpiniaceae	-	-	+	-	-	-	-	1
7	<i>Acacia catechu</i>	Mimosaceae	-	-	+	-	-	-	-	1
8	<i>Terminalia tomentosa</i>	Combretaceae	+	+	+	+	+	+	+	7
9	<i>Eucalyptus globulus</i>	Myrtaceae	-	-	+	-	-	-	-	1
10	<i>Callicarpa macrophylla</i>	Verbenaceae	-	-	-	+	+	-	-	2
11	<i>Ficus palmata</i>	Moraceae	-	-	+	+	+	-	-	3
Total			6	6	9	7	7	6	6	
Shrubs										
Sr. No.	Scientific name	Family	Rajban C ₆	Rajban C ₇	Lai C ₂₈	Kukron C ₁₅	Rajban C ₁₀	Gorakhpur C ₇	Kukron C ₁₄	Total
1	<i>Adhatoda vasica</i>	Acanthaceae	+	+	+	+	+	+	+	7
2	<i>Ardisia solanacea</i>	Myrsinoideae	+	+	+	+	+	+	+	7
3	<i>Asparagus racemosus</i>	Liliaceae	+	+	+	+	+	+	+	6
4	<i>Baliospermum montanum</i>	Euphorbiaceae	+	+	-	+	+	-	+	5
5	<i>Carissa carandas</i>	Apocynaceae	+	+	+	+	+	+	+	7
6	<i>Clerodendron infortunatum</i>	Verbenaceae	+	+	+	+	+	+	+	7
7	<i>Lantana camara</i>	Verbenaceae	+	+	+	+	+	+	+	7
8	<i>Lonicera japonica</i>	Caprifoliaceae	+	+	-	-	-	-	-	2
9	<i>Murraya koenigii</i>	Rutaceae	+	+	+	+	+	+	+	7
10	<i>Phyllodium longipes</i>	Fabaceae	-	-	-	+	-	-	-	1
11	<i>Rubus ellipticus</i>	Rosaceae	-	-	-	+	+	+	-	3
12	<i>Solanum indicum</i>	Solanaceae	+	+	+	-	+	+	+	6
13	<i>Solanum virum</i>	Solanaceae	-	-	+	+	+	+	-	4
Total			10	10	9	11	11	10	9	
Herbs										
Sr. No.	Scientific name	Family	Rajban C ₆	Rajban C ₇	Lai C ₂₈	Kukron C ₁₅	Rajban C ₁₀	Gorakhpur C ₇	Kukron C ₁₄	Total
1	<i>Achranthus bidentata</i>	Amaranthaceae	+	+	+	+	+	+	+	7
2	<i>Ageratum conyzoides</i>	Asteraceae	+	+	+	+	+	+	+	7
3	<i>Apluda mutica</i>	Poaceae	+	+	+	+	+	-	+	6
4	<i>Bidens bipinnata</i>	Asteraceae	+	+	+	+	+	+	+	7
5	<i>Cynodon dactylon</i>	Poaceae	+	+	-	+	+	+	+	6
6	<i>Cyperus rotundus</i>	Cyperaceae	+	+	+	-	-	-	-	3
7	<i>Dicliptera paniculata</i>	Acanthaceae	+	+	+	-	+	+	+	6
8	<i>Digitaria sanguinalis</i>	Poaceae	+	+	+	+	-	+	+	6
9	<i>Parthenium hysterophorus</i>	Asteraceae	+	+	+	+	+	+	+	7
10	<i>Pogostemon benghalensis</i>	Lamiaceae	+	+	+	+	+	+	+	7
Total			10	10	9	8	8	8	9	

In nutshell, the total inter-compartmental variation in representation of trees shrubs and herbs was less. This can be owed to the fact that different compartments under investigations are located within the same forest range and thus limited micro-environment variation. Mishra *et al.* (1997) opined that species composition varies from site to site mostly due to micro environmental changes and pattern of distribution, depends both on physico-chemical nature of environment and biological peculiarities of the organisms themselves. The floristic composition of the trees, shrubs and herbs in the present study is lower than that reported by Divakara (2015) in sal forests of Jhankhand and Dutta and Devi (2013) in the Doboka reserve forest of Assam's tropical wet deciduous sal forest. It is evident from the Table 6 that most common tree associate of sal in all the compartments of Paonta Sahib forest range were *Syzygium cuminii*, *Cordia dichotoma* and *Mallotus philippinensis*, *Terminalia tomentosa*, while, *Bauhinia variegata* and *Acacia catechu* were present only in Lai C₂₈. In the understorey layer, the most common species of shrubs which showed their presence in all the compartments are- *A. vasica*, *A. solanacea*, *A. racemosus* *Carissa carandas*, *C. infortunatum*, *M. koenigii* and *L. camara* and *Rubus ellipticus* shown its presence in compartments of Kukron C₁₅, Rajban C₁₀, Gorakhpur C₇, only. While, *P. longipes* was present in Kukron C₁₅. In the herbs layer, the of species of *Achranthus bidentata*, *Ageratum conyzoides*, *Bidens bipinnata*, *Cyperus rotundus*, *Parthenium hysterophorus* and *Pogostemon benghalensis* were present in all the compartments being investigated. While, *Cyperus rotundus* showed its presence in only in Rajban C₆, Rajban C₇ and Lai C₂₈. Thus based on floristic composition of the trees, shrubs and herbs we can infer that most of the species are common among all the compartments of the present investigation.

4.2 Phyto-sociological studies

Phyto-sociological parameters of trees, shrubs and herbs pertaining to different compartments are presented in Table 7. *Shorea robusta* was the dominant species in Rajban C₆, with the highest relative density (47.57 %) and IVI (152.50), followed by *Terminalia tomentosa* (11.65 %, 37.64), *Cordia dictoma* (12.62 %, 35.75), *Mallotus philippensis* (13.59 %, 30.55) and *Syzygium cuminii* (12.62 %, 33.55), respectively. *Cassia fistula*, on the other hand, exhibited the lowest relative density (3.88 %), relative basal area (0.60 %) and IVI values (15.01). *Shorea robusta* also had the highest relative basal area contribution (83.87 %) followed by *Terminalia tomentosa* (10.20 %).

The most dominant shrub species in Rajban C₆ is *Ardisia solanacea*, which had the highest relative density (47.38 %), relative frequency (14.29 %), relative basal area (24.94 %)

and IVI (86.61) followed by *Carissa carandas* with relative density (8.52 %), relative frequency (11.43 %), relative basal area (21.57 %) and IVI (86.61) and *lantana camara* [relative density (6.55 %), relative frequency (10.71 %), relative basal area (18.39 %) and IVI (86.6 (35.66)]. In contrast, *Baliospermum montanum* had the lowest relative density (3.71 %), relative frequency (7.86 %), relative basal area (0.57 %) and IVI (12.14) followed by *Asparagus racemosus* with relative density (3.93 %), relative frequency (8.57 %), relative basal area (0.31 %) and IVI (12.82).

Table 7 Phyto-sociological status of Rajban C₆ compartment of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Component	Sr. No.	Scientific Name	RD	RF	RBA	IVI
Trees	1	<i>Syzyguim cuminii</i>	10.68	15.79	2.08	28.55
	2	<i>Cordia dichotoma</i>	12.62	21.01	2.07	35.75
	3	<i>Mallotus philippenensis</i>	13.59	15.79	1.17	30.55
	4	<i>Cassia fistula</i>	3.88	10.53	0.60	15.01
	5	<i>Terminalia tomentosa</i>	11.65	15.79	10.20	37.64
	6	<i>Shorea robusta</i>	47.57	21.05	83.87	152.50
	Total			100	100	100
Shrubs	1	<i>Adhatoda vasica</i>	8.08	11.43	11.93	31.44
	2	<i>Asparagus racemosus</i>	3.93	8.57	0.31	12.82
	3	<i>Ardisia solanacea</i>	47.38	14.29	24.94	86.61
	4	<i>Baliospermum montanum</i>	3.71	7.86	0.57	12.14
	5	<i>Carissa carandas</i>	8.52	11.43	21.57	41.52
	6	<i>Lantana camara</i>	6.55	10.71	18.39	35.66
	7	<i>Murraya koenigii</i>	7.42	10.56	6.84	24.26
	8	<i>Solanum indicum</i>	3.93	7.14	3.39	14.46
	9	<i>Lonicera japonica</i>	4.59	8.57	3.24	16.39
	10	<i>Clerodendron infortunatum</i>	5.9	10.45	8.88	24.77
	Total			100	100	100
Herbs	1	<i>Dicliptera paniculata</i>	12.96	9.57	21.75	44.28
	2	<i>Digitaria sanguinalis</i>	11.12	10.43	10.38	31.81
	3	<i>Achranthus bidentata</i>	9.35	10.78	5.49	25.63
	4	<i>Bidens bipinnata</i>	7.86	10.09	3.96	21.93
	5	<i>Ageratum conyzoides</i>	8.04	10.43	6.34	24.82
	6	<i>Apluda mutica</i>	14.31	12.17	28.66	55.14
	7	<i>Cyperus rotundus</i>	6.56	7.48	3.87	17.91
	8	<i>Cynodon dactylon</i>	10.94	8.87	4.73	24.54
	9	<i>Parthenium hysterophorus</i>	10.56	9.19	9.98	29.73
	10	<i>Pogostemon benghalensis</i>	8.37	10.26	5.71	24.34
	Total			100	100	100

RD = Relative density, RF= Relative frequency, RBA= Relative basal area, IVI = Importance value index

In case of herb species inside of Rajban C₆, the compartment was dominated by *Apluda mutica* with maximum value of relative density (14.33 %), relative frequency (12.17 %), relative basal area (28.66 %) and IVI (55.14), which was closely followed by *Dicliptera paniculata* with IVI value of 44.28. The minimum value of relative density (6.56 %), relative frequency (7.48 %), relative basal area (3.87 %) and IVI (17.91) was recorded for *Cyperus rotundus* followed by *Bidens bipinnata* [relative density (7.88 %), relative frequency (10.09 %), relative basal area (3.96 %) and IVI (20.61)].

Phyto-sociological parameters of trees, shrubs and herbs are shown in Table 8. It demonstrate that Rajban C₇ was dominated by *S. robusta* with maximum value for relative density (41.00 %), relative basal area (75.86 %) and IVI value (137.91) followed by *C. dichotoma* (18 %, 4.24 % and 43.29). However, the maximum value for relative frequency was recorded for *C. dichotoma* (21.05 %). The other most frequently occurring species were *S. cuminii*, *M. philippinensis* and *T. tomentosa*. *C. fistula*, on the other hand, exhibited the lowest relative density (4.00 %), relative basal area (0.70 %) and IVI (15.23).

The under-storey vegetation of Rajban C₇ was dominated by *A. solanacea*, which had the highest relative density (53.20 %), relative frequency (14.49 %), relative basal area (25.23 %), and IVI (92.92) followed by *I. camara* having a relative density of 7.14%, relative frequency (11.59 %), relative basal area (23.66 %) and IVI (42.40), *C. carandas* with relative density (6.91 %), relative frequency (10.87 %), relative basal area (19.60 %) and IVI (37.37). While, the least dominating species was *Solanum indicum* with relative density of 1.97 per cent, relative frequency of 5.80 per cent and relative basal area of 1.32 per cent and IVI value of 9.09.

In herb layer, the compartment of Rajban C₇ was dominated by *Digitaria sanguinalis* with maximum value for relative density (14.64 %), relative frequency (10.73 %), relative basal area (36.5 %) and IVI value of 61.95 followed by *A. mutica* with maximum relative density of 13.56 %, relative frequency of 9.12 per cent, relative basal area of 18.31 per cent and IVI value of 40.99. Whereas, the minimum value for relative frequency (7.69 %), and relative basal area (2.37 %) and IVI (16.95) was recorded for *Cyperus rotundus*. Further, *Pogostemon benghalensis* had lowest relative density of 6.57 per cent.

Table 8 Phyto-sociological studies of Rajban C₇ compartment in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Component	Sr. No.	Scientific Name	RD	RF	RBA	IVI
Trees	1	<i>Syzygium cuminii</i>	10.00	15.79	1.82	27.61
	2	<i>Cordia dichotoma</i>	18.00	21.05	4.24	43.29
	3	<i>Mallotus philippinensis</i>	14.00	15.79	4.07	33.86
	4	<i>Cassia fistula</i>	4.00	10.53	0.70	15.23
	5	<i>Terminalia tomentosa</i>	13.00	15.79	13.30	42.09
	6	<i>Shorea robusta</i>	41.00	21.05	75.86	137.91
	Total			100	100	100
Shrubs	1	<i>Adhatoda vasica</i>	6.16	11.59	10.80	28.55
	2	<i>Asparagus racemosus</i>	3.94	8.70	0.47	13.11
	3	<i>Ardisia solanacea</i>	53.20	14.49	25.23	92.92
	4	<i>Baliospermum montanum</i>	3.20	8.70	0.51	12.39
	5	<i>Carissa carandas</i>	6.91	10.87	19.6	37.37
	6	<i>Lantana camara</i>	7.14	11.59	23.66	42.4
	7	<i>Murraya koenigii</i>	5.42	8.70	2.96	23.90
	8	<i>Solanum indicum</i>	1.97	5.80	1.32	9.09
	9	<i>Lonicera japonica</i>	6.16	9.42	9.06	24.64
	10	<i>Clerodendron infortunatum</i>	5.91	10.14	6.41	22.46
	Total			100	100	100
Herbs	1	<i>Dicliptera paniculata</i>	11.63	8.59	14.48	34.69
	2	<i>Digitaria sanguinalis</i>	14.64	12.16	36.58	61.95
	3	<i>Achranthus bidentata</i>	10.98	12.16	5.29	24.86
	4	<i>Bidens bipinnata</i>	7.75	8.59	3.78	20.83
	5	<i>Ageratum conyzoides</i>	7.75	10.73	4.34	22.82
	6	<i>Apluda mutica</i>	13.56	9.12	18.31	40.99
	7	<i>Cyperus rotundus</i>	6.89	7.69	2.37	16.95
	8	<i>Cynodon dactylon</i>	11.41	10.55	6.02	27.99
	9	<i>Parthenium hysterophorus</i>	8.83	11.09	4.15	23.92
	10	<i>Pogostemon benghalensis</i>	6.57	10.02	4.83	21.41
	Total			100	100	100

The phyto-sociological parameters of trees, shrubs and herbs in Kukron C₁₄ presented in Table 9 reveals that *S. robusta* was dominant species with a highest value for relative density (45.54 %), relative frequency (22.22 %), relative basal area (83.59 %) and IVI value of 153.35 followed by *T. tomentosa* (12.30 %, 16.67 %, 9.75 % and 38.72). However, *S. cuminii*, *C. dichotoma*, *M. philippinensis* and *T. tomentosa* had the identical value for relative frequency (16.67 %). Further, *C. fistula* had the minimum value for relative density (7.38 %), relative frequency (11.11 %), relative basal area (0.84 %) and IVI (19.32), respectively.

A. solanacea was the most dominating shrub species of Kukrn C₁₄ with maximum value of relative density (53.79 %), relative frequency (15.04 %), relative basal area (30.08 %) and IVI (99.63) followed by *L. camara* [relative density (7.22 %), relative frequency (10.53 %), relative basal area (32.74 %) and IVI (50.48)] and *C. infortunatum* [relative

density (5.05 %), relative frequency (12.03 %), relative basal area (10.08 %) and IVI (27.17)], respectively. The lowest value for relative density (6.86 %), relative basal area (30.08 %) and IVI (99.63) was recorded for *Baliospermum montanum*. Furthermore, *C. carandas* had lowest relative frequency of 3.97 per cent.

Table 9 Phyto-sociological status of Kukron C₁₄ compartment in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

component	Sr. No.	Scientific Name	RD	RF	RBA	IVI
Trees	1	<i>Syzyguim cumini</i>	9.02	16.67	1.22	26.90
	2	<i>Cordia dichotoma</i>	10.66	16.67	1.50	28.83
	3	<i>Mallotus philippenensis</i>	13.11	16.67	3.11	32.89
	4	<i>Cassia flstula</i>	7.38	11.11	0.84	19.32
	5	<i>Terminalia tomentosa</i>	12.30	16.67	9.75	38.72
	6	<i>Shorea robusta</i>	47.54	22.22	83.59	153.35
	Total			100	100	100
Shrubs	1	<i>Adhatoda vasica</i>	6.86	9.77	7.26	23.9
	2	<i>Asparagus racemosus</i>	5.78	11.28	0.45	17.51
	3	<i>Ardisia solanacea</i>	53.79	15.04	30.8	99.63
	4	<i>Baliospermum montanum</i>	6.86	9.02	0.44	16.32
	5	<i>Carissa carandas</i>	3.97	11.28	5.27	20.52
	6	<i>Lantana camara</i>	7.22	10.53	32.74	50.48
	7	<i>Murraya koenigii</i>	4.69	12.03	8.78	25.50
	8	<i>Solanum indicum</i>	5.78	9.02	4.18	18.97
	9	<i>Clerodendron infortunatum</i>	5.05	12.03	10.08	27.17
Total			100	100	100	300
Herbs	1	<i>Dicliptera paniculata</i>	15.60	9.39	27.34	52.34
	2	<i>Digitaria sanguinalis</i>	15.60	11.69	8.22	35.52
	3	<i>Achranthus bidentata</i>	9.60	13.36	2.54	25.50
	4	<i>Bidens bipinnata</i>	8.93	13.57	9.79	32.28
	5	<i>Ageratum conyzoides</i>	9.68	11.48	9.84	31.01
	6	<i>Apluda mutica</i>	18.30	12.32	28.05	58.68
	7	<i>Cynodon dactylon</i>	4.65	5.43	0.33	10.41
	8	<i>Parthenium hysterophorus</i>	9.15	11.69	8.51	29.36
	9	<i>Pogostemon benghalensis</i>	8.48	11.06	5.38	24.92
Total			100	100	100	300

In case of herb species, Kukron C₁₄ was dominated by *A. mutica* with maximum relative density of 18.30 per cent, relative basal area of 28.05 per cent and IVI value of 58.68 which was closely followed by *Dicliptera paniculata* with relative density of 15.60 %, relative frequency of 9.39 per cent, relative basal area of 27.34 per cent and IVI value of 52.34. Maximum relative frequency of 13.57 per cent was reported in *Bidens bipinnata*. The minimum value of relative density (4.65 %), relative basal area (0.33 %) and IVI (10.41) was reported for *Cynodon dactylon*.

The phyto-sociological parameters of trees, shrubs, and herbs are shown in Table 10. It reveals that *S. robusta* was the most dominant tree species in Rajban C₁₀, also having

maximum value for relative density (54.17 %), relative basal area (81.37 %) and IVI value of 156.59, followed by *M. philippensis* (10.00 %, 6.46 and 32.25) and *T. tomentosa* (9.17 %, 5.62 % and 30.58), respectively. However, *S. cuminii*, *C. dichotoma*, *M. philippensis* and *T. tomentosa* exhibited the identical value of relative frequency (15.79 %), except for *Callicarpa japonica*, which had shown minimum relative frequency value of 5.26 per cent. *Ficus palmata*, on the other hand, presented the lowest relative density (5.00 %), relative frequency (10.53 %), relative basal area (1.46 %) and IVI values (16.99).

Table 10 Phyto-sociological status of Rajban C₁₀ compartment in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Component	Sr. No.	Scientific Name	RD	RF	RBA	IVI
Trees	1	<i>Syzygium cuminii</i>	10.00	16.67	1.12	26.91
	2	<i>Shorea robusta</i>	54.17	21.05	81.37	156.59
	3	<i>Cordia dichotoma</i>	10.00	15.79	3.40	29.19
	4	<i>Mallotus philippinensis</i>	10.00	15.79	6.46	32.25
	5	<i>Terminalia tomentosa</i>	9.17	15.79	5.62	30.58
	6	<i>Calicapra japonica</i>	1.67	5.26	0.56	7.49
	7	<i>Ficus palmata</i>	5.00	10.53	1.46	16.99
	Total		100	100	100	300
Shrubs	1	<i>Adhatoda vasica</i>	6.96	9.21	5.26	21.44
	2	<i>Asparagus racemosus</i>	5.54	10.53	0.66	16.72
	3	<i>Ardisia solanacea</i>	38.75	13.16	20.44	72.35
	4	<i>Baliospermum montanum</i>	4.11	7.89	1.28	13.28
	5	<i>Carissa carandas</i>	9.64	9.87	15.40	34.91
	6	<i>Lantana camara</i>	6.43	8.55	24.45	39.43
	7	<i>Murraya koenigii</i>	10.18	10.53	19.40	40.11
	8	<i>Rubus ellipticus</i>	3.93	8.55	1.13	13.61
	9	<i>Solanum indicum</i>	3.04	5.92	1.05	9.97
	10	<i>Clerodendron infortunatum</i>	8.57	10.53	9.94	29.04
	11	<i>Solanum viarum</i>	2.86	5.26	1.00	9.12
	Total		100	100	100	300
Herbs	1	<i>Dicliptera paniculata</i>	18.97	12.03	29.32	60.32
	2	<i>Achranthus bidentata</i>	13.44	14.48	3.55	31.47
	3	<i>Bidens bipinnata</i>	9.93	14.92	10.45	35.31
	4	<i>Ageratum conyzoides</i>	11.13	13.14	10.88	35.15
	5	<i>Apluda mutica</i>	19.42	12.47	29.41	61.30
	6	<i>Cynodon dactylon</i>	5.90	6.68	0.45	13.03
	7	<i>Parthenium hysterophorus</i>	12.32	13.59	10.60	36.51
	8	<i>Pogostemon benghalensis</i>	8.89	12.69	5.34	26.93
	Total		100	100	100	300

A. solanacea dominated the understory vegetation of Rajban C₁₀, with a maximum relative density of 38.75 per cent, relative frequency of 13.16, relative basal area of 20.44 per cent and IVI of 72.35, followed by *Murraya koenigii* with relative density of 10.18 per cent, relative frequency of 10.53 per cent, relative basal area of 19.40 per cent and IVI of 40.11. The least dominant species, however, was *Solanum viarum*, which had a relative density of

2.86 per cent, a relative frequency of 5.26 per cent, a relative basal area of 1.05 per cent and an IVI value of 9.12.

In herb layer, Rajban C₁₀ with maximum relative density of 19.42 per cent, relative basal area of 29.41 per cent and IVI value of 61.30 was reported in *A. mutica* which was closely followed by *D. paniculata* with relative density of 18.97 per cent, relative frequency of 12.03 per cent, relative basal area of 29.32 per cent and IVI value of 60.32. *Bidens bipinnata* had maximum relative frequency of 14.92 per cent. The minimum value of relative density (5.90 %), relative frequency (6.68 %), relative basal area (0.33 %) and IVI (13.03) was reported for *Cynodon dactylon*.

The phyto-sociological parameters of trees, shrubs and herbs in respect of Kukron C₁₅, in Table 11 reveals that *S. robusta* is the dominant tree species, with the maximum overall relative density (52.94 %), relative frequency (21.05 %), relative basal area (77.94 %) and IVI value of 151.94, followed by *T. tomentosa* (10.92 %, 15.79, 11.97 and 38.69) and *M. philippenensis* (12.61 %, 15.79, 5.38, and 33.77), respectively. Conversely, *C. dichotoma*, *Ficus palmata*, and *C. japonica* all exhibited the identical relative frequency (10.53 %). While, *F. palmata* had the minimum density (2.52 %), relative basal area (0.80 %) and IVI values (13.35).

A. solanacea, which had a maximum relative density of 40.98 per cent, relative frequency of 12.90 per cent, relative basal area of 23.13 per cent and IVI of 74.53, dominated the under-storey vegetation extensively. *M. koenigii* came in second with relative density (11.37 %), relative frequency (10.32 %), relative basal area (20.64%) and IVI value (44.83). *C. carandas* had a relative density of 8.82 per cent, a relative frequency of 10.32 per cent, a relative basal area of 17.13 per cent and an IVI value of 36.28, whereas, *C. infortunatum* had a relative density of 11.37 per cent, a relative frequency of 10.32 per cent, a relative basal area of 23.13 per cent and an IVI value of 44.83. *S. indicum*, on the contrary, was the least dominant species, with a relative density of 2.55 per cent, a relative frequency of 5.16 per cent, a relative basal area of 2.67 per cent and an IVI value of 14.14.

In the case of herb species, *A. mutica* had the maximum relative density of 21.07 per cent, relative frequency of 12.63 per cent, relative basal area of 53.11 per cent and IVI value of 86.81, followed by *Digitaria sanguinalis*, which had a relative density of 17.65 per cent, a relative frequency of 12.42 per cent, a relative basal area of 12.16 per cent and an IVI value of 42.22. Further, *Pogostemon benghalensis* had maximum relative frequency of 14.99 per

cent. In terms of relative density, frequency, relative basal area and IVI, *C. dactylon* had the minimum values at 6.12 per cent, 8.78 per cent, 0.48 per cent and 15.38, respectively.

Table 11 Phyto-sociological status of Kukron C₁₅ compartment in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Component	Sr. No.	Scientific Name	RD	RF	RBA	IVI
Trees	1	<i>Syzygium cuminii</i>	11.76	15.79	2.13	29.69
	2	<i>Shorea robusta</i>	52.94	21.05	77.94	151.94
	3	<i>Cordia dichotoma</i>	12.61	15.79	5.38	33.77
	4	<i>Mallotus philippinensis</i>	5.88	10.53	0.86	17.27
	5	<i>Terminalia tomentosa</i>	10.92	15.79	11.97	38.69
	6	<i>Calicapra japonica</i>	2.52	10.53	0.80	13.85
	7	<i>Ficus palmata</i>	3.36	10.53	0.91	14.80
	Total			100	100	100
Shrubs	1	<i>Adhatoda vasica</i>	7.45	9.68	7.62	24.75
	2	<i>Asparagus racemosus</i>	5.10	10.32	0.83	16.25
	3	<i>Ardisia solanacea</i>	40.98	12.90	23.13	77.01
	4	<i>Baliospermum montanum</i>	4.51	7.74	0.31	12.56
	5	<i>Carissa carandas</i>	8.82	10.32	17.13	36.28
	6	<i>Lantana camara</i>	4.51	8.39	10.29	23.18
	7	<i>Murraya koenigii</i>	11.37	10.32	20.64	42.33
	8	<i>Rubus ellipticus</i>	2.75	7.11	1.34	11.18
	9	<i>Solanum indicum</i>	2.55	5.16	0.62	8.33
	10	<i>Clerodendron infortunatum</i>	3.73	7.74	2.67	14.14
	11	<i>Solanum viarum</i>	8.24	10.32	15.41	33.97
	Total			100	100	100
Herbs	1	<i>Dicliptera paniculata</i>	17.65	12.42	12.16	42.22
	2	<i>Achranthus bidentata</i>	10.49	13.06	2.03	25.58
	3	<i>Bidens bipinnata</i>	10.11	13.28	9.39	32.76
	4	<i>Ageratum conyzoides</i>	11.61	12.42	7.66	31.69
	5	<i>Apluda mutica</i>	21.07	12.63	53.11	86.81
	6	<i>Cynodon dactylon</i>	6.12	8.78	0.48	15.38
	7	<i>Parthenium hysterophorus</i>	12.56	14.99	8.85	36.40
	8	<i>Pogostemon benghalensis</i>	10.41	12.42	6.33	29.16
	Total			100	100	100

The phyto-sociological parameters of trees, shrubs, and herbs in Gorakhpur C₇ (Table 12) reveals that *Shorea robusta* was having highest value for relative density (49.61 %), relative basal area (56.05 %) and IVI value of 126.72, followed by *Syzygium cuminii* (18.60 %, 12.22 and 51.88) and *Terminalia tomentosa* (8.53 %, 22.80 % and 47.12) , respectively. However, *Cordia dichotoma*, *M. philippinensis* and *Terminalia tomentosa* exhibited the identical relative frequency (15.79 %) likewise, *Shorea robusta* and *S. cuminii* exhibited the identical relative frequency (21.05 %), while, *C. fistula* displayed the lowest relative density (3.10 %), relative frequency (10.53 %), relative basal area (0.96 %) and IVI values (14.59).

The most dominant shrub species in Gorakhpur C₇ was *A. solanacea*, which had the maximum relative density (58.67 %), relative frequency (14.71%), relative basal area (36.60 %) and IVI (109.98) which was followed by *L. camara* with a relative density of 8.38 %, relative basal area (19.60 %), and IVI (37.75). Identical relative frequencies (11.76 %) were noted for *A. vasica*, *L. camara*, *M. koenigii* and *C. infortunatum*. On the other hand, *R. ellipticus* and *S. indicum* had the lowest identical value for relative frequency (5.88 %). Likewise, minimum values of relative density (58.67 %) was in *S. indicum* (2.31 %) and relative basal area (1.54 %), and IVI (9.61) were documented in *R. ellipticus*.

Table 12 Phyto-sociological status of Gorakhpur C₇ compartment in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Component	Sr. No.	Scientific Name	RD	RF	RBA	IVI
Trees	1	<i>Syzygium cuminii</i>	18.6	21.05	12.22	51.88
	2	<i>Shorea robusta</i>	49.61	21.05	56.05	126.72
	3	<i>Cordia dichotoma</i>	7.75	15.79	2.61	26.16
	4	<i>Mallotus philippinensis</i>	12.40	15.79	5.35	33.54
	5	<i>Cassia fistula</i>	3.10	10.53	0.96	14.59
	6	<i>Terminalia tomentosa</i>	8.53	15.79	22.80	47.12
	Total			100	100	100
Shrubs	1	<i>Adhatoda vasica</i>	5.2	11.76	8.75	25.71
	2	<i>Asparagus racemosus</i>	4.34	10.29	0.54	15.17
	3	<i>Ardisia solanacea</i>	58.67	14.71	36.6	109.98
	4	<i>Carissa carandas</i>	4.62	8.82	0.68	14.13
	5	<i>Lantana camara</i>	8.38	11.76	19.60	39.74
	6	<i>Murraya koenigii</i>	5.20	11.76	17.60	34.56
	7	<i>Rubus ellipticus</i>	2.60	5.88	1.12	9.61
	8	<i>Solanum indicum</i>	2.31	5.88	1.54	9.74
	9	<i>Clerodendron infortunatum</i>	5.78	11.76	12.32	29.86
	10	<i>Solanum viarum</i>	2.89	7.35	1.25	11.49
Total			100	100	100	300
Herbs	1	<i>Dicliptera paniculata</i>	18.91	13.24	34.44	66.59
	2	<i>Digitaria sanguinalis</i>	14.7	11.52	16.04	42.25
	3	<i>Achranthus bidentata</i>	9.01	12.09	5.55	26.66
	4	<i>Bidens bipinnata</i>	7.35	11.32	5.54	24.21
	5	<i>Ageratum conyzoides</i>	9.39	11.52	8.03	28.94
	6	<i>Cyperus rotundus</i>	9.39	8.25	5.09	22.73
	7	<i>Cynodon dactylon</i>	11.69	9.98	6.41	28.08
	8	<i>Parthenium hysterophorus</i>	11.05	10.56	11.73	33.34
	9	<i>Pogostuimon benghalensis</i>	8.50	11.52	7.18	27.20
Total			100	100	100	300

In case of herb species inside of Gorakhpur C₇, the compartment was dominated by *D. paniculata* with maximum relative density of 18.91 per cent, relative frequency of 13.24 per

cent, relative basal area of 34.44 per cent and IVI value of 66.59, which was closely followed by *D. sanguinalis* (14.70 %, relative 16.04 % and 42.25) and *P. hysterophorus* (11.05 %, 11.73 % and 36.02). *D. sanguinalis*, *Ageratum conyzoides* and *P. benghalensis* exhibited the identical relative frequency (11.52 %). The minimum value of relative frequency (8.25 %), relative basal area (5.09 %) and IVI (22.73) was reported for *C. rotundus*. Further, Relative density (8.50 %) was lowest in *P. benghalensis*.

The results pertaining to the phyto-sociological parameters of trees, shrubs and herbs in Lai C₂₈ (Table 13) reveals that *S. robusta* was documented with highest value for relative density (45.59 %), relative frequency (16.67 %), relative basal area (76.70 %) and IVI value of 135.96 followed by *M. philippinensis* with relative density (12.96 %), relative basal area (3.96 %) and IVI value of 29.43 and *Eucalyptus globulus* (8.33 %, 3.94 % and 24.77). However, *S. cuminii*, *C. dichotoma*, *M. philippinensis* and *E. globulus* exhibited the identical values for relative frequency (12.50 %). On the other hand, *B. variegata*, *A. catechu*, *T. tomentosa* and depicted lowest identical values for relative frequency (8.33 %). Whereas, *F. palmata* presented the lowest relative density (3.70 %), relative basal area (1.47 %) and IVI values (13.50).

The most dominant shrub species in Lai C₂₈ was *A. solanacea*, which had the maximum relative density (42.93 %), relative frequency (16.52 %), relative basal area (19.69 %), and IVI (79.14) followed by *L. camara* with a relative density of 9.00 %, relative basal area of 26.71% and IVI value of 49.62 and *C. infortunatum* with a relative density (8.23), relative basal area (16.99) and IVI values (39.13). Identical relative frequencies were noted for *L. camara* and *C. infortunatum* (13.91 %) followed by *Asparagus racemosus* and *M. koenigii* (10.43 %) and *C. carandas*, *S. indicum* and *S. viarum* (6.96). *S. indicum* showed the lowest relative density (4.11 %), relative basal area (1.30 %) and IVI values (12.37).

In the herb layer, inside of Lai C₂₈, *A. mutica* had the maximum relative density of 17.38 per cent, relative basal area of 27.77 per cent and IVI value of 56.79 followed by *D. paniculata* with relative density of 16.82 per cent, relative basal area of 26.95 per cent and IVI value of 55.24, which was closely followed by *D. sanguinalis* (14.43 %, 7.67 % and 33.14, respectively). Identical relative frequencies were noted for *D. sanguinalis*, *A. conyzoides* and *Pogostuimon benghalensis*. The minimum value of relative density (9.39 %), relative frequency (8.25 %) and IVI (22.73) was reported for *C. rotundus* and relative basal area of *C. carandas* was 0.46 per cent.

Table 13 Phyto-sociological status of Lai C₂₈ compartment in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Component	Sr. No.	Scientific Name	RD	RF	RBA	IVI
Trees	1	<i>Syzygium cuminii</i>	9.26	12.50	2.22	23.98
	2	<i>Shorea robusta</i>	42.59	16.67	76.70	135.96
	3	<i>Cordia dichotoma</i>	8.33	12.50	1.72	22.55
	4	<i>Mallotus philippinensis</i>	12.96	12.50	3.94	29.41
	5	<i>Bauhinia variegata</i>	5.56	8.33	2.30	16.19
	6	<i>Acacia catachu</i>	5.56	8.33	3.29	17.18
	7	<i>Terminalia tomentosa</i>	3.70	8.33	4.41	16.45
	8	<i>Eucalyptus globulus</i>	8.33	12.50	3.94	24.77
	9	<i>Ficus palmata</i>	3.70	8.33	1.47	13.50
		Total		100	100	100
Shrubs	1	<i>Adhatoda vasica</i>	6.43	13.91	14.72	35.06
	2	<i>Asparagus racemosus</i>	5.66	10.43	0.50	16.59
	3	<i>Ardisia solanacea</i>	42.93	16.52	19.69	79.14
	4	<i>Carissa carandas</i>	7.71	6.96	0.46	15.13
	5	<i>Lantana camara</i>	9.00	13.91	26.71	49.62
	6	<i>Murraya koenigii</i>	10.28	10.43	18.32	39.04
	7	<i>Solanum indicum</i>	4.11	6.96	1.30	12.37
	8	<i>Clerodendron infortunatum</i>	8.23	13.91	16.99	39.13
	9	<i>Solanum viarum</i>	5.66	6.96	1.31	13.92
		Total		100	100	100
Herbs	1	<i>Dicliptera paniculata</i>	16.82	10.65	26.95	54.42
	2	<i>Digitaria sanguinalis</i>	14.43	11.05	7.67	33.14
	3	<i>Achranthus bidentata</i>	9.99	12.62	2.73	25.35
	4	<i>Bidens bipinnata</i>	9.64	13.21	10.43	33.29
	5	<i>Ageratum conyzoides</i>	9.36	11.65	27.77	29.94
	6	<i>Apluda mutica</i>	17.38	11.64	26.95	56.79
	7	<i>Cyperus rotundus</i>	4.79	6.90	0.35	12.04
	8	<i>Parthenium hysterophorus</i>	9.64	11.83	9.51	30.98
	9	<i>Pogostuimon benghalensis</i>	7.95	11.05	5.06	24.05
		Total		100	100	100

Phytosociological studies help in understanding the structure and composition of plant communities (Braun and blanquet *et al.*, 1965). Floristic composition is important to judge the state of natural forests in any region and to formulate conservation and management strategies. In the present study, it was found that most of species of trees shrubs and herbs were common among different compartment, except Lai C₂₈ indicating uniformity in habitat and topography, prevailing climatic conditions, and thus implies application of similar management practices for the compartments under investigations with slight variation for Lai C₂₈. In the present study, *Shorea robusta* was found to be extensively prevailing in all compartments, followed *M. philippinensis*, *T. tomentosa*, *C. dichotoma* and *S. cuminii*, with the rest of the species exhibiting non-frequent population pattern, Similarly, Mandal and Joshi (2014), while studying vegetation dynamics and plant diversity in dry deciduous forests

of Doon valley region adjoining to the present study area, *M. philippinensis*, *T. tomentosa* and *S. cuminii*, found to be the main associates of sal forest. The number of species recorded in the present study was found to be lower than that reported by earlier worker in other climatic condition, which indicate uniformity within the compartments under investigation in respect of habitat, climate, soil and geographical location.

In forest ecosystems, the magnitude of variation is investigated through phytosociological aspects, mainly by relative density, relative frequency, relative basal area and IVI values. In all the compartments investigated in the current study, it was found that *S. robusta* mainly accounts for values of RD, RBA and IVI values. On the basis of RD and IVI values it can be ascertained that almost 50 per cent occupation of these compartment is under the *S. robusta*. The most common associates of *S. robusta* in all the compartments are *M. philippinensis*, *T. tomentosa*, *C. dichotoma* and *S. cuminii*, while, excepting Lai C₂₈. In Lai C₂₈, in addition to these associates *E. globulus*, *B. variegata*, *A. catechu* and *F. palmata* were also present in insignificant proportion based on their IVI values. In shrub layer, *A. solanacea* was the most common species (IVI values) occurring in almost all the compartments. while, in the herbaceous layer, *Apluda mutica* was the most dominating associates of *S. robusta* in the Rajban C₆ and Rajban C₇, Kukron C₁₄, Rajban C₁₀, Kukron C₁₅ and Lai C₂₈. However, in Gorakhpur C₇ *Dicliptera peniculata* was the main associate. Analysis of IVI values showed that *S. robusta* was the dominant species in all the compartments (IVI value~150), which is well within the limits of earlier studies (Rawat and Bhainsora, 1999). Tree species with higher IVI values indicate good regenerative capability, better adaptability and wide ecological amplitude. Thus, on the basis of present investigations, we can conclude that there is little variation among the common associates of *S. robusta* among tree shrub and herb layer excepting in Lai C₂₈ compartment.

Phytosociological data from these forests were quantitatively analyzed to work out the density, relative density, basal area and important value index (IVI). In our study, the variation under different compartments can be clearly seen for tree density that ranged between 322 to 250 N ha⁻¹ having basal area of 0.37 to 1.19 m² ha⁻¹. It may be because there is less competition for space and light in compartments with higher tree density. Environmental factors include site factors (moisture and temperature, wind conditions, soil and soil nutrients) and stand factors (competition for light, moisture, and nutrients from other trees). With access to light (i.e., no taller trees shading it), good soil depth and site quality are the key limiting constraint for the distribution of the tree among the

compartments with lesser number of trees. The soil and climate in compartments constrain development, resulting in heterogeneity in stand characteristics. *S. robusta* documented highest value for relative density (41.00-57.17 %), relative frequency (16.67-22.22 %), relative basal area (56.05-83.87 %) and IVI value (126.72-156.94). Kumar *et al.* (2006) also observed the similar range for tree density (380 trees ha⁻¹-260 trees ha⁻¹) in sub tropical forest of the Garhwal Himalaya. Although the basal area (0.78 to 1.43 m² ha⁻¹) was higher than present study. Mandal and Joshi (2014) studied the vegetation dynamics and plant diversity in dry deciduous forests of Doon Valley and concluded that *Shorea robusta* was the main dominant species and *M. philippensis*, *S. Cumini* were its associates. The highest IVI (150) indicated dominance of *S. robusta*. Additionally, similar patterns were observed in the Doboka reserve forest of Assam's tropical wet deciduous sal (*Shorea robusta* Gaertn. f) forest *S. robusta* had the highest IVI (125.30) density, which was found to be higher in the lower girth class, i.e., 30-60 cm (Dutta and Devi, 2013). In the present study, *S. robusta* was found to be extensively dispersed in all compartments, followed by *M. philippensis*, *T. tomentosa*, *C. dichotoma* and *S. cuminii*, with the rest of the species exhibiting non-frequent population pattern. In addition, *S. robusta* showed considerably maximum values in all the compartments with highest IVI (156.59) for Rajban C₁₀. IVI values for shrubs ranged between 8.35 and 27.33. The results confirmed that diversity (species richness) for tree species was highest followed by shrubs and herbs. Results of present phytosociological studies of trees are in line with the similar findings of Deka *et al.* (2012), who suggested that *Shorea robusta* has contributed about 90 per cent of the total stand density (2559 individual ha⁻¹) of the forest and exhibited the highest IVI (212.67), However, the low basal area recorded in our present study resulted from low stocking among the large size diameter classes (i.e., 60-80 cm) despite the presence of some small diameter class trees. Differences in basal area can be related to altitudinal variances, age structure, forest successional stage, species composition and disturbance (Gogoi and Sahoo, 2018). The forest was heterogenous in composition with high dominance of *S. robusta* in tree and regenerating stage. In our study, the dominance of *A. solanacea* an invasive plant exotic shrub with IVI ranged from 71.31-109.98. It could be another possible reason for the observed trend and lower shrub and herb diversity of different compartments under current study. In all the compartments, relative basal area, density and frequency of *Ardisia thickets* had the maximum share compared to other shrubs and herbs. This may be attributed to thick monoculture of *A. solanacea* that alters the microenvironment below its understory, and inhibit the germination and growth of *S. robusta* and other associate species that results in the exclusion of native

plants, probably through a strong decrease in understory light availability (Sharma and Raghubanshi, 2007; kumar *et al.*, 2022). Furthermore, Koop and Horvitz (2005) studied spatial and temporal variation in the population dynamics of an invasive species, *Ardisia elliptica*, across a range of habitat types to identify contributing factors for its demographic success. Mean population density was highest at the *Ardisia* thicket (358.5 N m⁻²) and relatively low at the other sites (5.4–47.0 N m⁻²). While, deep shade generated by a continuously dense canopy of adults in the *Ardisia* thicket, has suppressed the growth of seedlings and juveniles. However, high water availability has probably resulted in high germination rates of seeds and a dominance of seedlings and small juveniles (Koop, 2003). The invasive potential, population dynamics of *A. elliptica* on native communities may be strongly influenced by light and water availability (Koop, 2004), which resulted in reduced population growth of *S. robusta*. All these trends may indicate the influence of different forest management regimes in the compartments.

4.3 DIVERSITY INDICES

The intercompartmental variation in the biodiversity indices is studied through various diversity indices viz., Simpson Index of dominance index (Cd), Simpson Index of diversity (D), Shannon Index of diversity (H'), Menheink index of species richness (Mel), Margalef's Index of richness (MI) and Pielou's Equitability (Eq) (Table 14).

The Simpson Index of dominance index(Cd), ranged from 0.23(Lai C₂₈) to 0.33 (Kukron C₁₄); Simpson Index of diversity (D) from 0.67 (Kukron C₁₄) to 0.77 (Lai C₂₈); Shannon Index of diversity (H') from 1.44 (Gorakhpur C₇) to 1.83 (Lai C₂₈); Menheink index of species richness (Mel) from 0.33 (Gorakhpur C₇) to 0.55 (Lai C₂₈); Margalef's Index of richness (MI) from 0.87 (Rajban C₁₀ and Gorakhpur C₇) and Pielou's Equitability (Eq) from 0.75 (Kukron C₁₄) to 0.88 (Rajban C₇).

Different indices of diversity (Table 14) did not depict much variation in shrub and herb diversity. Several climatic and edaphic factors including habitat heterogeneity species composition, forest age and anthropogenic disturbances are responsible for difference in diversity and structure of sal forest along its geographic range (Champion and Seth, 1968; Gautam and Devoe, 2006). Very less variation among different compartments as depicted in form of various diversity indices investigated under the current study could be owed to their uniformity in management class (reserve forest), same age class (PB I or PB IV); a very

close groups) and minimum anthropogenic disturbances. Further, the lower values of diversity indices among various compartments were lower than the normal usual values reported for these indices could be owed to their uniformity in the crop composition and closeness (space) of compartments.

The index of similarity and dissimilarity of trees, shrubs and herb layer in respect of different compartment is depicted in Table 15. It is evident from the table that the Compartments viz., Rajban C₆ and perfectly similar with Rajban C₇, Kukron C₁₄ and Gorakhpur C₇. Similarly, Rajban C₇ bears perfect similarity with Kukron C₁₄ and Gorakhpur C₇; Rajban C₁₀ with Gorakhpur C₇, kukron C₁₄ with Kukron C₁₅. The compartment of Lai C₂₈ has minimum similarity with other compartments under investigations. A very high level of different similarity among different compartments necessitates application of uniform management practices for attaining high productivity. However, the Lai C₂₈ requires different set of management prescription. Likewise, in the shrub and herb layers, there is similarity among different compartments, indicating similarity in surface environment, which has implication for initiating natural regeneration.

Several climatic and edaphic factors including habitat heterogeneity, species composition, forest age and anthropogenic disturbances are responsible for differences in diversity and structure of sal forests along its geographic range (Champion and Seth, 1968; Gautam and Devoe, 2006). The values in the current study were found to be well within the range of values of The Shannon–Wiener diversity index (H₀) for Indian forests which ranged from 0.83 to 4.10 (Jha and Singh, 1990; Ayyappan and Parthasarathy, 1999; Pandey, 2000). In contrast, Kumar and Saikia, (2020) reported higher the values of Shannon diversity index (2.25 for trees, 2.72 for shrubs and 2.98 for herbs) than the present study. However, they are in close proximity to the values reported by Banik *et al.* (2018) for Sal forests under two forest management regimes (Sal forest and Sal plantation) in Tripura, Northeast India. The range of diversity indices from the present study were lower than those found by Divakara (2015), who evaluated the floristic composition of semi-dense and open forests in two districts of different sal forests in Jharkhand. The maximum Shannon-Wiener diversity index (H' = 2.5754, R' = 2.4071), Simpsons index of diversity (D = 0.8900, D = 0.8596), Margalef richness index (R' = 4.5806, R' = 4.5122), and evenness index (E = 0.6677, E = 0.6062) were obtained in Latehar. On the other hand, open and dense forests of Hazaribagh showed lowest for Shannon-Wiener diversity index (H' = 1.3825 H' = 1.1658). However,

lowest Simpsons index of diversity ($D = 0.6096$), Margalef richness index ($R' = 2.2216$) and evenness index ($E = 0.4100$) was found in dense forests of Latehar.

Table 14 Diversity indices of trees, shrubs and herbs among different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Trees							
Diversity indices	Rajban C ₆	Rajban C ₇	Rajban C ₁₀	Kukron C ₁₄	Kukron C ₁₅	Gorakhpur C ₇	Lai C ₂₈
Simpson concentration of dominance index (Cd)	0.29	0.25	0.28	0.33	0.32	0.31	0.23
Simpson diversity index(D)	0.71	0.75	0.72	0.67	0.68	0.69	0.77
Shannon Wiener Index of diversity (H')	1.50	1.57	1.53	1.46	1.47	1.44	1.83
Menheink index of species richness (Mel)	0.37	0.38	0.34	0.40	0.40	0.33	0.55
Margalef Index of species richness (MI)	0.90	0.90	0.87	1.05	1.05	0.87	1.43
Pielou Equitability (Ep)	0.84	0.88	0.85	0.75	0.76	0.80	0.83
Shrubs							
Diversity indices	Rajban C ₆	Rajban C ₇	Rajban C ₁₀	Kukron C ₁₄	Kukron C ₁₅	Gorakhpur C ₇	Lai C ₂₈
Simpson concentration of dominance index (Cd)	0.26	0.31	0.32	0.19	0.21	0.37	0.23
Simpson diversity index(D)	0.74	0.69	0.68	0.81	0.79	0.63	0.77
Shannon Wiener Index of diversity (H')	1.82	1.69	1.64	2.02	1.97	1.56	1.85
Menheink index of species richness (Mel)	0.10	0.11	0.12	0.10	0.11	0.12	0.11
Margalef Index of species richness (MI)	0.99	1.00	0.93	1.07	1.08	1.02	0.89
Pielou Equitability (Ep)	0.79	0.73	0.75	0.84	0.82	0.68	0.84
Herbs							
Diversity indices	Rajban C ₆	Rajban C ₇	Rajban C ₁₀	Kukron C ₁₄	Kukron C ₁₅	Gorakhpur C ₇	Lai C ₂₈
Simpson concentration of dominance index (Cd)	0.11	0.11	0.13	0.14	0.14	0.12	0.13
Simpson diversity index(D)	0.89	0.89	0.87	0.86	0.86	0.88	0.87
Shannon Wiener Index of diversity (H')	2.28	2.27	2.13	2.02	2.02	2.15	2.13
Menheink index of species richness (Mel)	0.02	0.02	0.03	0.03	0.02	0.02	0.04
Margalef Index of species richness (MI)	0.74	0.74	0.68	0.59	0.60	0.67	0.67
Pielou Equitability (Ep)	0.99	0.98	0.97	0.97	0.97	0.98	0.97

A persual of data regarding similarity and dissimilarity index of trees shrubs and herbs is demonstrated in Table 15. The similarity index of trees in different compartments ranged from 0.67 to 1.00. Rajban C₆ and Rajban C₇ had the maximum similarity index (1.00) with Kukron C₁₄ and Gorakhpur C₇ while minimum value for similarity index (0.67) was reported with Lai C₂₈. Similarly, Kukron C₁₄ had the maximum similarity index (1.00) with Gorakhpur C₇. On the other hand, for tree species Rajban C₆, Rajban C₇, Kukron C₁₄ and

Rajban C₁₀ reported minimum value for similarity index (0.67) with Lai C₂₈. In case of shrub species, Rajban C₆ had the maximum similarity index (1.00) with Rajban C₇. Maximum similarity index of 0.95 was reported in Rajban C₇ with Kukron C₁₄ and minimum value for similarity index (0.76) was reported with Kukron C₁₅. Furthermore, Kukron C₁₄ showed maximum similarity index of 0.90 with Rajban C₁₀. In respect of herb species, Rajban C₆ had the maximum similarity index (1.00) with Rajban C₇. Lai C₂₈ showed minimum similarity index (0.82) with Rajban C₁₀, Kukron C₁₅ and Gorakhpur C₇.

Table 15 Index of similarity and dissimilarity of trees shrubs and herbs under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Similarity Dissimilarity	Rajban C ₆	Rajban C ₇	Kukron C ₁₄	Rajban C ₁₀	Kukron C ₁₅	Gorakhpur C ₇	Lai C ₂₈
Trees							
Rajban C ₆	-	1.00	1.00	0.77	0.77	1.00	0.67
Rajban C ₇	0.00	-	1.00	0.77	0.77	1.00	0.67
Rajban C ₁₀	0.00	0.00	-	0.77	0.77	1.00	0.67
Kukron C ₁₄	0.23	0.23	0.23	-	1.00	0.77	0.75
Kukron C ₁₅	0.23	0.23	0.23	0.00	-	0.77	0.75
Gorakhpur C ₇	0.00	0.00	0.00	0.23	0.23	-	0.67
Lai C ₂₈	0.33	0.33	0.33	0.25	0.25	0.33	-
Shrubs							
Rajban C ₆	-	1.00	0.95	0.86	0.76	0.80	0.84
Rajban C ₇	0.00	-	0.95	0.86	0.76	0.80	0.84
Rajban C ₁₀	0.05	0.05	-	0.90	0.80	0.84	0.89
Kukron C ₁₄	0.14	0.14	0.10	-	0.91	0.95	0.90
Kukron C ₁₅	0.24	0.24	0.20	0.09	-	0.86	0.80
Gorakhpur C ₇	0.20	0.20	0.16	0.05	0.14	-	0.95
Lai C ₂₈	0.16	0.16	0.11	0.10	0.20	0.05	-
Herbs							
Rajban C ₆	-	1.00	0.95	0.89	0.89	0.89	0.95
Rajban C ₇	0.00	-	0.95	0.89	0.78	0.89	0.95
Rajban C ₁₀	0.05	0.05	-	0.94	0.94	0.94	0.89
Kukron C ₁₄	0.11	0.11	0.06	-	0.88	0.88	0.82
Kukron C ₁₅	0.11	0.22	0.06	0.13	-	0.88	0.82
Gorakhpur C ₇	0.11	0.11	0.06	0.13	0.13	-	0.82
Lai C ₂₈	0.05	0.05	0.11	0.18	0.18	0.18	-

On the other hand, for tree species, Rajban C₆ reported minimum value for dissimilarity index (0.00) with Rajban C₇. Similarly, Kukron C₁₄ reported minimum value of dissimilarity index (0.00) with Lai C₂₈. Gorakhpur C₇ and minimum value of dissimilarity index (0.00) was documented with Rajban C₆, Rajban C₇ and Kukron C₁₄. Whereas, maximum value was recorded by Rajban C₁₀ and Kukron C₁₅ with Rajban C₆, Rajban C₇ and Kukron

C₁₄. In case of shrub species, Rajban C₆ recorded minimum value for dissimilarity index (0.00) with Rajban C₇. Kukron C₁₅ had the maximum dissimilarity index (0.24) with Rajban C₆ and Rajban C₇. In respect of herb species, Rajban C₆ reported minimum value for dissimilarity index (0.00) with Rajban C₇, however, maximum value was recorded by Kukron C₁₅ (0.22) followed by Lai C₂₈ with Rajban C₁₀, Kukron C₁₅ and Gorakhpur C₇.

4.4 SPECIES WISE DISTRIBUTION OF DENSITY BIOMASS AND CARBON STOCK

The data in Table 16-22 presents the distribution of density, above ground biomass (AGB), belowground biomass (BGB), total biomass (TB) and carbon stock of different species present under different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh.

Table 16 Species wise density (N ha⁻¹), Volume (m³ ha⁻¹), AGB (Mg ha⁻¹), BGB (Mg ha⁻¹), TB (Mg ha⁻¹) and carbon (Mg C ha⁻¹) of trees in Rajban C₆ compartment under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Density (N ha ⁻¹)	Volume (m ³ ha ⁻¹)	Above ground biomass (Mg ha ⁻¹)	Below ground biomass (Mg ha ⁻¹)	Total biomass (Mg ha ⁻¹)	Carbon density (Mg C ha ⁻¹)
1	<i>Shorea robusta</i>	122.50	140.03	176.89	76.03	252.92	120.14
2	<i>Syzygium cuminii</i>	27.50	1.52	1.49	0.85	2.34	1.11
3	<i>Mallotus philippinensis</i>	35.00	1.11	1.07	0.76	1.83	0.87
4	<i>Terminalia tomentosa</i>	30.00	11.26	11.10	5.91	17.01	8.08
5	<i>Cordia dichotoma</i>	32.50	1.07	0.78	0.35	1.13	0.54
6	<i>Cassia fistula</i>	10.00	0.86	0.69	0.4	1.09	0.52
	TOTAL	257.50	155.86	192.02	84.30	276.32	131.25

In Rajban C₆ (Table 16), 257.50 N ha⁻¹ contributed to the total volume of 155.86 m³ ha⁻¹, AGB of 124.24 Mg ha⁻¹, BGB of 56.89 Mg ha⁻¹, TB of 181.14 Mg ha⁻¹ and carbon stock of 86.04 Mg C ha⁻¹. Out of which 122.50 N ha⁻¹ were of *S. robusta*, which was followed by *M. philippinensis* (35.00 N ha⁻¹), *C. dichotoma* (32.50 N ha⁻¹) and *T. tomentosa* (30.00 N ha⁻¹), respectively. The maximum volume was contributed by *S. robusta* (140.03 m³ ha⁻¹) which was followed by *T. tomentosa* (11.26 m³ ha⁻¹), *S. cuminii* (11.26 m³ ha⁻¹) *M. philippinensis* (1.11 m³ ha⁻¹), respectively. Furthermore, *S. robusta* had the maximum above ground biomass (176.89 Mg ha⁻¹), below ground biomass (76.03 Mg ha⁻¹), total biomass (252.92 Mg ha⁻¹) and carbon stock (120.14 Mg C ha⁻¹), which was followed by *T. tomentosa*, *S. cuminii*, *M. philippinensis*, respectively. The minimum contribution was of *C. fistula* with a density of 10.00 N ha⁻¹, volume of 0.86 m³ ha⁻¹, AGB of 0.78 Mg ha⁻¹, BGB of 0.35 Mg ha⁻¹, TB of 1.13 Mg ha⁻¹ and carbon stock of 0.54 Mg C ha⁻¹, respectively. However, the contribution for

volume, AGB, BGB, TB and carbon stock follows the order; *S.robusta*>*T. tomentosa*>*S. cuminii*>*M. philippinensis*> *C. dichotoma* >*C. fistula*, respectively.

The data in Table 17 reveals that under Rajan C₇ compartment a total density of 250 N ha⁻¹, volume of 103.71 m³ ha⁻¹, AGB of 124.24 Mg ha⁻¹, BGB of 56.89 Mg ha⁻¹, TB of 181.14 Mg ha⁻¹ and carbon stock of 86.04 Mg C ha⁻¹ was recorded. Density-wise *S. robusta* is the dominant species of the compartment with maximum density of 102.50 N ha⁻¹ followed by *C. dichotoma* (45.00 N ha⁻¹), *M. philippinensis* (35.00 N ha⁻¹) and *T. tomentosa* (32.50 N ha⁻¹), respectively. However, the maximum volume was contributed by *S. robusta* (82.49 m³ ha⁻¹), which was followed by *T. tomentosa* (15.32 m³ ha⁻¹), *M. philippinensis* (3.08 m³ ha⁻¹) and *C. dichotoma* (1.66 m³ ha⁻¹), respectively. Furthermore, *S. robusta* had the maximum contribution for above ground biomass (104.12 Mg ha⁻¹), below ground biomass (46.15 Mg ha⁻¹), total biomass (150.27 Mg ha⁻¹) and carbon stock (71.38 Mg C ha⁻¹); followed by *T. tomentosa*, *M. philippinensis*, *C. dichotoma*, *S. cuminii* and *C. fistula*, respectively. The contribution for volume, AGB, BGB, TB and carbon stock followed the order; *S. robusta* > *T. tomentosa*, *M. philippinensis*, *C. dichotoma*, *S. cuminii* and *C. fistula*, respectively.

Table 17 Species wise density (N ha⁻¹), Volume (m³ ha⁻¹), AGB (Mg ha⁻¹), BGB (Mg ha⁻¹), TB (Mg ha⁻¹) and carbon (Mg C ha⁻¹)of trees in Rajban C₇ compartment under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Density (N ha ⁻¹)	Volume (m ³ ha ⁻¹)	Above ground biomass (Mg ha ⁻¹)	Below ground biomass (Mg ha ⁻¹)	Total biomass (Mg ha ⁻¹)	Carbon density (Mg C ha ⁻¹)
1	<i>Shorea robusta</i>	102.50	82.49	104.12	46.15	150.27	71.38
2	<i>Syzygium cuminii</i>	25.00	0.74	0.73	0.52	1.25	0.59
3	<i>Mallotus philippinensis</i>	35.00	3.08	2.96	1.87	4.83	2.29
4	<i>Terminalia tomentosa</i>	32.50	15.32	15.02	7.42	22.44	10.66
5	<i>Cordia dichotoma</i>	45.00	1.66	1.07	0.76	1.83	0.87
6	<i>Cassia fistula</i>	10.00	0.42	0.35	0.17	0.52	0.25
	TOTAL	250.00	103.71	124.24	56.89	181.14	86.04

The data in Table 17 presents the density, volume, biomass and carbon density, distribution among different tree species in Rajban C₇ compartment of Sal working circle. It is evident from the data that *S. robusta* contributed to maximum value of density, volume, above, below and total biomass and carbon density on per hectare basis. The contribution of *S. robusta* to total carbon density of the stand was 86.04 per cent.

The data presented in Table 18 shows the species-wise distribution of density, above ground biomass (AGB), belowground biomass (BGB), total biomass (TB) and carbon stock of trees in Kukron C₁₄, this compartment was having total density of 305.00 N ha⁻¹, volume of 277.88 m³ ha⁻¹, AGB of 343.96 Mg ha⁻¹, BGB of 143.39 Mg ha⁻¹, TB of 487.35 Mg ha⁻¹, and carbon density of 232.66 Mg C ha⁻¹. Among which *S. robusta* had the maximum tree density (145.00 N ha⁻¹) which was followed by *M. philippinensis* (40.00 N ha⁻¹), *C. dichotoma* (37.50 N ha⁻¹) and *T. tomentosa* (32.50 N ha⁻¹). Whereas, *C. fistula* had lowest tree density (22.50 N ha⁻¹). The maximum volume was contributed by *S. robusta* (254.56 m³ ha⁻¹) which was followed by *T. tomentosa* (16.46 m³ ha⁻¹), *M. philippinensis* (40.00 m³ ha⁻¹) and *S. cuminii* (16.46 m³ ha⁻¹). However, the minimum value for volume was recorded for *C. fistula* (0.52 m³ ha⁻¹). Furthermore, *S. robusta* was recorded to have maximum value of AGB (321.56 Mg ha⁻¹), BGB (121.25 Mg ha⁻¹), TB (442.82 Mg ha⁻¹) and carbon stock (210.34 Mg C ha⁻¹) which was followed by *T. tomentosa*, *M. philippinensis* and *S. cuminii*. While, AGB (0.45 Mg ha⁻¹), BGB (0.29 Mg ha⁻¹), TB (0.74Mg ha⁻¹) and carbon density (0.35 Mg ha⁻¹) was documented for *C. fistula*. The species wise contribution for volume, BGB, TB and carbon stock is arranged in following order; *S. robusta* > *T.tomentosa*, *M. philippinensis*, *S. cuminii*>*C. dichotoma*>*C. fistula*, respectively.

Table 18 Species wise density (N ha⁻¹), Volume (m³ ha⁻¹), AGB (Mg ha⁻¹), BGB (Mg ha⁻¹), TB (Mg ha⁻¹) and carbon (Mg C ha⁻¹) of trees in compartment Kukron C₁₄ under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Density (N ha ⁻¹)	Volume (m ³ ha ⁻¹)	Above ground biomass (Mg ha ⁻¹)	Below ground biomass (Mg ha ⁻¹)	Total biomass (Mg ha ⁻¹)	Carbon density (Mg C ha ⁻¹)
1	<i>Shorea robusta</i>	145.00	254.56	321.57	121.25	442.82	210.34
2	<i>Syzygium cuminii</i>	27.50	1.18	0.78	0.42	1.21	0.57
3	<i>Cordia dichotoma</i>	37.50	1.16	0.58	0.37	0.95	0.45
4	<i>Mallotus philippinensis</i>	40.00	4.00	3.84	2.41	6.25	2.97
5	<i>Cassia fistula</i>	22.50	0.52	0.45	0.29	0.74	0.35
6	<i>Terminalia tomentosa</i>	32.50	16.46	16.74	18.65	35.38	17.97
	TOTAL	305.00	277.88	343.96	143.39	487.35	232.66

The results pertaining to the species-wise distribution of density, above ground biomass (AGB), belowground biomass (BGB), total biomass (TB) and carbon density of trees is presented in Table 19. The total tree density (300.00 N ha⁻¹), volume (209.19 m³ ha⁻¹), AGB (258.46 Mg ha⁻¹), BGB (112.74 Mg ha⁻¹), TB (371.20 Mg ha⁻¹) and carbon density (176.32 Mg C ha⁻¹) was recorded in Rajban C₁₀. *S. robusta* displayed maximum tree density

(162.50 N ha⁻¹) followed by *S. cuminii*, *C. dichotoma*, and *M. philippinensis* demonstrated an identical value of tree density (30.00 N ha⁻¹), *T. tomentosa* (27.50 N ha⁻¹), *F. palmata* (15.00 N ha⁻¹), and *C. japonica* (83.33 N ha⁻¹), respectively. However, *S. robusta* displayed maximum volume contribution (188.61 m³ ha⁻¹) followed by *T. tomentosa* (10.25 m³ ha⁻¹), *M. philippensis* (5.56 m³ ha⁻¹) and *Ficus palmata* (1.72 m³ ha⁻¹). Further, *C. dichotoma* had the minimum contribution of volume (0.56 m³ ha⁻¹), AGB (0.71 Mg ha⁻¹), BGB (0.40 t ha⁻¹), TB (1.11 Mg ha⁻¹) and carbon stock (0.53 Mg C ha⁻¹), respectively. On the contrary, The maximum values for AGB (48.07 Mg ha⁻¹), BGB (25.06 Mg ha⁻¹), TB (73.12 Mg ha⁻¹) and carbon density (34.73 Mg C ha⁻¹) was displayed by *S. robusta* followed by *T. tomentosa* > *M. philippensis* > *F. palmata* > *C. japonica* > *S. cuminii* > *C. dichotoma*.

Table 19 Species wise density (N ha⁻¹), Volume (m³ ha⁻¹), AGB (Mg ha⁻¹), BGB (Mg ha⁻¹), TB (Mg ha⁻¹) and carbon (Mg C ha⁻¹) of trees in Rajban C₁₀ compartment under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Density (N ha ⁻¹)	Volume (m ³ ha ⁻¹)	Above ground biomass (Mgha ⁻¹)	Below ground biomass (Mg ha ⁻¹)	Total biomass (Mg ha ⁻¹)	Carbon density (Mg C ha ⁻¹)
1	<i>Shorea robusta</i>	162.50	188.61	238.26	101.59	339.85	161.43
2	<i>Syzygium cuminii</i>	30.00	1.30	1.27	0.58	1.85	0.88
3	<i>Cordia dichotoma</i>	30.00	0.56	0.71	0.40	1.11	0.53
4	<i>Mallotus philippensis</i>	30.00	5.56	5.47	3.22	8.69	4.13
5	<i>Terminalia tomentosa</i>	27.50	10.25	10.02	5.70	15.72	7.47
6	<i>Callicarpa japonica</i>	5.00	1.19	1.31	0.60	1.91	0.91
7	<i>Ficus palmata</i>	15.00	1.72	1.42	0.65	2.07	0.98
	TOTAL	300.00	209.19	258.46	112.74	371.20	176.32

The data illustrated in Table 20 shows the density, above ground biomass (AGB), belowground biomass (BGB), total biomass (TB) and carbon stock for Kukron C₁₅. A total density of 297.50 N ha⁻¹, volume of 182.48 m³ ha⁻¹, AGB of 222.86 Mg ha⁻¹, BGB of 94.98 Mg ha⁻¹, TB of 317.84 Mg ha⁻¹, and carbon stock of 152.58 Mg C ha⁻¹ was recorded, out of which *S. robusta* had the maximum tree density (157.50 N ha⁻¹), which was followed by *M. philippinensis* (37.50 N ha⁻¹), *S. cuminii* (35.00 N ha⁻¹) and *T. tomentosa* (32.50 N ha⁻¹). Whereas, *F. palmata* had lowest tree density (7.50 N ha⁻¹). The maximum volume was contributed by *S. robusta* (163.62 m³ ha⁻¹), which was followed by *T. tomentosa* (11.05 m³ ha⁻¹), *M. philippinensis* (3.65 m³ ha⁻¹) and *S. cuminii* (1.50 m³ ha⁻¹). However, the minimum value for volume was recorded for *C. dichotoma* (0.52 m³ ha⁻¹). Furthermore, *S. robusta* was recorded to have maximum value of AGB (204.69 Mg ha⁻¹), BGB (77.75 Mg ha⁻¹), TB (282.44 Mg ha⁻¹) and carbon stock (133.41 Mg C ha⁻¹), which was followed by *T. tomentosa*, *M. philippinensis* and *S. cuminii*. While, the minimum contribution of AGB (0.37 Mg ha⁻¹),

BGB (0.35 Mg ha⁻¹), TB (0.72Mg ha⁻¹) and carbon density (0.31 Mg C ha⁻¹) was for *C. dichotoma*.

Table 20 Species wise density (N ha⁻¹), Volume (m³ ha⁻¹), AGB (Mg ha⁻¹), BGB (Mg ha⁻¹), TB (Mg ha⁻¹) and carbon (Mg C ha⁻¹) of trees in Kukron C₁₅ compartment under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Density (N ha ⁻¹)	Volume (m ³ ha ⁻¹)	Above ground biomass (Mg ha ⁻¹)	Below ground biomass (Mg ha ⁻¹)	Total biomass (Mg ha ⁻¹)	Carbon density (Mg C ha ⁻¹)
1	<i>Shorea robusta</i>	157.50	163.62	204.69	77.75	282.44	133.41
2	<i>Syzygium cuminii</i>	35.00	1.50	1.47	1.45	2.92	1.27
3	<i>Mallotus philippinensis</i>	37.50	3.65	3.98	3.88	7.86	4.98
4	<i>Terminalia tomentosa</i>	32.50	11.05	10.02	9.55	19.57	10.62
5	<i>Cordia dichotoma</i>	17.50	0.52	0.37	0.35	0.72	0.31
6	<i>Ficus palmata</i>	7.50	1.02	1.05	0.98	2.03	0.82
7	<i>Callicarpa japonica</i>	10.00	1.12	1.29	1.02	2.31	1.18
	TOTAL	297.50	182.48	222.86	94.98	317.84	152.58

The data evinced in Table 21 shows the distribution of total density, volume, above ground biomass (AGB), belowground biomass (BGB), total biomass (TB) and carbon stock among different species in Gorakhpur C₇. The total tree density of 322.50 number ha⁻¹, volume of 68.95 m³ ha⁻¹, AGB of 81.91 Mg ha⁻¹, BGB of 41.98 Mg ha⁻¹, TB of 123.89 Mg ha⁻¹ and carbon density of 58.85 Mg C ha⁻¹ was recorded. In Gorakhpur C₇ compartment *S. robusta* was the dominant species with maximum density of 160.00 number ha⁻¹, AGB of 64.80 Mg ha⁻¹, BGB of 32.43 Mg ha⁻¹, TB of 97.23 Mg ha⁻¹ and carbon density of 46.18 Mg C ha⁻¹ which was followed by *S. cuminii* (60.00 N ha⁻¹), *M. philippinensis* (40.00 N ha⁻¹). Whereas, *C. dichotoma* (25.50 N ha⁻¹) and *T. tomentosa* (27.00 N ha⁻¹) *C. fistula*. On the other hand, had the lowest tree density (10.00 N ha⁻¹). The contribution of different species to the carbon storage potential in the forest followed the order: *S. robusta* > *T. tomentosa* > *S. cuminii* > *M. philippinensis* > *C. dichotoma* > *C. fistula*.

Table 21 Species wise density (N ha⁻¹), Volume (m³ ha⁻¹), AGB (Mg ha⁻¹), BGB (Mg ha⁻¹), TB (Mg ha⁻¹) and carbon (Mg C ha⁻¹) of trees in Gorakhpur C₇ compartment under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Density (N ha ⁻¹)	Volume (m ³ ha ⁻¹)	Above ground biomass (Mg ha ⁻¹)	Below ground biomass (Mg ha ⁻¹)	Total biomass (Mg ha ⁻¹)	Carbon density (Mg C ha ⁻¹)
1	<i>Shorea robusta</i>	160.00	51.29	64.80	32.43	97.23	46.18
2	<i>Syzygium cuminii</i>	60.00	4.37	4.28	2.64	6.93	3.29
3	<i>Mallotus philippinensis</i>	40.00	1.60	1.53	1.05	2.58	1.23
4	<i>Terminalia tomentosa</i>	27.00	10.69	10.49	5.24	15.73	7.47
5	<i>Cordia dichotoma</i>	25.50	0.71	0.46	0.35	0.80	0.38
6	<i>Cassia fistula</i>	10.00	0.29	0.35	0.26	0.61	0.29
	TOTAL	322.50	68.95	81.91	41.98	123.89	58.85

The data presented in Table 22 shows the total density of 270.00 number ha⁻¹, volume of 131.39 m³ ha⁻¹, AGB of 163.71 Mg ha⁻¹, BGB of 72.60 Mg ha⁻¹, TB of 236.31 Mg ha⁻¹, and carbon density of 112.25 Mg ha⁻¹ in Lai C₂₈. *S. robusta* was the most contributing species (115.00 N ha⁻¹), followed by *M. philippinensis* (35.00 N ha⁻¹), *S.cuminii* (25.00 N ha⁻¹), *C. dictoma* and *Eucalyptus globulus* and *Acacia catechu* and *Bauhinia variegata* both displaying identical values for density (22.50, 15.00 N ha⁻¹). While, *T. tomentosa* and *F. palmata* had the lowest tree density (10.00 N ha⁻¹). *S. robusta* was recorded to have maximum value of volume, AGB, BGB, TB and carbon stock (118.03 m³ ha⁻¹, 150.76 m³ ha⁻¹, 60.21 Mg ha⁻¹, 210.65 Mg ha⁻¹ and 100.21 Mg ha⁻¹), respectively, followed by *T. tomentosa*, *A. catachu* and *M. philippinensis*. The least contributing species having minimum contribution of storage potential of volume (0.80 m³ ha⁻¹), AGB (0.52 m³ ha⁻¹, 0.45 Mg ha⁻¹), BGB (0.29 Mg ha⁻¹), TB (0.74 Mg ha⁻¹) and carbon density (0.35 Mg ha⁻¹) was *C. dicotoma*.

The data depicted in Table 16-22 for the species wise distribution of density, volume, above, below and total biomass and carbon density reveals quite variation among different compartments of Sal Working Circle of Paonta Forest Range. The density ranged from 250 N ha⁻¹ (Rajban C₇) to 325 N ha⁻¹ (Gorakhpur C₇). Similarly, volume, above and below ground biomass, total biomass and carbon density showed a lot of intercompartmental variation. The volume of sal, principal species followed the order of Gorakhpur C₇ (51.2 m³ ha⁻¹) > Rajban C₇ (82.49 m³ ha⁻¹) > Lai C₂₈ (118.03 m³ ha⁻¹) > Rajban C₆ (140.03 m³ ha⁻¹) > Kkukron C₁₅ (163.62 m³ ha⁻¹) > Rajban C₁₀ (188.61 m³ ha⁻¹) > Kukron C₁₄ (254.56 m³ ha⁻¹).

Table 22 Species wise density (N ha⁻¹), Volume (m³ ha⁻¹), AGB (Mg ha⁻¹), BGB (Mg ha⁻¹), TB (Mg ha⁻¹) and carbon stock (Mg C ha⁻¹) of trees in Lai C₂₈ compartment under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Density (N ha ⁻¹)	Volume (m ³ ha ⁻¹)	Above ground biomass (Mgha ⁻¹)	Below ground biomass (Mg ha ⁻¹)	Total biomass (Mg ha ⁻¹)	Carbon density (Mg C ha ⁻¹)
1	<i>Syzyguim cuminii</i>	25.00	1.11	1.09	0.94	2.03	0.96
2	<i>Cordia dichotoma</i>	22.50	0.80	0.78	0.38	1.16	0.55
3	<i>Shorea robusta</i>	115.00	118.03	150.76	60.21	210.97	100.21
4	<i>Mallotus philippenensis</i>	35.00	1.53	1.41	1.26	2.67	1.27
5	<i>Bauhinia variegata</i>	15.00	1.25	1.20	1.10	2.30	1.09
6	<i>Acacia catachu</i>	15.00	1.56	1.52	2.55	4.07	1.93
7	<i>Terminalia tomentosa</i>	10.00	4.90	4.85	4.56	9.41	4.47
8	<i>Eucalyptus globulus</i>	22.50	1.36	1.30	1.15	2.45	1.16
9	<i>Ficus palmata</i>	10.00	0.85	0.80	0.45	1.25	0.59
	TOTAL	270.00	131.39	163.71	72.60	236.31	112.25

This indicate that there is enough scope for imposing optimum treatments, like density manipulation of mixture to create favourable environment for growth of Sal so that volume realization and carbon storage capacity from the low yielding compartments, like Gorakhpur C₇ Rajban C₇, Lai C₂₈ and Rajban C₇, etc. can be enhanced.

4.5 STAND STRUCTURE

Stand structure (N ha⁻¹) under different compartments of Sal Working Circle is depicted in Table 23. In case of Rajban C₆, a total tree density of 258 N ha⁻¹ were recorded of which the majority of distribution (103 N ha⁻¹) was in D₁ diameter class followed by D₃ (48 N ha⁻¹) and D₄ (31 N ha⁻¹). Likewise, the total tree density of 250 N ha⁻¹ was recorded in Rajban C₇ of which diameter class D₁ (110 N ha⁻¹) had the maximum contribution followed by D₃ (64 N ha⁻¹) and D₄ (41 N ha⁻¹) and Kukron C₁₅ followed the same trend for distribution of trees among diameter classes with a total density of 298 N ha⁻¹ of which diameter class D₁ (113 N ha⁻¹) had the maximum contribution followed by D₃ (65 N ha⁻¹) and D₄ (43 N ha⁻¹), respectively.

Table 23 Stand structure (N ha⁻¹) of different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Diameter classes (cm)	Compartments						
	Rajban C ₆	Rajban C ₇	Kukron C ₁₄	Rajban C ₁₀	Kukron C ₁₅	Gorakhpur C ₇	Lai C ₂₈
10-20 (D₁)	103	110	120	102	113	197	98
20-30 (D₂)	30	15	33	55	40	68	70
30-40 (D₃)	48	64	60	54	65	58	37
40-50 (D₄)	31	41	28	47	42	-	20
50-60 (D₅)	14	10	23	10	13	-	10
60-70 (D₆)	20	10	15	33	15	-	25
70-80 (D₇)	9	-	18	-	10	-	10
80-90 (D₈)	5	-	10	-	-	-	-
Total	258	250	305	300	298	323	270

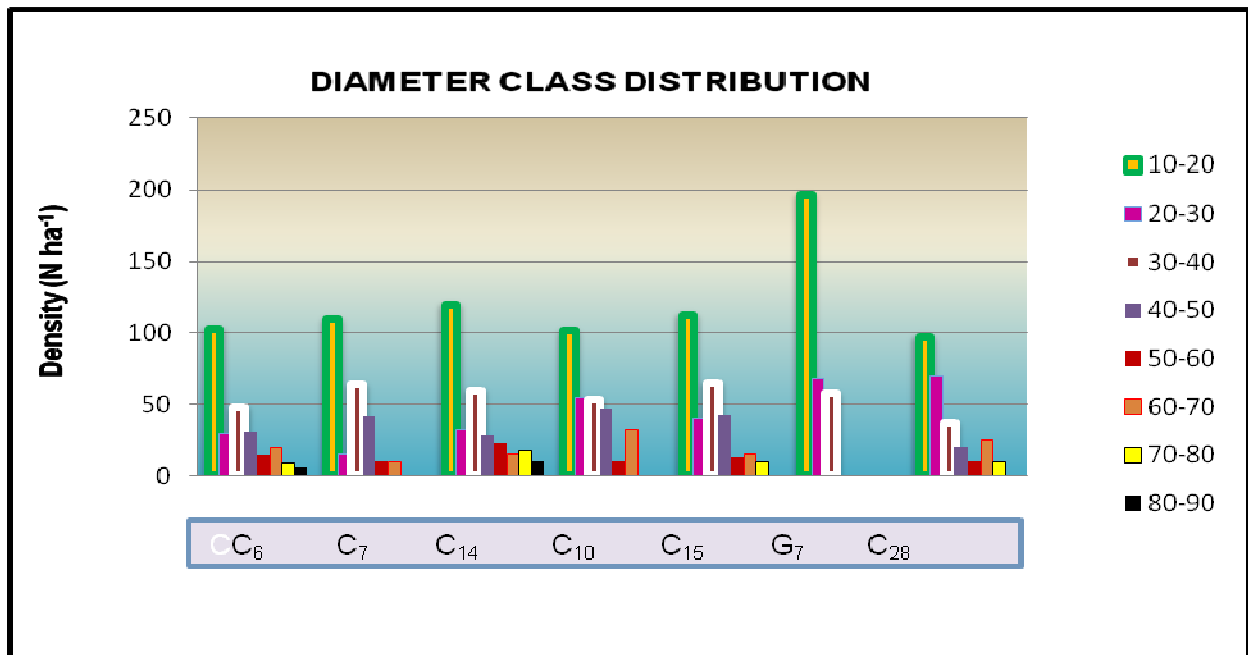


Fig. 3 Stand structure ($N\ ha^{-1}$) under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Data presented in the Table 23 indicated that in general the number of the trees declined from the lowest to higher diameter classes excepting in Gorakhpur C₇ compartment. This characteristic decline in the number of the tree from the lowest to higher diameter classes is a characteristic feature of the natural/selection forest ecosystems. The compartments under our investigation are managed under the shelterwood system even then compartments tends to follow the reverse J-shaped curve. This distribution pattern of the stems in the compartments indicate towards the good environmental conditions prevailing under these compartments which induces the regeneration and lack of anthropogenic/biotic pressure. In addition to this, it also indicates towards the ability of the sal tree and its associates to regenerate under less opened up canopy. This pyramidal structure the population under *S. robusta* forest of the compartments also indicate towards the gradual progression of the population and protection of the forests from the fire and other disturbances. The pyramidal structure of the population as recorded in our study has been reposted by other workers in the sal species (Poudel and Devkota, 2022; Adhikari *et al.*, 2017). In both Rajban C₇ and Rajban C₁₀ distribution of the trees is only upto D₆ (60-70 cm diameter class). Similiarly in Kukron C₁₅ and Lai C₂₈ tree distribution is upto 70-80 cm diameter class out of the seven compartments under study only Gorakhpur C₇ has most restricted distribution of the trees i.e., in only three diameter classes.

High proportion of individuals in lower diameter class indicates a healthy and growing population. The absence or presence of a higher number of trees in the different diameters class of various compartments is due prescribed felling carried out in these compartments. The reverse J-shaped curve indicates heavy exploitation in higher girth classes (Rao *et al.*, 1990). Although, this shape of curve is a good indicator for development and regeneration of forest stand and the growth of forest are also indicated by the movement of trees in various diameter classes. According to Phillip and Gentry (1993), a reverse 'J' shape is common for natural forests with active regeneration and recruitment. In general, trees belonging to bigger diameter classes contribute greater basal area, as compare to the lower diameter classes (Hailemariam and Temam, 2018). Our study is in conformity with Kumar and Saikia (2020) who reported the Girth class distribution that showed a reverse J-shaped population curve and decline in tree density with an increase in girth class, with very few (9.30 %) mature trees with higher girth (> 120 cm) which is closer to and within range of our study. Moreover, the lesser number of trees in bigger diameter classes in Gorakhpur C₇ indicate towards anthropogenic disturbances, like logging, fuel wood extraction, and encroachments of the area as this compartment is in proximity to habitation. Human-induced disruptions influenced stand characteristics in all study sites, regardless of management regime. However, the diameter class distribution of the tree species revealed that the highest number of individuals were concentrated in the lower diameter classes indicating a young and expanding population of *S. robusta* in Gorakhpur C₇. (Nag and Gupta, 2014).

Table 24 Population dynamics (N ha⁻¹) of different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Seedling (N ha ⁻¹)	Sapling (N ha ⁻¹)	Pole (N ha ⁻¹)	Trees (N ha ⁻¹)
Rajban C₆	4688	2125	290	258
Rajban C₇	4625	2000	230	250
Kukron C₁₄	6000	2438	440	305
Rajban C₁₀	5688	3063	190	300
Kukron C₁₅	4875	2125	220	298
Gorakhpur C₇	5438	2250	310	323
Lai C₂₈	5250	2563	160	270

The results pertaining to the Population dynamics (N ha⁻¹) of different compartments are presented in Table 24. Kukron C₁₄ had maximum seedling density (6000 N ha⁻¹) followed by Rajban C₁₀ (5688 N ha⁻¹) and Gorakhpur C₇ (5438 N ha⁻¹), while, Rajban C₇ had the minimum seedling density (4625 N ha⁻¹). Rajban C₁₀, on the other hand, had the maximum recorded sapling density at 3063 N ha⁻¹, followed by Lai C₂₈ with 2563 N ha⁻¹ and Kukron

C₁₄ with 2438 N ha⁻¹, respectively. Rajban C₇ recorded the minimum reported sapling density (2000 N ha⁻¹). In the case of pole density, the maximum value was recorded in Kukron C₁₄ (440 N ha⁻¹) followed by Gorakhpur C₇ (310 N ha⁻¹) and Rajban C₆ (290 N ha⁻¹). Rajban C₇ recorded the minimum pole density (160 N ha⁻¹). Whereas, Gorakhpur C₇ (323 N ha⁻¹) recorded maximum value of tree density followed by Kukron C₁₄ (305 N ha⁻¹). Differences in the relative proportions of seedlings, saplings, and trees in various compartments in our study can be traced to anthropogenic disturbances as well as natural phenomena such as climate, soil, seed and biotic conditions of the forest. The overall population structure based on the density of seedling, sapling and pole individuals formed a pyramidal structure in all the forest compartments. The reverse J-shaped population curve may be due to evolving/expanding or climax/stable population indicating a natural regeneration and healthy population in the studied forests (Sahu *et al.*, 2012).

Experiment II: Assessment of stand characteristics biomass carbon density and site quality of different compartments of sal forest.

4.6 STAND CHARACTERISTICS

Stand characteristics of trees under different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh has been presented and discussed under following sub-heads (Table 25).

4.6.1 Tree density (N ha⁻¹)

The data pertaining to density (number ha⁻¹) of trees is depicted in Table 25. It shows that Gorakhpur C₇ had significantly maximum tree density (322.50 N ha⁻¹) which was statistically at par with Kukron C₁₄ (305.00 N ha⁻¹) and Rajban C₁₀ (300.00 N ha⁻¹) followed by Rajban C₁₀ (300.00 N ha⁻¹), which was statistically at par with Kukron C₁₅ (297.50 N ha⁻¹). Tree density in kukron C₁₅ (297.50 N ha⁻¹) was statistically at par with Lai C₂₈ (300.00 N ha⁻¹). However, Rajban C₇ displayed the lowest tree density (250 N ha⁻¹), which was found to be statistically at par with Rajban C₆ (257.50 N ha⁻¹) only.

4.6.2 Tree Diameter (cm)

A perusal of the data presented in Table 25 reveals that maximum average diameter (33.27 cm) was recorded in Kukron C₁₄, which remained statistically at par with Rajban C₁₀ (31.51 cm), Rajban C₆ (31.15 cm) and Kukron C₁₅ (31.05 cm). Further, average diameter in Rajban C₆ was statistically at par with Kukron C₁₅, Rajban C₇ (28.73 cm) Lai C₂₈ (28.01 cm). Significantly minimum diameter was recorded in Gorakhpur C₇ (20.27 cm), which remain statistically at par with Lai C₂₈ only.

4.6.3 Basal area (m² ha⁻¹)

A significant variation in basal area of trees under different compartments (Table 25). Significantly maximum value for basal area (1.19 m² ha⁻¹) was recorded in Kukron C₁₄ which was statistically at par with Rajban C₆ (1.01 m² ha⁻¹), Rajban C₆ remain statistically at par with Rajban C₁₀ (0.99 m² ha⁻¹) and Kukron C₁₅ (0.95 m² ha⁻¹). The minimum value of basal area was estimated in Gorakhpur C₇ (0.37 m² ha⁻¹).

4.6.4 Tree height (m)

The data presented in Table 25 delineates significant inter compartmental variation for tree height among different compartments. The maximum tree height (15.10 m) was recorded in Rajban C₁₀, which was statistically at par with Kukron C₁₄ (14.97 m), Gorakhpur C₇ (14.16 m) and Kukron C₁₅ (13.51 m). Whereas, the minimum tree height was recorded in Rajban C₇ (11.60 m), which was found to be statistically at par with Lai C₂₈ (11.71 m) and Rajban C₆ (12.37 m).

4.6.5 Volume (m³ ha⁻¹)

The volume of trees had shown a significant variation among different compartments (Table 25). Significantly maximum volume (277.88 m³ ha⁻¹) was recorded in Kukron C₁₄, which was followed by Rajban C₁₀ (209.19 m³ ha⁻¹) and Kukron C₁₅ (182.48 m³ ha⁻¹), respectively in descending order. However, Kukron C₁₅ (182.48 m³ ha⁻¹) was statistically at par with Rajban C₆ (155.86 m³ ha⁻¹). Whereas, the lowest value for volume was recorded in Gorakhpur C₇ (68.95 m³ ha⁻¹), which was observed to be statistically at par with Rajban C₇ (103.71 m³ ha⁻¹), only.

Table 25 Stand characteristics of trees under different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Density(number ha ⁻¹)	Tree diameter (cm)	Basal area(m ² ha ⁻¹)	Tree height (m)	Volume (m ³ ha ⁻¹)
Rajban C ₆	257.50 ± 6.29	31.15 ± 1.05	1.01 ± 0.06	12.37 ± 0.80	155.86 ± 6.92
Rajban C ₇	250.00 ± 7.07	28.73 ± 0.90	0.80 ± 0.03	11.60 ± 0.49	103.71 ± 7.54
Kukron C ₁₄	305.00 ± 6.46	33.27 ± 2.09	1.19 ± 0.14	14.97 ± 0.84	277.88 ± 34.70
Rajban C ₁₀	300.00 ± 6.46	31.51 ± 1.12	0.99 ± 0.05	15.10 ± 0.68	209.19 ± 14.37
Kukron C ₁₅	297.50 ± 7.50	31.05 ± 0.76	0.95 ± 0.03	13.51 ± 0.46	182.48 ± 9.34
Gorakhpur C ₇	322.50 ± 8.54	20.27 ± 0.71	0.37 ± 0.03	14.16 ± 0.53	68.95 ± 4.86
Lai C ₂₈	270.00 ± 9.13	28.01 ± 0.30	0.81 ± 0.02	11.71 ± 0.25	131.39 ± 3.54
C.D. _{0.05}	22.95	3.06	0.18	1.59	46.51

4.6.6 Density (N ha⁻¹) and Basal area (cm² ha⁻¹) of shrubs

The data pertaining to the density (N ha⁻¹) of shrubs under different compartments is depicted in Table 26. The significantly maximum shrub density was recorded in Rajban C₁₀ (11,200.00 N ha⁻¹), which was followed by Kukron C₁₅ (10,200.00 N ha⁻¹), Rajban C₆ (9,100.00 N ha⁻¹), Rajban C₇ (8,120.00 N ha⁻¹), Lai C₂₈ (7,780.00 N ha⁻¹) and Gorakhpur C₇ (6,920.00 N ha⁻¹), respectively in decreasing order. The significantly lowest shrub density (5,540.00 N ha⁻¹) was recorded in Kukron C₁₄.

4.6.7 Basal area (cm² ha⁻¹) of shrubs

The basal area of shrubs (Table 26) shows that there is a significant variation among different compartments. The maximum basal area (81,326.94 cm² ha⁻¹) was recorded in Rajban C₁₀, which remains statistically at par with Kukron C₁₅ (75,465.85 cm² ha⁻¹) and was followed by Rajban C₇ (66,123.78 cm² ha⁻¹), Rajban C₆ (63,392.72 cm² ha⁻¹), Lai C₂₈ (52,248.02 cm² ha⁻¹) and Gorakhpur C₇ (41,294.04 cm² ha⁻¹), respectively in decreasing order. Whereas, the significantly minimum basal area (29,991.88 cm² ha⁻¹) was recorded in Kukron C₁₄.

Table 26 Density (number ha⁻¹) and basal area (cm² ha⁻¹) shrubs and herbs under different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Shrubs		Herbs	
	Density (number ha ⁻¹)	Basal Area (cm ² ha ⁻¹)	Density (number ha ⁻¹)	Basal Area (cm ² ha ⁻¹)
Rajban C ₆	9,100.00±38.30	63,392.72±4,928.33	133,300.00±2,106.34	189,511.00±6,039.29
Rajban C ₇	8,120.00±51.64	66,123.78±725.30	142,100.00±574.46	201,513.70±7,621.02
Kukron C ₁₄	5,540.00±88.694	29,991.88±2,673.93	185,800.00±783.16	212,444.10±25,733.77
Rajban C ₁₀	11,200.00±73.03	81,326.94±2,119.19	181,200.00±4,335.90	207,540.80±29,026.23
Kukron C ₁₅	10,200.00±105.83	75,465.85±2,280.10	167,000.00±1,851.13	134,552.70±8,493.24
Gorakhpur C ₇	6,920.00±23.09	41,294.04±1,012.16	155,000.00±2,923.47	211,661.90±8,540.27
Lai C ₂₈	7,780.00±191.49	52,248.02±1,662.40	182,800.00±683.13	143,948.90±528.81
C.D. _{0.05}	284.30	7151.24	6954.45	40,203.13

4.6.8 Density (N ha⁻¹) of Herbs

A perusal of data presented in Table 26 shows that Kukron C₁₄ (185,800.00 N ha⁻¹) had maximum herb density, which remains statistically at with Lai C₂₈ (182,800.00 N ha⁻¹) and Rajban C₁₀ (181,200.00 N ha⁻¹). Rajban C₆ was recorded with lowest herb density (133,300.00 N ha⁻¹).

4.6.9 Basal area ($\text{cm}^2 \text{ha}^{-1}$) of Herbs

Herbage basal area varied significantly among different compartments of sal (Table 26). Kukron C₁₄ displayed maximum basal area of herbs ($212,444.10 \text{ cm}^2 \text{ha}^{-1}$), which was found to be statistically at par with Gorakhpur C₇ ($211,661.90 \text{ cm}^2 \text{ha}^{-1}$) and followed by Rajban C₁₀ ($207,540.80 \text{ cm}^2 \text{ha}^{-1}$), Rajban C₇ ($201,513.70 \text{ cm}^2 \text{ha}^{-1}$) and Rajban C₆ ($189,511.00 \text{ cm}^2 \text{ha}^{-1}$), respectively in descending order. Whereas, the minimum basal area ($495.81 \text{ cm}^2 \text{ha}^{-1}$) was recorded in Kukron C₁₅, which remained statistically at par with Lai C₂₈.

4.7 BIOMASS AND CARBON STOCK

4.7.1 Stem biomass (Mg ha^{-1})

The stem biomass of tree under different compartments is presented in Table 27. Significantly maximum stem biomass was recorded in compartment of Kukron C₁₄ ($199.32 \text{ Mg ha}^{-1}$), which was followed by Rajban C₁₀ ($150.10 \text{ Mg ha}^{-1}$), respectively in descending order followed by Kukron C₁₅ ($130.66 \text{ Mg ha}^{-1}$) and Rajban C₆ ($111.45 \text{ Mg ha}^{-1}$). Further remained statistically at par with Rajban C₆ ($111.45 \text{ Mg ha}^{-1}$) remained statistically at par with Lai C₂₈ (94.37 Mg ha^{-1}) and Rajban C₇ (72.88 Mg ha^{-1}). The minimum value for stem biomass was displayed by Gorakhpur C₇ (48.53 Mg ha^{-1}), which was found to be at par with Rajban C₇ (72.88 Mg ha^{-1}). Overall, the stem biomass under different compartments followed the order: Kukron C₁₄ > Rajban C₁₀ > Kukron C₁₅ > Rajban C₆ > Lai C₂₈ > Rajban C₇ > Gorakhpur C₇.

4.7.1.1 Above Ground Biomass (AGB) (Mg ha^{-1})

The above ground biomass of tree under different compartments is shown in Table 27. Significantly maximum AGB ($343.96 \text{ Mg ha}^{-1}$) was recorded in Kukron C₁₄, which was followed by Rajban C₁₀ ($258.46 \text{ Mg ha}^{-1}$), C₁₅ ($224.87 \text{ Mg ha}^{-1}$). Furthermore, Kukron C₁₅ ($224.87 \text{ Mg ha}^{-1}$) remains statistically at par with Rajban C₆ ($192.02 \text{ Mg ha}^{-1}$), respectively. Rajban C₆ ($192.02 \text{ Mg ha}^{-1}$) remains statistically at par with Lai C₂₈ ($163.71 \text{ Mg ha}^{-1}$), which further remains statistically at par with Rajban C₇ ($124.22 \text{ Mg ha}^{-1}$). The minimum value for AGB was displayed by Gorakhpur C₇ (81.91 Mg ha^{-1}) which remained at par with Rajban C₇ ($124.22 \text{ Mg ha}^{-1}$). Overall, the AGB under different compartments followed the trend: Kukron C₁₄ > Rajban C₁₀ > Kukron C₁₅ > Rajban C₆ > Lai C₂₈ > Rajban C₇ > Gorakhpur C₇.

4.7.1.2 Below Ground Biomass (BGB) (Mg ha⁻¹)

The below ground biomass was computed from the AGB for different compartments is shown in Table 27. The BGB of tree under different compartments is illustrated in Table 27. Significantly maximum BGB (143.39 Mg ha⁻¹) was recorded in Kukron C₁₄ and followed by Rajban C₁₀ (112.74 Mg ha⁻¹), respectively in descending order. Furthermore, Kukron C₁₅ (94.98 Mg ha⁻¹) remains statistically at par with Rajban C₆ (84.30 Mg ha⁻¹) and Lai C₂₈ (72.60 Mg ha⁻¹), respectively. However, Lai C₂₈ (72.60 Mg ha⁻¹), which remained statistically at par with Rajban C₇ (56.89 Mg ha⁻¹). The minimum value for BGB was displayed by Gorakhpur C₇ (41.98 Mg ha⁻¹). The AGB under different compartments followed the order: Kukron C₁₄> Rajban C₁₀> Kukron C₁₅> Rajban C₆> Lai C₂₈> Rajban C₇> Gorakhpur C₇.

4.7.1.3 Total biomass (TB) (Mg ha⁻¹)

The Total biomass was computed by adding the AGB and BGB under different compartments and is shown in Table 27. Significantly maximum TB (487.35 Mg ha⁻¹) was recorded in Kukron C₁₄ which was followed by Rajban C₁₀ (371.20 Mg ha⁻¹), Kukron C₁₅ (317.84 Mg ha⁻¹), respectively in descending manner. Furthermore, Kukron C₁₅ (317.84 Mg ha⁻¹) remains statistically at par with Rajban C₆ (276.32Mg ha⁻¹) and Lai C₂₈ (236.31 Mg ha⁻¹). However, Lai C₂₈ (236.31 Mg ha⁻¹) remained statistically at par with Rajban C₇ (181.14 Mg ha⁻¹). While, the minimum value for total biomass was reported by Gorakhpur C₇ (123.89 Mg ha⁻¹) at par with Rajban C₇ (181.14 Mg ha⁻¹). The trend of total biomass under different compartments followed the trend: Kukron C₁₄> Rajban C₁₀>Kukron C₁₅>Rajban C₆>Lai C₂₈>Rajban C₇> Gorakhpur C₇.

Table 27 Biomass (Mg ha⁻¹) of tree component under different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Stem biomass (Mg ha ⁻¹)	Above ground biomass (Mg ha ⁻¹)	Below ground biomass (Mg ha ⁻¹)	Total biomass (Mg ha ⁻¹)
Rajban C ₆	111.45±5.19	192.02±9.27	84.30±3.79	276.32±13.03
Rajban C ₇	72.88±5.10	124.24±8.44	56.89±3.62	181.14±12.85
Kukron C ₁₄	199.32±25.51	343.96±44.71	143.39±17.11	487.35±61.80
Rajban C ₁₀	150.10±10.07	258.46±16.94	112.74±7.30	371.20±24.23
Kukron C ₁₅	130.66±6.36	222.86±10.55	94.98±4.72	317.84±12.27
Gorakhpur C ₇	48.54±3.40	81.91±5.76	41.98±4.83	123.89±10.43
Lai C ₂₈	94.37±2.54	163.71±4.18	72.60±1.48	236.31±7.52
C.D. 0.05	33.79	58.64	23.06	80.23

4.7.3 SHRUB BIOMASS ($t\ ha^{-1}$)

4.7.3.1 Above ground shrub biomass (AGB) ($Mg\ ha^{-1}$)

The above ground shrub biomass under different compartments is shown in Table 28. Table depicts that significantly maximum value for above ground shrub biomass ($1.25\ Mg\ ha^{-1}$) was in Rajban C₁₀, this was followed by Kukron C₁₅ ($0.98\ Mg\ ha^{-1}$), which remains statistically at par with Rajban C₆ ($0.92\ Mg\ ha^{-1}$). Further, Rajban C₆ ($0.92\ Mg\ ha^{-1}$) remains statistically at par with Rajban C₇ ($0.85\ Mg\ ha^{-1}$) and Gorakhpur C₇ ($0.83\ Mg\ ha^{-1}$). Whereas, the lowest value for above ground shrub biomass ($0.70\ Mg\ ha^{-1}$) was recorded in Kukron C₁₄, which was found to be statistically at par with in Lai C₂₈ ($0.80\ Mg\ ha^{-1}$).

4.7.3.2 Below ground shrub biomass (BGB) ($Mg\ ha^{-1}$)

The results pertaining to the below ground shrub biomass under different compartments is shown in Table 28. Significantly maximum value of below ground shrub biomass ($0.83\ Mg\ ha^{-1}$) was recorded in Kukron C₁₅, which was followed by Gorakhpur C₇ ($0.64\ Mg\ ha^{-1}$), Rajban C₆ ($0.60\ Mg\ ha^{-1}$), Lai C₂₈ ($0.57\ Mg\ ha^{-1}$), Rajban C₇ ($0.55\ Mg\ ha^{-1}$) and Rajban C₁₀ ($0.55\ Mg\ ha^{-1}$), respectively. Moreover, the lowest value for below ground shrub biomass was recorded in Kukron C₁₄ ($0.49\ Mg\ ha^{-1}$) which remains statistically at par with Rajban C₇ ($0.55\ Mg\ ha^{-1}$), Kukron C₁₅ ($0.55\ Mg\ ha^{-1}$) and Lai C₂₈ ($0.57\ Mg\ ha^{-1}$).

4.7.3.3 Total Shrub biomass ($Mg\ ha^{-1}$)

A perusal of the data presented in Table 28 shows the total shrub biomass under different compartments. Significantly maximum value for total shrubs biomass ($2.07\ Mg\ ha^{-1}$) was recorded in Rajban C₁₀, which was followed by Kukron C₁₅ ($1.62\ Mg\ ha^{-1}$) and Rajban C₆ ($1.52\ Mg\ ha^{-1}$), respectively.. Whereas, Rajban C₆ ($1.52\ Mg\ ha^{-1}$) was found to be statistically at par with Rajban C₇ ($1.40\ Mg\ ha^{-1}$) and Gorakhpur C₇ ($1.38\ Mg\ ha^{-1}$). Gorakhpur C₇ ($1.38\ Mg\ ha^{-1}$) was found to be statistically at par with Lai C₂₈ ($1.33\ Mg\ ha^{-1}$). The lowest value for total shrub biomass ($1.18\ Mg\ ha^{-1}$) was estimated in Kukron C₁₄, which was followed by Lai C₂₈ ($1.33\ Mg\ ha^{-1}$).

Table 28 Biomass (Mg ha⁻¹) of shrub component of different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Above ground shrub biomass (Mg ha ⁻¹)	Below ground shrub biomass (Mg ha ⁻¹)	Total shrub biomass (Mg ha ⁻¹)
Rajban C ₆	0.92±0.02	0.60±0.01	1.52±0.03
Rajban C ₇	0.85±0.03	0.55±0.02	1.40±0.05
Kukron C ₁₄	0.70±0.05	0.49±0.05	1.18±0.06
Rajban C ₁₀	1.25±0.05	0.55±0.07	2.07±0.08
kukron C ₁₅	0.98±0.03	0.83±0.02	1.62±0.04
Gorakhpur C ₇	0.83±0.03	0.64±0.02	1.38±0.05
Lai C ₂₈	0.80±0.02	0.57±0.03	1.33±0.03
C.D. _{0.05}	0.10	0.11	0.16

4.7.4 Herb biomass (t ha⁻¹)

4.7.4.1 Above ground herb biomass (Mg ha⁻¹)

The above ground herb biomass under different compartments is displayed in Table 29. It shows that maximum value for above ground herb biomass (4.58 Mg ha⁻¹) was reported in Gorakhpur C₇, which remains statistically at par with Rajban C₇ (4.07 Mg ha⁻¹). While Lai C₂₈ (3.36 Mg ha⁻¹) and Rajban C₁₀ (3.30 Mg ha⁻¹) remains statistically at par with each other. Whereas, the lowest value for above ground herb biomass (2.68 Mg ha⁻¹) was recorded in Kukron C₁₅, which was found to be statistically at par with Kukron C₁₄ (3.19 Mg ha⁻¹).

Table 29 Biomass (Mg ha⁻¹) in herb component of different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Above ground herb biomass (Mg ha ⁻¹)	Below ground herb biomass (Mg ha ⁻¹)	Total herb biomass (Mg ha ⁻¹)
Rajban C ₆	3.89±0.02	2.53±0.02	6.42±0.04
Rajban C ₇	4.07±0.04	2.64±0.02	6.71±0.06
Kukron C ₁₄	3.19±0.04	2.07±0.03	5.26±1.01
Rajban C ₁₀	3.30±0.06	2.15±0.04	5.45±0.11
Kukron C ₁₅	2.68±0.03	1.73±0.02	4.41±0.05
Gorakhpur C ₇	4.58±0.46	2.98±0.30	7.55±0.75
Lai C ₂₈	3.36±0.03	2.19±0.02	5.55±0.05
C.D. _{0.05}	0.51	0.54	0.56

4.7.4.2 Below ground herb biomass (Mg ha⁻¹)

Variation in below ground herb biomass under different compartments is presented in Table 29. A similar trend as in above ground herb biomass can be seen. Maximum value for below ground herb biomass (2.98 Mg ha⁻¹) was reported in Gorakhpur C₇. Rajban C₆ (2.53 Mg ha⁻¹) remains statistically at par with Lai C₂₈ (2.19 Mg ha⁻¹). While, Lai C₂₈ (2.19 Mg ha⁻¹) and Rajban C₁₀ (2.15 Mg ha⁻¹) remains statistically at par with each other. Whereas, the lowest value for below ground herb biomass (1.73 Mg ha⁻¹) was recorded in Kukron C₁₅, which was found to be statistically at par with Kukron C₁₄ (2.07 Mg ha⁻¹).

4.7.4.3 Total herb biomass (Mg ha⁻¹)

The results pertaining to the total herb biomass under different compartments (Table 29) shows that maximum value was recorded in Gorakhpur C₇ (7.55 Mg ha⁻¹), which remains statistically at par with Rajban C₇ (6.71 Mg ha⁻¹) and Rajban C₆ (6.42 Mg ha⁻¹). However, significantly lowest value for total herb biomass (4.41 Mg ha⁻¹) was recorded in Kukron C₁₅.

4.7.5 Carbon density (Mg C ha⁻¹)

The carbon density present in different layers of sal forest compartments as well as total has been depicted in Table 30.

4.7.5.1 Tree carbon density (Mg C ha⁻¹)

A perusal of the data in Table 39 reveals that significant maximum value for tree carbon density (232.66 Mg C ha⁻¹) was recorded for Kukron C₁₄, which was followed by Rajban C₁₀ (176.32 Mg C ha⁻¹). The tree carbon recorded in Rajban C₁₀ (176.32 Mg C ha⁻¹) was statistically at par with Kukron C₁₅ (152.58 Mg C ha⁻¹). Further, Kukron C₁₅ remains statistically at par with Rajban C₆ (131.25 Mg C ha⁻¹). Whereas, the lowest tree carbon density (58.85 Mg C ha⁻¹) was in Gorakhpur C₇, which remained statistically at par with Rajban C₇ (86.04 Mg C ha⁻¹).

4.7.5.2 Shrub carbon density (Mg C ha⁻¹)

Significantly maximum shrub carbon density was found in Rajban C₁₀ (0.98 Mg C ha⁻¹) which was followed by Kukron C₁₅ (0.77 Mg C ha⁻¹), which remained statistically at par with Rajban C₆ (0.72 Mg C ha⁻¹). Shrub carbon density in Rajban C₆ (0.72 Mg C ha⁻¹) remains statistically at par with Rajban C₇ (0.66 Mg C ha⁻¹) and Gorakhpur C₇ (0.65 Mg C ha⁻¹). Further, Gorakhpur C₇ was statistically at par with Lai C₂₈ (0.63 Mg C ha⁻¹). Whereas,

Kukron C₁₄ (0.56 Mg C ha⁻¹) had minimum value and remained statistically at par with Lai C₂₈ (0.63Mg C ha⁻¹).

4.7.5.3 Herb carbon density (Mg C ha⁻¹)

For herb carbon density, the maximum value was recorded in Gorakhpur C₇ (3.59 Mg C ha⁻¹), which remains statistically at par with Rajban C₇ (3.19 Mg C ha⁻¹) and Rajban C₆ (3.05 Mg C ha⁻¹). Rajban C₆ (3.05 Mg C ha⁻¹) remained statistically at par with Lai C₂₈ (2.63 Mg C ha⁻¹), (2.59 Mg C ha⁻¹) and Rajban C₁₀ (2.49 Mg C ha⁻¹). The lowest value for herb carbon density was recorded in Kukron C₁₅ (2.09 Mg C ha⁻¹), which remained statistically at par with Kukron C₁₄ (2.49 Mg C ha⁻¹), Rajban C₁₀ (2.59 Mg C ha⁻¹) and Lai C₂₈ (2.63 Mg C ha⁻¹).

4.7.5.4 Total carbon density (Mg C ha⁻¹)

The total carbon density (Mg C ha⁻¹) recorded under different compartments of sal working circle in Paonta Forest Range (Table 30) varied significantly. Significantly maximum value was recorded in Kukron C₁₄ (234.26 Mg C ha⁻¹), which was followed by Rajban C₁₀ (179.57 Mg C ha⁻¹) Kukron C₁₄ remained statistically at par with Kukron C₁₅ (155.44 Mg C ha⁻¹). Further, Kukron C₁₅ remained statistically at par with Rajban C₆ (135.02 Mg C ha⁻¹), which remained at par with Lai C₂₈ (115.51 Mg C ha⁻¹), Lai C₂₈ remained statistically at par with Rajban C₇ (89.99 Mg C ha⁻¹). Whereas, Gorakhpur C₇ (63.09 Mg C ha⁻¹) had the lowest value for total carbon density which remained statistically at par with Rajban C₇ (89.99 Mg C ha⁻¹).

Table 30 Total carbon density of trees, herbs and shrubs under different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Tree carbon density (Mg C ha ⁻¹)	Shrub carbon density(Mg C ha ⁻¹)	Herb carbon density(Mg C ha ⁻¹)	Total carbon (Mg C ha ⁻¹)
Rajban C ₆	131.25 ± 6.19	0.72±0.01	3.05±0.02	135.02±6.21
Rajban C ₇	86.04 ± 6.10	0.66±0.03	3.19±0.03	89.89±6.10
Kukron C ₁₄	232.66 ± 29.36	0.56±0.03	2.49±0.48	234.26±29.45
Rajban C ₁₀	176.32 ± 11.51	0.98±0.04	2.59±0.05	179.57±11.54
Kukron C ₁₅	152.58 ± 5.83	0.77±0.02	2.09±0.02	155.44±5.83
Gorakhpur C ₇	58.85 ± 4.95	0.65±0.02	3.59±0.36	63.09±4.25
Lai C ₂₈	112.25 ± 4.95	0.63±0.02	2.63±0.02	115.51±3.55
C.D. _{0.05}	38.11	0.08	0.66	38.2

4.7.6.1 Leaf litter (Mg ha⁻¹)

A perusal of data presented in Table 31 shows the Leaf litter biomass under different compartments of sal forest. Maximum value (5.35 Mg ha⁻¹) for Leaf litter biomass was recorded for Kukron C₁₄ which remained statistically at par with Rajban C₁₀ (5.30 Mg ha⁻¹), Lai C₂₈ (5.15 Mg ha⁻¹) and Kukron C₁₅ (5.11Mg ha⁻¹). Whereas, the minimum value of Leaf litter biomass (3.99 Mg ha⁻¹) in Rajban C₇, which remained statistically at par with Rajban C₆ (4.10 Mg ha⁻¹).

4.7.6.2 Dead twigs and branches (Mg ha⁻¹)

The dead twig and branch biomass under different compartments as is shown in Table 31. The maximum value (0.85 Mg ha⁻¹) was recorded Kukron C₁₄, which remains statistically at par with Rajban C₁₀ (0.80 Mg ha⁻¹) and followed by Kukron C₁₅. Kukron C₁₅ remained statistically at par with Lai C₂₈ (0.44 Mg ha⁻¹), Gorakhpur C₇ (0.36 Mg ha⁻¹) and Rajban C₆ (0.34 Mg ha⁻¹). Whereas, the lowest value was recorded in Rajban C₇ (0.31 Mg ha⁻¹), which remained statistically at par with Rajban C₆ (0.34 Mg ha⁻¹), Gorakhpur C₇ (0.36 Mg ha⁻¹) and Lai C₂₈ (0.44 Mg ha⁻¹), respectively.

4.7.6.3 Dead trees (Mg ha⁻¹)

Dead tree biomass under different compartments is shown in Table 31. Table depicts that the maximum value (0.96 Mg ha⁻¹) for Kukron C₁₄, which remains statistically at par with Lai C₂₈ (0.89 Mg ha⁻¹) and Gorakhpur C₇ (0.83 Mg ha⁻¹) followed by Gorakhpur C₇ which remained statistically at par with Rajban C₆ (0.74 Mg ha⁻¹), Rajban C₁₀ (0.72 Mg ha⁻¹) and Kukron C₁₅ (0.70 Mg ha⁻¹). Whereas, the lowest value was recorded in Rajban C₇ (0.67 Mg ha⁻¹), which remained statistically at par with Kukron C₁₅ (0.70 Mg ha⁻¹), Kukron C₁₄ (0.72 Mg ha⁻¹) and Rajban C₆ (0.74 Mg ha⁻¹), respectively.

4.7.6.4 Total detritus biomass (Mg ha⁻¹)

Total detritus biomass under different compartments is shown in Table 31. It reveals significantly maximum value (7.16 Mg ha⁻¹) for Kukron C₁₄ is followed by Rajban C₁₀ (6.82 Mg ha⁻¹), which remains statistically at par with Lai C₂₈ (6.49 Mg ha⁻¹). Further, Lai C₂₈ remains statistically at par with Kukron C₁₅ (6.29 Mg ha⁻¹) and Gorakhpur C₇ (5.57 Mg ha⁻¹). Whereas, the minimum value was recorded in Rajban C₇ (4.97 Mg ha⁻¹), which remained statistically at par with Rajban C₆ (5.18 Mg ha⁻¹).

Table 31 Detritus biomass (t ha⁻¹) in different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Leaf litter (Mg ha ⁻¹)	Dead twigs and branches (Mg ha ⁻¹)	Dead trees (Mg ha ⁻¹)	Total detritus biomass (Mg ha ⁻¹)
Rajban C ₆	4.10±0.02	0.34±0.06	0.74±0.04	5.18±0.05
Rajban C ₇	3.99±0.02	0.31±0.05	0.67±0.04	4.97±0.06
Kukron C ₁₄	5.35±0.18	0.85±0.04	0.96±0.05	7.16±0.16
Rajban C ₁₀	5.30±0.18	0.80±0.04	0.72±0.01	6.82±0.21
Kukron C ₁₅	5.11±0.04	0.48±0.03	0.70±0.03	6.29±0.06
Gorakhpur C ₇	4.38±0.03	0.36±0.04	0.83±0.08	5.57±0.09
Lai C ₂₈	5.15±0.02	0.44±0.07	0.89±0.06	6.49±0.10
C.D. _{0.05}	0.11	0.15	0.15	0.36

4.7.7 Carbon density (Mg C ha⁻¹) in different pools

Data presented in Table 32 reveals that the carbon density (Mg C ha⁻¹) present among different pools of the compartments being studied. The maximum value of vegetation carbon density was recorded in Kukron C₁₄ (234.26 Mg C ha⁻¹) which was followed by Rajban C₁₀ (179.57 Mg C ha⁻¹). Further, Kukron C₁₅ remains statistically at par with Rajban C₆ (135.02 Mg C ha⁻¹). Whereas, Gorakhpur C₇ (63.09 Mg C ha⁻¹) had the lowest value for vegetation carbon density which remains statistically at par with Rajban C₇ (89.99 Mg C ha⁻¹).

Table 32 Carbon density (Mg C ha⁻¹) in different pools of the compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Parameters						
	Vegetation carbon density (Mg C ha ⁻¹)	Humus carbon (Mg C ha ⁻¹)	Soil carbon density (Mg C ha ⁻¹)	Total carbon density (humus +soil) (Mg C ha ⁻¹)	Detritus carbon density (Mg C ha ⁻¹)	Ecosystem carbon density (Mg C ha ⁻¹)	Carbon stock(Mg C ha ⁻¹)
Rajban C ₆	135.02±6.21	3.92 ±0.08	71.19±3.24	75.11±2.00	2.46 ±0.02	212.59±10.47	7,640.03
Rajban C ₇	89.89±6.10	3.51± 0.13	54.09±6.31	57.60 ±4.83	2.36± 0.03	149.85±7.83	5,774.63
Kukron C ₁₄	234.26±29.45	6.07±0.06	43.83±4.63	49.92 ±4.65	3.40 ±0.07	287.58±34.24	9,314.10
Rajban C ₁₀	179.57±11.54	5.23±0.07	50.22±7.99	55.45± 5.27	3.24± 0.10	238.26±9.72	8,378.27
kukron C ₁₅	155.44±5.83	5.13 ±0.10	45.63±5.64	50.76 ±5.76	2.99 ±0.03	209.19±9.62	7,216.34
Gorakhpur C ₇	63.09±4.25	5.14 ±0.06	43.35±3.00	48.79±5.15	2.65± 0.04	114.53±25.4	4,718.12
Lai C ₂₈	115.51±3.55	4.71 ±0.04	40.90±4.81	45.61 ±4.79	3.08± 0.05	164.20±7.26	5,909.95
C.D. _{0.05}	38.20	0.26	16.39	14.48	0.17	50.75	

4.7.7.1 Humus carbon density (Mg C ha⁻¹)

Significantly maximum humus carbon density (6.07 Mg C ha⁻¹) was recorded in Kukron C₁₄, which was followed by Rajban C₁₀ (5.23 Mg C ha⁻¹), Gorakhpur C₇ (5.14 Mg C ha⁻¹), Kukron C₁₅ (5.13 Mg C ha⁻¹), Lai C₂₈ (5.14 Mg C ha⁻¹) and Rajban C₆ (5.14 Mg C

ha⁻¹), respectively. Whereas, Rajban C₆ had significantly minimum value (3.92 Mg C ha⁻¹) among all compartments.

4.7.7.2 Soil carbon density (Mg C ha⁻¹)

The soil carbon density recorded in the 0-40 cm soil layer is depicted in Table 32. Significantly maximum value for soil carbon density was revealed in Rajban C₆ (71.19 Mg C ha⁻¹) followed by Rajban C₇ (54.09 Mg C ha⁻¹), Rajban C₁₀ (50.22 Mg C ha⁻¹), Kukron C₁₅ (45.63 Mg C ha⁻¹), Kukron C₁₄ (43.83 Mg C ha⁻¹) and Gorakhpur C₇ (48.79 Mg C ha⁻¹), respectively. Whereas, the lowest value for soil carbon density (45.61 Mg C ha⁻¹) was recorded for Lai C₂₈.

4.7.7.3 Total carbon density [(humus +soil (Mg C ha⁻¹)]

Total carbon density [humus+soil (0-40 cm)] showed similar trend as soil carbon density with significantly maximum value of total carbon density reported in Rajban C₆ (75.11 Mg C ha⁻¹) followed by Rajban C₇ (57.60 Mg C ha⁻¹), Rajban C₁₀ (55.45 Mg C ha⁻¹), Kukron C₁₅ (50.76 Mg C ha⁻¹), Kukron C₁₄ (49.92 Mg C ha⁻¹) and Gorakhpur C₇ (43.35 Mg C ha⁻¹), respectively. Whereas, Lai C₂₈ recorded minimum value for total carbon density (40.90 Mg C ha⁻¹).

4.7.7.4 Detritus carbon density (Mg C ha⁻¹)

Detritus carbon density under different compartments shown in Table 32 depicts significantly maximum value (3.40 Mg C ha⁻¹) in Kukron C₁₄, which remained statistically at par with Rajban C₁₀ (3.24 Mg C ha⁻¹). Further, Rajban C₁₀ (3.24 Mg C ha⁻¹) remains statistically at par with Lai C₂₈ (3.08 Mg C ha⁻¹), Kukron C₁₅ (2.99 Mg C ha⁻¹) and Gorakhpur C₇ (2.65 Mg C ha⁻¹). Whereas, the minimum value for detritus carbon density (2.36 Mg C ha⁻¹) was recorded in Rajban C₇, which was found to be statistically at par with Rajban C₇ (2.46 Mg C ha⁻¹).

4.7.7.5 Ecosystem carbon density (Mg C ha⁻¹)

The significantly maximum ecosystem carbon density was recorded in Kukron C₁₄ (287.58 Mg C ha⁻¹), which was followed by Rajban C₁₀ (238.26 Mg C ha⁻¹) which remained statistically at par with Rajban C₆ (212.59 Mg C ha⁻¹) and Kukron C₁₅ (209.19 Mg C ha⁻¹). Further, Kukron C₁₅ remains statistically at par with Lai C₂₈ (164.20 Mg C ha⁻¹) and Lai C₂₈ was found to be statistically at par with Rajban C₇ (149.85 Mg C ha⁻¹) and Gorakhpur C₇

(114.53 Mg C ha⁻¹). Whereas, the minimum ecosystem carbon density was shown in Gorakhpur C₇ (164.20 Mg C ha⁻¹), which remains statistically at par with Rajban C₇ (149.85 Mg C ha⁻¹) and Lai C₂₈ (164.20 Mg C ha⁻¹).

4.7.7.6 Carbon stock (Mg C ha⁻¹)

Total carbon stock potential under different compartments of the Sal Working Circle of Paonta Forest Range has been calculated by multiplying the ecosystem carbon density with the total area of the respective compartment.

Total carbon stock potential under different compartments is presented in Table 32. The maximum value for carbon stock (9,314.10 Mg C ha⁻¹) was recorded for Kukron C₁₄ which was followed by Rajban C₁₀ (8,378.27 Mg C ha⁻¹), Rajban C₆ (7,640.03 Mg C ha⁻¹), Kukron C₁₅ (7,216.34 Mg C ha⁻¹), Lai C₂₈ (5,909.95 Mg C ha⁻¹) and Rajban C₇ (5,774.63 Mg C ha⁻¹). Whereas, the minimum carbon stock was recorded in Gorakhpur C₇ (4,718.12 Mg C ha⁻¹).

The tree height, tree diameter, volume, biomass and carbon stock of different compartments varied significantly. The maximum tree height (11.60-15.10 m) recorded under different compartments can be attributed to vigorous growth due to crown opening after felling in the selected compartments under SQ II and SQ III. In addition, height growth can be attributed to site conditions of the area, as tree height is the indicator of site quality (Luna 1995 and Kozlowski, 1979). However, the average stand characteristics of the compartment under investigation are lower than the values reported by Raj and Jhariya (2021) who evaluated stand characteristics in Sal-dominated mixed tropical forests in Chhattisgarh, by compartment model approach. In different SQ, the density (individuals ha⁻¹) and basal area (m² ha⁻¹) ranged from 710 to 1010 and 33.5 to 46.8 in a tree in varying SQ. On the contrary, the significant contribution of individuals of higher dbh classes to total AGB and carbon stock in different compartments i.e., Kukron C₁₄ (33.27 cm) and Rajban C₁₀ (31.51cm) indicates the absence of biotic and anthropogenic causes or that the forest community is reaching its maximal potential in terms of CO₂ sequestration (Majumdar *et al.*, 2016).

Tree biomass and carbon stock in forests varies with forest type, species composition, stand age, size class of trees, site conditions, rainfall pattern, edaphic factors and altitude (Sharma *et al.*, 2011; Zhao *et al.*, (2014). Rabha (2014) examined the aboveground biomass and carbon stocks of an undisturbed Sal forest in the Goalpara district of Assam, Northeast

India. The average AGB and C levels were 239.45 12.8 Mg ha⁻¹ and 119.73 6.4 Mg ha⁻¹, respectively, that coincides with our results. Raj and Jhariya (2021) opined that the total biomass varied from 182.27 to 375.84 t ha⁻¹ depending on site quality. Trees varied in total carbon content from 79.86 to 163.63 t ha⁻¹. Carbon density in the above-ground and below-ground biomass of trees at various locations ranged from 72.32 to 143.36 t ha⁻¹ and 7.54 to 20.27 t ha⁻¹, respectively. As per models, forest received 14.63, 10.81, 8.19 and 6.83 t ha⁻¹ yr⁻¹ of C input through net primary production (NPP) in SQ-I, SQ-II, SQ-III and SQ-IV, respectively which are depleted as 3.55, 3.12, 2.77 and 2.33 t ha⁻¹ yr⁻¹ as total C input in the soil. Moreover 1.77 (SQ-I), 1.60 (SQ-II), 1.46 (SQ-III) and 1.30 (SQ-IV) t ha⁻¹ yr⁻¹ of C were transferred from foliage to litter compartment, respectively.

The present study demonstrated that the total biomass of 123.89 Mg ha⁻¹ - 487.35 Mg ha⁻¹) and tree carbon density of 58.85 Mg C ha⁻¹-232.66 Mg C ha⁻¹ under different compartments and the AGB and carbon accumulation was greater in the higher diameter class studied by Chaudhury *et al.* (2022). They studied biomass and carbon stock along disturbance gradients in differently managed protected forests (PA), reserved forests (RF) and village forests (VF) of Assam, northeast India and concluded that the mean aboveground biomass (AGB) was 172.90 ±12.98 Mg ha⁻¹ in the PAs, 82.89±8.47 Mg ha⁻¹ in the RFs and 88.48±19.89 Mg ha⁻¹ in the VFs. The mean belowground biomass (BGB) was 84.77±14.23, 40.81±1.50 and 40.20±8.18 Mg ha⁻¹ in the PAs, RFs and VFs, respectively and reported biomass and carbon stock lower than the current study. The mean above ground biomass (AGB) ranged from 82.89 to 172.90 12.98 Mg ha⁻¹ across the study areas, below ground biomass (BGB) ranged from 40.20 to 84.77 Mg ha⁻¹, and AGB C stock ranged from 81.95 to 39.29 Mg ha⁻¹. BGB C stock varied between 15.18 and 46.93 Mg C ha⁻¹.

The present study results coincides with the observations of Shahid and Joshi (2015) who studied three forest ranges of Dehra Dun Forest Division of Doon Valley, Western Himalaya, India. Biomass and carbon status in the moist deciduous forest were estimated using volumetric equations and reported the biomass range of 338.40 Mg ha⁻¹ to 438.17 Mg ha⁻¹ and carbon density from 169.20 Mg ha⁻¹ to 219.08 Mg ha⁻¹ at different study sites. *S. robusta* had the maximum aboveground biomass of 202.26 - 240.43 Mg ha⁻¹. The total biomass (438.17 Mg ha⁻¹) and carbon density (219.08 Mg ha⁻¹) were maximum in moist deciduous forest of Lachchiwala Range, which was followed by Thano Range with total biomass of 422.44 Mg ha⁻¹ and carbon stocks of 211.22 Mg ha⁻¹. Moist deciduous forest in

Barkot Range has the 338.40 Mg ha⁻¹ total biomass and 169.20 Mg ha⁻¹ carbon stocks. The results of this study are higher than the values reported by Biswas *et al.* (2021) for total biomass (78.88 and 93.011 t ha⁻¹) and carbon stock (39.44 and 46.51 t C ha⁻¹, respectively). Meanwhile, *S. robusta* had the greatest C stock in both ranges of their study. The results of present study are in agreement with the findings of Mishra *et al.* (2022), who assessed AGB (255.24 Mg ha⁻¹) and total carbon (119.96 Mg C ha⁻¹) of all recorded trees using a non-destructive method. The most prominent tree species, *S. robusta*, adapted better to subtropical climatic conditions and has the largest AGB (81.80 Mg ha⁻¹) and carbon stock (34.45 Mg C ha⁻¹). Other native tree species with low density, basal area, AGB, and carbon density were observed in *B. variegata* (0.01 Mg ha⁻¹ and 0.004 Mg C ha⁻¹) and *C. fistula* (0.08 Mg ha⁻¹, and 0.03 Mg C ha⁻¹).

The current observation of AGB is within the reported range (28.1 to 330.87 Mg ha⁻¹) of various tropical deciduous forests of India (Ranawat and Vyas, 1975; Singh and Singh, 1981 and Salunkhe *et al.*, 2016). However, the current study above ground biomass is higher than the AGB of Sal plantation forest of Meghalaya, Northeast India (406 Mg ha⁻¹) (Baishya *et al.*, 2009). The estimated carbon stock in litter and fine root within range (3.26 C Mg ha⁻¹ - 3.94 Mg C ha⁻¹) of our study (Bhattarai and Mandal, 2018). In our study, the range of total detritus biomass (4.97-7.16 Mg ha⁻¹) revealed that the maximum value of forest floor, litter floor, and fine root biomass was seen in site quality (SQ) II, followed by SQ-III in different seasons shows a synergy between site quality, stand structure, and biomass, all of which influence ecosystem structure and function. The current study results are consistent with total biomass (187.39 to 383.46 t ha⁻¹), fine root (2.44 to 4.20 t ha⁻¹), forest floor biomass (2.32 to 2.83 t ha⁻¹) and total litter fall (4.18 to 5.69 t ha⁻¹ yr⁻¹) as reported by Raj and Jhariya (2021).

Shrub and herb biomass accounts for a sizable proportion of total biomass in forest ecosystems. Due to the lack of a perfect approach and the complexity of estimation, they are often excluded from research that compute biomass (Karki, 2002). In the present study, the biomass of herbs (2.20 Mg ha⁻¹) and shrubs (1.18 Mg ha⁻¹) was minimum in Kukron C₁₄, where tree density (305 N ha⁻¹) was maximum. The area with scattered or lesser number of trees, first dominated by shrub and then under this the limited space and light is utilized by herbs. The density and biomass of herbs are inversely proportional to the shrub and tree density (Puri *et al.*, 1992 and Pandey *et al.*, 2000). Hence, herbs can only contribute significantly to total biomass production in ecosystems with low tree density. In our study,

the highest herb biomass was seen in Gorakhpur C₇ (7.55 Mg ha⁻¹), where tree density was lowest with an open canopy due to severe human pressure (Matayaya *et al.*, 2017) they found that disturbance regimes enhanced herb biomass but decreased total ecosystem biomass.

The exploitation of ecosystems has been seen to alter the composition of plants and aboveground biomass (Vitousek *et al.*, 1997). Nevertheless, the highest biomass (487.35 Mg ha⁻¹) and carbon density (232.66 Mg C ha⁻¹) (Table 27, 29). Maximum biomass and carbon density found in Kukron C₁₄, which were attributed to larger dbh classes and higher density (Slik *et al.*, 2013) *S. robusta*, the dominating species in all compartments, had the most individuals (Table 18) Moreover, the high specific gravity and biomass expansion factor play an important role in estimating biomass and carbon stock. Smaller trees in Gorakhpur C₇, on the other hand, may contribute to the lower volume and biomass levels (Padmakumar *et al.*, 2018). Excessive biomass harvesting, which is widespread around settlements since all compartments are close to a road (Rajban C₆, Rajban C₇, Rajban C₁₀, Gorakhpur C₇ and Lai C₁₈) alters forest structure and has both direct and negative consequences on vegetation biomass and carbon stock (Sapkota *et al.*, 2018). This variation in biomass and carbon stock levels among different compartments can be related to species diversity, tree structure, basal area, diameter class heterogeneity, soil characteristics, study site conditions, and other anthropogenic influences (Lewis *et al.*, 2013; Dar and Sundarapandian, 2015). Lower values in some compartments may also be attributable to illicit felling of larger trees or small-scale timber production of sal wood in these forests due to their proximity to human areas. On the contrary, the variation in growth parameters within compartments may be due to variation in species composition, species richness and presence of single dominating species with bigger diameter.

Experiment III: Studies on natural regeneration status through seeds and coppice shoots under different compartments of sal forest.

4.8 REGENERATION STUDIES

The current study looked at the natural regeneration status of recruits (ha⁻¹), Un-established (ha⁻¹), Established (ha⁻¹), Regeneration success (%) and coppice regeneration (%) in different compartments of the Paonta Forest Division in Himachal Pradesh. Regeneration survey was conducted in different compartments in the years of 2018-2020, which comprises of Rajban C₆, Rajban C₇, Rajban C₁₀, Gorakhpur C₇, Kukron C₁₄, Kukron C₁₅ and Lai C₁₈. The results are presented here under compartment wise, Table 33-39 depicts the natural regeneration through seeds and coppice shoots.

Table 33 Regeneration status of Kukron C₁₄ compartment through seeds under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Recruits (ha ⁻¹)	Un-established (ha ⁻¹)	Established (ha ⁻¹)	Establishment stocking (%)	Regeneration Success (%)
1	<i>Shorea robusta</i>	5125	687.50	500.00	12.61	26.88
2	<i>Syzyguim cuminii</i>	125	187.50	62.50	4.32	4.38
3	<i>Cordia dichotoma</i>	250	62.50	125.00	4.20	5.63
4	<i>Mallotus philippinensis</i>	375	312.50	125.00	6.54	8.13
5	<i>Terminalia tomentosa</i>	125	250.00	125.00	7.78	7.50
	Total	6000	1500.00	937.50	35.46	52.50

4.8.1 Natural regeneration through seeds

The regeneration status of the Kukron C₁₄ compartment is presented in Table 33. It depicts that a total of 6000 recruits ha⁻¹ were recorded, *S. robusta* (5125 recruits ha⁻¹) had the maximum recruits followed by *M. philippinensis* (375 recruits ha⁻¹), *C. dichotoma* (250 recruits ha⁻¹) and *T. tomentosa* and *S. cuminii* (125 recruits ha⁻¹), respectively. Among total un-established regeneration (1500 N ha⁻¹) and established regeneration (937.50 N ha⁻¹), *S. robusta* had the maximum number (687.50 N ha⁻¹ and 500 N ha⁻¹) followed by *M. philippinensis* (312.50 N ha⁻¹ and 125 N ha⁻¹) and *T. tomentosa* (250 N ha⁻¹ and 125 N ha⁻¹) un-established and established regeneration of *S. cuminii* and *C. dichotoma* were 187.50 and 62.50 N ha⁻¹ and 125 N ha⁻¹, respectively. Furthermore, the establishment stocking per cent and regeneration success (%) of the Kukron C₁₄ compartment were 35.46 per cent and 52.50 per cent, with the species ranked as follows: *S. robusta*>*M. philippinensis*>*T. tomentosa*>*C. dichotoma*>*S. cuminii*

Table 34 Regeneration status of Rajban C₁₀ compartment through seeds under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Recruits (ha ⁻¹)	Un-established (ha ⁻¹)	Established (ha ⁻¹)	Establishment stocking (%)	Regeneration Success (%)
1	<i>Shorea robusta</i>	5000.00	1312.50	250.00	4.86	23.13
2	<i>Syzyguim cuminii</i>	187.50	312.50	62.50	5.26	5.63
3	<i>Cordia dichotoma</i>	250.00	250.00	125.00	8.57	7.50
4	<i>Mallotus philippinensis</i>	250.00	187.50	125.00	8.23	6.88
5	<i>Terminalia tomentosa</i>	125.00	187.50	62.50	7.15	4.38
	Total	5812.50	2250.00	625.00	34.06	47.50

Table 34 illustrates the regeneration status of the Rajban C₁₀ compartment, with a total of 5812.50 recruits ha⁻¹. Out of which *S. robusta* had the maximum number (5000 recruits

ha⁻¹) followed by *M. philippinensis* and *C. dichotoma* with individual value (250 N ha⁻¹), *S. cuminii* (187.50 N ha⁻¹) and *T. tomentosa* (125 N ha⁻¹), respectively. *S. robusta* had the maximum value (1312.50 N ha⁻¹). Out of all un-established seedlings (2250 N ha⁻¹), *S. robusta* had the maximum value (1312.50 N ha⁻¹) followed by *S. cuminii* (312.50 N ha⁻¹), *C. dichotoma* (250 N ha⁻¹) and *T. tomentosa* of 187.50 N ha⁻¹. A total number of 250.00 established seedlings ha⁻¹ were recorded from which *S. robusta* had maximum value followed by *M. philippinensis* and *C. dichotoma* with individual value (125 N ha⁻¹), *S. cuminii* (125 N ha⁻¹) and *T. tomentosa* (62.50 N ha⁻¹), respectively. Rajban C₁₀ compartment had a total establishment stocking index of 35.69 per cent and a regeneration success rate of 46.25 per cent. The highest establishment stocking index was recorded for *C. dichotoma* (8.57 %), followed by *M. philippinensis* (8.23 %), *T. tomentosa* (7.15 %), *S. cuminii* (5.26 %) and *S. robusta* (4.86 %). Regeneration success (47.50 %) of the compartment with the following species ranked as: *S. robusta* (23.13 %) was followed by *C. dichotoma* (7.50 %), *M. philippinensis* (6.88 %), *S. cuminii* (5.63 %) and *T. tomentosa* (4.38 %), respectively.

Table 35 Regeneration status of Lai C₂₈ compartment through seeds under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Recruits (ha ⁻¹)	Un-established (ha ⁻¹)	Established (ha ⁻¹)	Establishment stocking (%)	Regeneration Success (%)
1	<i>Shorea robusta</i>	4437.50	1000.00	187.50	3.65	17.50
2	<i>Syzyguim cuminii</i>	187.50	125.00	62.50	3.20	3.75
3	<i>Cordia dichotoma</i>	250.00	187.50	125.00	8.15	6.88
4	<i>Mallotus philippinensis</i>	250.00	312.50	187.50	12.24	10.62
5	<i>Terminalia tomentosa</i>	125.00	250.00	125.00	5.36	7.50
	Total	5250.00	1875.00	687.50	33.23	46.25

In Lai C₂₈ compartment (Table 35) five species were recorded with total number of 5250.00 recruits ha⁻¹, out of which *S. robusta* had the maximum recruits (4437.50 recruits ha⁻¹) followed by *M. philippinensis* and *C. dichotoma* with similar values i.e., 250 recruits ha⁻¹, *S. cuminii* (187.50 recruits ha⁻¹) and *T. tomentosa* (125 recruits ha⁻¹), respectively. For un-established regeneration of 1875 N ha⁻¹, *S. robusta* had the maximum value (1000 N ha⁻¹) followed by *M. philippinensis* (312.50 individual ha⁻¹), *T. tomentosa* (250 N ha⁻¹) and *C. dichotoma* (187.50 N ha⁻¹) and *S. cuminii* (125 N ha⁻¹). The total established regeneration recorded in this compartment was 687.50 individuals ha⁻¹. *S. robusta* and *M. philippinensis* had identical values of 187.50 N ha⁻¹ followed by *C. dichotoma*, *T. tomentosa* 125 N ha⁻¹

each and *S. cuminii* (62.50 N ha⁻¹). The total establishment stocking per cent was 33.23. *M. philippinensis* and *S. cuminii* displayed maximum value (12.24 %) and minimum value (3.20 %), respectively. The regeneration success of Lai C₂₈ was 46.25 per cent and the regeneration success of different species were in following order: *S. robusta*>*M. philippinensis*>*T. tomentosa*> *C. dichotoma*> *S. cuminii*, respectively.

Table 36 Regeneration status of Gorakhpur C₇ compartment through seeds under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Recruits (ha ⁻¹)	Un-established (ha ⁻¹)	Established (ha ⁻¹)	Establishment stocking (%)	Regeneration Success (%)
1	<i>Shorea robusta</i>	4312.50	937.50	187.50	3.81	16.88
2	<i>Syzygium cuminii</i>	375.00	62.50	250.00	17.30	10.63
3	<i>Cordia dichotoma</i>	312.50	250.00	125.00	7.91	7.50
4	<i>Mallotus philippinensis</i>	250.00	187.50	62.50	4.74	4.38
5	<i>Terminalia tomentosa</i>	187.50	125.00	62.50	3.92	3.75
	Total	5437.50	1562.50	687.50	37.67	43.13

The regeneration status of prevailing tree species in the Gorakhpur C₇ compartment is depicted in Table 36. Total number of 5437.50 recruits ha⁻¹ were recorded in the compartment. *S. robusta* had the maximum number of recruits ha⁻¹ (4312.50) followed by *S. cuminii* (375 recruits ha⁻¹), *C. dichotoma* (312.50 recruits ha⁻¹), *M. philippinensis* (250 recruits ha⁻¹) and *T. tomentosa* (187.50 recruits ha⁻¹), respectively. The total un-established regeneration of this compartment was 1562.50 individual ha⁻¹, *S. robusta* (937.50 N ha⁻¹) had the maximum un-established seedlings followed by *C. dichotoma* (250 recruits ha⁻¹), *M. philippinensis* (187.50 N ha⁻¹) and *T. tomentosa* (125 N ha⁻¹) and *S. cuminii* (62.50 N ha⁻¹). The number of established seedlings recorded in this compartment was 687.50 N ha⁻¹ with *S. cuminii* having the maximum number (250 N ha⁻¹), followed by *Shorea robusta* (187.50 N ha⁻¹), *C. dichotoma* (125 N ha⁻¹) and *T. tomentosa* and *M. philippinensis* having identical values of 62.50 N ha⁻¹. In addition, the establishment stocking percentage was 37.67, with *S. cuminii* having the highest percentage value (17.30 %) followed by *C. dichotoma*, *M. philippinensis*, *S. robusta* and *T. tomentosa*. also, the regeneration success (43.13 %) of different species is arranged as followed the order; *S. robusta* > *S. cuminii*>*C. dichotoma*>*M. philippinensis*>*T. tomentosa*. Regeneration success (43.13 %) of the compartment with the following species ranked as: *S. robusta* (16.88 %) was followed by *S. cuminii* (10.63 %) *C. dichotoma* (7.50 %), *M. philippinensis* (4.38 %) and *T. tomentosa* (3.75 %), respectively.

Table 37 Regeneration status of Kukron C₁₅ compartment through seeds under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Recruits (ha ⁻¹)	Un-established (ha ⁻¹)	Established (ha ⁻¹)	Establishment stocking (%)	Regeneration Success (%)
1	<i>Shorea robusta</i>	4062.50	812.50	250.00	15.59	18.13
2	<i>Syzyguim cuminii</i>	187.50	125.00	62.50	3.66	3.75
3	<i>Cordia dichotoma</i>	250.00	250.00	187.50	7.98	10.00
4	<i>Mallotus philippinensis</i>	312.50	187.50	125.00	7.91	6.88
5	<i>Terminalia tomentosa</i>	125.00	62.50	62.50	3.66	3.13
	Total	4937.50	1437.50	687.50	38.80	41.88

In Kukron C₁₅ compartment (Table 37) total recruits (4937.50 recruits ha⁻¹) of five species were recorded of which *S. robusta* had the maximum number (4062.50 recruits ha⁻¹) followed by *M. philippinensis* (312.50 recruits ha⁻¹), *C. dichotoma* (250 recruits ha⁻¹) and *S. cuminii* (187.5 recruits ha⁻¹) and *T. tomentosa* (125.00 recruits ha⁻¹). However, un-established regeneration of all the species followed the pattern i.e., *S. robusta* (812.50 N ha⁻¹), *C. dichotoma* (250.00 N ha⁻¹), *M. philippinensis* (250.00 N ha⁻¹) and *S. cuminii* (250.00 N ha⁻¹) and *T. tomentosa* (62.50 N ha⁻¹) were present with a total number of 1437.50 N ha⁻¹. Furthermore, the established regeneration (687.50 N ha⁻¹) with establishment stocking per cent of 38.80 per cent, respectively, i.e., *S. robusta* had 250 N ha⁻¹ and 15.59 per cent stocking, *C. dichotoma* had 187.50 individual ha⁻¹ and 7.98 per cent stock. *M. philippinensis* had 125.00 N ha⁻¹ and 7.91 per cent stocking, *S. cuminii* and *T. tomentosa* had identical value of 62.5 N ha⁻¹ and 3.66 per cent stocking. The overall regeneration success of 41.88 per cent of the species in the compartment was as followed the order; *S. robusta* (18.13 %)>*C. dichotoma* (10.00 %)>*M. philippinensis* (6.88 %) >*S. cuminii* (3.75 %) >*T. tomentosa* (3.13 %), respectively.

Table 38 Regeneration status of Rajban C₆ compartment through seeds under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Recruits (ha ⁻¹)	Un-established (ha ⁻¹)	Established (ha ⁻¹)	Establishment stocking (%)	Regeneration Success (%)
1	<i>Shorearobusta</i>	3875.00	750.00	187.50	3.65	15.00
2	<i>Syzyguimcuminii</i>	125.00	125.00	62.50	2.46	3.75
3	<i>Cordia dichotoma</i>	250.00	250.00	125.00	2.91	7.50
4	<i>Mallotus philippinensis</i>	250.00	312.50	125.00	14.00	8.13
5	<i>Terminalia tomentosa</i>	187.50	125.00	62.50	2.68	3.75
	Total	4687.50	1562.50	562.50	25.69	38.13

In total 4687.50 recruits ha⁻¹ total recruits of all the species in Rajban C₆ compartment (Table 38) were recorded. Out of which, *S. robusta* had the maximum number (3875.00

recruits ha⁻¹) followed by *C. dichotoma* and *M. philippinensis* which was found to have identical values (250 recruits ha⁻¹) followed by *T. tomentosa* (187.5 recruits ha⁻¹) and *S. cuminii* (125 recruits ha⁻¹). The unestablished recruits followed the order: *S. robusta* (750 N ha⁻¹), *M. philippinensis* (312.50 N ha⁻¹), *C. dichotoma* (250.00 N ha⁻¹), *S. cuminii* and *T. tomentosa* (125 N ha⁻¹), were present with a total number of 1562.50 N ha⁻¹. Furthermore, the established regeneration (562.5 N ha⁻¹) with establishment stocking per cent of 25.69 per cent was recorded for the five species i.e., *S. robusta* (187.50 N ha⁻¹ and 3.65 %) followed by *M. philippinensis* (125 N ha⁻¹ and 14.00 %), *C. dichotoma* (125 N ha⁻¹ and 2.91 %), *S. cuminii* (62.50 N ha⁻¹ and 2.46 %) and *T. tomentosa* (62.5 N ha⁻¹ and 2.68 %) were recorded. The overall regeneration success of 38.13 per cent of the species is as followed the order; *S. robusta* (15.00 %), *M. philippinensis* (8.13 %), *C. dichotoma* (7.50 %) and *S. cuminii* and *T. tomentosa* having identical values (3.75 %), respectively.

Table 39 Regeneration status of Rajban C₇ compartment through seeds under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Sr. No.	Scientific Name	Recruits (ha ⁻¹)	Un-established (ha ⁻¹)	Established (ha ⁻¹)	Establishment stocking (%)	Regeneration Success(%)
1	<i>Shorea robusta</i>	3937.50	625.00	187.50	3.83	13.75
2	<i>Syzygium cuminii</i>	125.00	125.00	62.50	3.58	3.75
3	<i>Cordia dichotoma</i>	250.00	250.00	125.00	2.91	7.50
4	<i>Mallotus philippinensis</i>	187.50	312.50	125.00	14.69	8.13
5	<i>Terminalia tomentosa</i>	125.00	125.00	62.50	6.96	3.75
	Total	4625.00	1437.50	562.50	31.98	36.88

The regeneration status of the Rajban C₇ compartment is presented in Table 39. It depicts that a total of 4625 recruits ha⁻¹ were recorded, with *S. robusta* (3937.50 recruits ha⁻¹) having the maximum recruits followed by *C. dichotoma* (250 recruits ha⁻¹) *M. philippinensis* (187.50 recruits ha⁻¹), *S. cuminii* and *T. tomentosa* of 125.00 recruits ha⁻¹ each. Among total un-established regeneration (1437.50 N ha⁻¹) and established regeneration (562.50 N ha⁻¹), *S. robusta* had the maximum number (625.00 N ha⁻¹ and 187.50 N ha⁻¹) followed by *M. philippinensis* (312.50 N ha⁻¹ and 125.00 N ha⁻¹) *C. dichotoma* (250 N ha⁻¹ and 125 N ha⁻¹) and lastly *S. cuminii* and *T. tomentosa* with individual values (125 N ha⁻¹ and 62.5 N ha⁻¹), respectively. However, the establishment stocking per cent and regeneration success (%) of the Rajban C₇ compartment were 31.98 per cent and 36.88 per cent, respectively. The regeneration success followed the order: *S. robusta*>*M. philippinensis*>*C. dichotoma* >*T. tomentosa* =*S. cuminii*.



Plate 3: Natural regeneration through seed



Plate 4: Natural regeneration through coppice shoots

Table 40 Seed fall (kg ha⁻¹) of *Shorea robusta* in different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Compartments	Seed fall (kg /ha)
1	Rajban C ₆	159.70±1.25
2	Rajban C ₇	150.90±0.82
3	Kukron C ₁₄	202.70±2.62
4	Rajban C ₁₀	193.50±0.92
5	Kukron C ₁₅	175.40±0.84
6	Gorakhpur C ₇	167.20±0.57
7	Lai C ₂₈	189.50±0.13
	C.D. 0.05	3.75

The data in Table 40 presented the Seed fall (kg ha⁻¹) status of *Shorea robusta* under different compartments. Significantly maximum Seed fall (202.70 kg ha⁻¹) was recorded in Kukron C₁₄, which was followed by Rajban C₁₀ (193.50 kg ha⁻¹), Lai C₂₈ (189.50 kg ha⁻¹), Kukron C₁₅ (175.40 kg ha⁻¹), Rajban C₆ (159.70 kg ha⁻¹), Gorakhpur C₇ (167.20 kg ha⁻¹), respectively. Whereas, significantly minimum seed fall was recorded in Rajban C₇ (150.90 kg ha⁻¹).

4.8.2 Natural regeneration through coppice shoots

Table 41 Regeneration status of Lai C₂₈ compartment through coppice shoots under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Diameter class (cm)	Number of trees felled in the diameter class		Number of stumps having coppice shoots		Mean coppice height (cm)		Coppice regeneration in diameter class (%)	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
10-20	65.00	29.00	1.00	2.00	43.21	42.42	1.54	6.90
20-30	180.00	44.00	2.00	3.00	45.32	38.67	1.11	6.82
30-40	215.00	30.00	9.00	3.00	29.35	36.36	4.19	10.00
40-50	285.00	9.00	12.00	-	29.14	-	4.21	-
50-60	1511.00	6.00	7.00	-	27.24	-	4.64	-
60-70	70.00	-	2.00	-	42.68	-	2.86	-
70-80	30.00	-	2.0	-	43.44	-	6.67	-
80-90	13.00	-	-	-	-	-	-	-
90 & above	12.00	-	-	-	-	-	-	-
TOTAL	2381.00	118.00	35.00	8.00	37.20	39.15	1.47	6.78

The results in Table 41 demonstrated the regeneration status of Lai C₂₈ compartment through coppice shoots. Area wise marking of trees was done in the year of 2018-2019 and 2019-2020. The total number of trees felled in the felling was 2381 and 118 trees, with

stumps having coppice in 7 diameter classes, with highest coppice shoots in 40-45cm (12) and lowest coppice shoots (1) in 10-20 cm having maximum mean coppice height (45.32 cm) in 20-30cm, while in year 2019-2020, the total percentage of coppice regeneration in felling was 1.47 per cent and 6.78 per cent among all diameter classes. Further, the number of stumps with coppice was noted to be highest in 20-30 cm and lowest in 10-20 cm. maximum mean height Mean coppice height (38.67 cm and 45.32 cm) in 20-30 cm.

Table 42 Regeneration status of Rajban C₁₀ compartment through coppice shoots under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Diameter class (cm)	Number of trees felled in the diameter class	Number of stumps having coppice shoots	Mean Coppice height (cm)	Coppice regeneration in diameter class (%)
10-20	29.00	1.00	38.34	3.45
20-30	56.00	2.00	35.39	3.57
30-40	24.00	3.00	39.14	12.50
40-50	228.00	13.00	30.48	5.70
50-60	113.00	8.00	32.57	7.08
60-70	36.00	2.00	34.04	5.56
70-80	9.00	-	-	-
80-90	1.00	-	-	-
90 & above	-	-	-	-
TOTAL	496.00	29.00	34.99	5.85

The results in Table 42 showed the regeneration status of Rajban C₁₀ compartment through coppice shoots. The total number of trees felled in the felling (496), with stumps having coppice in 6 diameter classes, with highest coppice shoots in 40-45 cm (13) and lowest coppice shoots (1) in 10-20 cm. Mean coppice height (cm) was maximum in 30-40 cm (39.14). Furthermore, the overall percentage of coppice regeneration in the felling was 5.85 per cent among all diameter classes.

Table 43 Regeneration status of Gorakhpur C₇ compartment through coppice shoots under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Diameter class (cm)	Number of trees felled in the diameter class		Number of stumps having coppice shoots		Mean Coppice height (cm)		Coppice regeneration in diameter class(%)	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
10-20	610.00	726.00	3.00	8.00	33.05	29.58	0.49	1.10
20-30	66.00	186.00	4.00	3.00	29.65	31.45	6.06	1.61
30-40	8.00	66.00	-	2.00	-	34.59	-	3.03

40-50	230.00	680.00	7.00	9.00	30.45	29.75	3.04	1.32
50-60	254.00	449.00	6.00	8.00	31.37	32.45	2.36	1.78
60-70	155.00	287.00	6.00	4.00	34.76	30.62	3.87	1.39
70-80	69.00	119.00	2.00	2.00	38.48	32.52	2.90	1.68
80-90	15.00	24.00	-	-	-	-	-	-
90 & above	1.00	8.00	-	-	-	-	-	-
TOTAL	1408	2545	28.00	36.00	32.96	31.57	1.99	1.41

Table 43 illustrated the regeneration status of the Gorakhpur C₇ compartment through coppice shoots. Trees were marked by area in the years 2018-2019 and 2019-2020. The total number of trees felled in the initial falling was 1408. Stumps having coppice in 6 diameter classes and the highest coppice shoots in 70-80 cm and 60-70 cm were 38.48. Total percentage of coppice regeneration in diameter classes was 1.99 per cent across all diameter classes. While in 2019-2020, mean coppice height (cm) was shown to be maximum in 70-80 cm (38.48cm). However, the total percentage of regeneration was 1.41 per cent. There were 2545 trees that fell across all diameter classes, which revealed 1.41 per cent coppice regeneration. Furthermore, the number of stumps with coppice was found to be highest in the 40-50 cm and lowest in the 70-80 cm (32.52).

Table 44 Regeneration status of Kukron C₁₄ compartment through coppice shoots under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Diameter class (cm)	No of trees felled in the diameter class		Number of stumps having coppice		Mean Coppice height (cm)		Coppice regeneration in diameter class (%)	
	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020	2018-2019	2019-2020
10-20	11	10	-	-	-	-	-	-
20-30	23	43	-	1	-	31.05	-	2.33
30-40	35	92	3	3	30.14	28.26	8.57	3.26
40-50	497	436	7	13	26.485	25.48	1.41	2.98
50-60	286	136	5	8	23.28	26.47	1.75	5.88
60-70	111	278	4	6	23.87	24.36	3.6	2.16
70-80	23	-	-	1	-	33.56	-	-
80-90	2	-	-	-	-	-	-	-
90 & above	-	-	-	-	-	-	-	-
TOTAL	988	995	19	32	25.94	28.2	1.92	3.22

The results in Table 44 displays the regeneration status of the Kukron C₁₄ compartment through coppice shoots. Trees were marked by area in the years 2018-2019 and 2019-2020. The total number of trees felled in the first felling was 988, with stumps exhibiting coppice in six diameter classes, with the highest coppice shoots (13) in 40-45 cm and the lowest coppice shoots (1) in 20-30 and 70-80cm. While, mean coppice height (cm) was shown to be maximum in 30-40 cm (31.41cm). In second felling, the overall percentage of coppice regeneration was 1.92 per cent across all diameter classes. While, total percentage of regeneration, on the other hand, in 2019-2020, the total percentage of coppice regeneration in the felling was 3.22 per cent. Furthermore, the number of stumps with coppice was largest in the 40-50 cm and lowest in 20-30 cm and maximum mean coppice height (33.56 cm) in 70-80 cm diameter class.

Table 45 Regeneration status of Kukron C₁₅ compartment through coppice shoots under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Diameter class (cm)	No of trees felled in the diameter class	Number of stumps having coppice	Mean Coppice height (cm)	% of coppice regeneration in diameter class
10-20	29.00	2.00	32.72	6.90
20-30	44.00	5.00	24.69	11.36
30-40	30.00	3.00	30.16	10.00
40-50	9.00	-	-	-
50-60	6.00	-	-	-
60-70	-	-	-	-
70-80	-	-	-	-
80-90	-	-	-	-
90 & above	-	-	-	-
TOTAL	118.00	10.00	29.19	8.47

A perusal of the data in table 45 shows the regeneration status of the Kukron C₁₅ compartment through coppice shoots revealed an overall percentage of coppice regeneration of 8.47 per cent of all diameter classes, with 118 trees felled across all diameter classes. Furthermore, the number of stumps with coppice was found to be highest in the 20-30 cm (5) and lowest in the 10-20 cm (2). The number of stumps with coppice shoots were found only in three diameter classes. The average coppice height (32.72 cm) was in 10-20 cm diameter class.

Table 46 Regeneration status of Rajban C₆ compartment through coppice shoots under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Diameter class (cm)	No of trees felled in the diameter class	Number of stumps having coppice	Mean Coppice height (cm)	% of coppice regeneration in diameter class
10-20	33.00	2.00	30.89	6.06
20-30	97.00	8.00	28.26	8.25
30-40	57.00	5.00	29.47	8.77
40-50	25.00	-	-	-
50-60	8.00	-	-	-
60-70	4.00	-	-	-
70-80	1.00	-	-	-
80-90	-	-	-	-
90 & above	-	-	-	-
TOTAL	225.00	15.00	29.54	6.67

The data in Table 46 displays the regeneration status of the Rajban C₆ compartment through coppice shoots. The total number of trees felled in the first felling (225), with stumps having coppice shoots in 3 diameter classes only, with highest coppice shoots in 20-30 cm (8) and lowest coppice shoots (2) in 10-20 cm. average coppice height (cm) was maximum in 10-20 cm (30.89). The overall percentage of coppice regeneration was 6.67 per cent of all diameter classes.

Table 47 Regeneration status of Rajban C₇ compartment through coppice shoots under Sal Working Circle in Paonta Forest Division, Himachal Pradesh

Diameter class (cm)	No of trees felled in the diameter class	Number of stumps having coppice	Mean Coppice height (cm)	% of coppice regeneration in Diameter Class
10-20	-	-	-	-
20-30	4.00	-	-	-
30-40	7.00	1.00	30.15	14.29
40-50	68.00	5.00	24.29	7.35
50-60	1.00	-	-	-
60-70	-	-	-	-
70-80	-	-	-	-
80-90	-	-	-	-
90 & above	-	-	-	-
TOTAL	80.00	6.00	27.22	7.50

The data presented in Table 47 shows the regeneration status of the Rajban C₇ compartment through coppice shoots. An overall percentage of coppice regeneration of 7.50 per cent was observed in the compartment under all diameter classes, with 80 trees was felled across all diameter classes. Furthermore, the number of stumps with coppice was found to be highest in the 30-40 cm and lowest in the 40-50 cm number of stumps with coppice shoots was displayed in two diameter classes only. The mean coppice height (30.15 cm) was 30-40 cm. There was no coppice regeneration from 60-70 cm diameter classes.

The study of regeneration status is an important aspect in its ecological analysis because the ratio of various age groups in a population determines the reproductive status of the population and indicates the future course of action (Odum, 1971). In the current study, Sal demonstrated adequate regeneration with an uninterrupted growth pattern in the compartments studied, As a result, Sal's growth phase reveals an uninterrupted tendency of regeneration from saplings to mature stage, indicating Sal's establishment and development. A total of 4625 to 6000 recruits ha⁻¹, established regeneration of 562.50 to 937.50 N ha⁻¹, and un-established regeneration of 1437.50 to 2437.50 N ha⁻¹ were recorded in different compartments under study. Similarly, Nag and Gupta (2014) documented fair regeneration of Sal in three different managed forests in West Bengal's Dry Deciduous Forests and concluded that the density of regenerating individuals (seedling and sapling) was highest in Garhjungle (4266.7 N ha⁻¹) and lowest in Illambazar (2710 N ha⁻¹). The maximum seedling density was seen in Ballavpur (1016.7 N ha⁻¹) and is in agreement with our findings. The values for regeneration in the present study was lower than the values reported by Kumar and Saikia (2020) [seedling (54–22,071 N ha⁻¹), saplings (4–1239 N ha⁻¹) ranged, and adults (0.02–416 N ha⁻¹)] in Sal forests of Ranchi, Eastern India. However, findings of the present study are in line with the values (4375 N ha⁻¹ seedlings, 2562.5 sapling N ha⁻¹, and 209.37 N ha⁻¹ saplings) recorded in the Palpa district of central Nepal's tropical forest (Basyal *et al.*, 2011). The lowest value for recruits and established regeneration were found in Rajban C₇ and Gorakhpur C₇, whereas, Rajban C₆ and Rajban C₇ had minimum un-established regeneration. This may be because these compartments are easily accessible by the local communities, therefore, can be considered as vulnerable which clearly indicates the effect on regeneration. Biotic and abiotic pressure in the compartments, which eventually lead to the deprivation of plant and soil available nutrients and the loss of species richness, while favoring the abundance of unpalatable species.

However, seedlings of *S. robusta* were found to be more abundant than saplings and poles in all compartments; which was similar to study conducted by Weidelt (1988), who observed significantly fewer saplings than seedlings in his study area and noted that majority of the saplings develop into young trees, that may be attributed to seedlings transitioning into saplings owing to intensive competition. In the study conducted in the subtropical submontane zone of the Garhwal Himalaya, Tiwari *et al.* (2010) reported that *S. robusta* displayed the highest rate of regeneration of all species. The total number of sal seedlings saplings and trees (2681 ha⁻¹, 1576 ha⁻¹ and 380 ha⁻¹) reported by them falls within the scope of the current study. According to Saxena and Singh (1984) grazing and trampling by cattle affect the soil structure by compacting it which leads to lower moisture content and lower permeability. This may alter the habitat and make it less suitable for the establishment of seedlings. A Sal tree can produce thousands of seedlings in a good seed year, but only few seedlings can survive and establish. In nature, seed regeneration has frequently been hampered by adverse climatic circumstances during seed germination and seedling establishment. The highest mortality of seedlings was recorded in tropical forests during the winter season (Khan *et al.*, 1987).

Regeneration of Sal was assisted by the presence of associated tree species as well as the sufficient sunlight availability on ground due to adequate opening of canopy trees in Sal forest. Thus, it is concluded that the density of tree canopy, sunlight availability and associated tree species affected the regeneration of Sal in different compartments. However, Canopy opening by remedial felling may enhance light intensity, soil temperature, and competition for other resources, thereby facilitated seedling regeneration. Decreased canopy cover in Rajban C₆ and Rajban C₇ had a direct impact on seed production and may have an indirect impact on regeneration owing to changes in understory vegetation and soil characteristics (Vetaas, 2000). Sal regeneration was high in all compartments, but it gradually declines with the advancement of growth stages. Heavy infestation of all the compartments by the invasive species i.e., *A. solanacea* may be the reason for hampering seedling development and establishment. The current findings are congruent with those of Gautam *et al.* (2016), who found a negative relationship between disturbance and regeneration (both seedling and sapling), however, Sapkota *et al.* (2009) is of the opinion that mild disturbances encourage regeneration. Drought is a key cause of poor seedling survival in *S. robusta* and germination of freshly disseminated seeds was high between June and July, recruitment peaks in August, and the seedling population drops following the wet season, with increasing death

throughout the dry winter (Troup, 1921). However, Regeneration of *S. robusta* is also known to be affected by soil pH (Gupta, 1953), accumulation of leaf litter in moist forests (Champion and Seth, 1968), damage by wild animals, grazing and closure (Chaubey and Jamaluddin, 1989), shrubby growth and ground flora (Khan and Gupta, 1960), and the effect of standing crop (Chaubey and Sharma, 2013). Sapkota *et al.* (2009) in their studies reported that the density of seedlings of *S. robusta* was similar in canopy gaps and canopy cover, the gaps were occupied by the light demanding coppicers (Adhikari *et al.*, 2017). Dieback is a phenomenon often linked to the recruitment phase. The die back of Sal seedlings in different compartments varied from 6.56 to 11.31 per cent, regardless of seed fall (150.90-202.70 kg ha⁻¹) with Rajban C₆ having the highest severity (11.31 %) owing to edaphic conditions and canopy gaps. It witnessed dying back heavily during the rainy season in moist areas owing to damping off disease. In certain arid areas, however, most shoots die throughout the dry season, whereas roots often remain alive and only develop branches once rainfall begins. (Troup 1921; Rao and Singh, 1985). Drought stress, however, is related with limited rainfall and low temperatures during part of the sampling durations, or possibly owing to the competitive effects of the associated and understory vegetation on seedling survival and development (Saikia and Khan 2012, 2013). Remarkable competition between *S. robusta* seedlings with herbs and shrubs, and further between seedlings and big trees, were considerably stronger in all the compartments (Seth and Bhatnagar, 1960). Moreover, it is difficult to identify the precise sources and level of damage that result in seedling dieback at a given location. Seedlings have a lower tolerance to cold temperatures, resulting in frost damage (Sahu *et al.*, 2005). Similarly, high temperatures produce heat damage, which is lethal and causes dieback in fire situations in our study area.

The percentage of coppice regeneration was highest in semi-dense forests at 28.6% (3 species), followed by thick forests at 14.3 per cent (1 species), and open conditions at 38.1% (8 species), indicating the requirement for artificial regeneration support. The values of coppice regeneration in our study were lower than those reported by Divakara (2015), who evaluated *S. robusta* regeneration through coppices in semi-dense, dense, and open/mixed forests. The possible reason for the below average response of the felled stump to resprout may be slightly delayed felling (February–march) in all the compartments. Besides this, the age of the different diameter classes, stand density (particularly upper age groups) as coppicing is known to decline with age season of felling/harvesting and canopy opening.

Experiment IV: Estimation of physico-chemical characteristics under different compartments of Sal forest.

4.9 SITE CHARACTERISTICS

4.9.1 Humus depth (cm)

A perusal of Table 48 reveals that the Humus depth (cm) varied significantly under different compartments. Maximum value for Humus depth (3.91 cm) was recorded for Kukron C₁₄ followed by Rajban C₁₀ (3.29 cm) and Kukron C₁₅ (3.09 cm), respectively. Further, Gorakhpur C₇ (2.84 cm) remained statistically at par with Lai C₂₈ (2.78 cm), whereas, the minimum value of Humus depth was shown in Rajban C₇ (2.25 cm) which, however remains statistically at par with Rajban C₆ (2.31 cm).

Table 48 Humus depth (cm) of different compartments under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Sr. No.	Compartments	Humus depth (cm)
1	Rajban C ₆	2.31±0.01
2	Rajban C ₇	2.25±0.04
3	Kukron C ₁₄	3.91±0.01
4	Rajban C ₁₀	3.29±0.05
5	Kukron C ₁₅	3.09±0.05
6	Gorakhpur C ₇	2.84±0.02
7	Lai C ₂₈	2.78±0.02
C.D. _{0.05}		0.09

A significant variation in soil pH, electrical conductivity and bulk density was observed with the soil depths (Table 49). However, compartment could exercise significantly influence on the electrical conductivity only. The interaction failed to exert significant influence any of soil characteristics. E.C. declined significantly with soil depth. Similarly, The bulk density enhanced significantly with increase in soil depth. Data presented in Table 49 reveals that maximum EC (0.44 dsm⁻¹) was recorded in Kukron C₁₄, which remain statistically at par with Rajban C₆, Rajban C₇, Rajban C₁₀. While, minimum EC was recorded in the Gorakhpur C₇ (0.24 dsm⁻¹) which remained statistically in at par with Kukron C₁₅ and Lai C₂₈.

Table 49 pH, Electrical conductivity (dSm⁻¹) and Bulk density (gcm⁻³) in different compartments under Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	pH			Electrical conductivity (dSm ⁻¹)			Bulk density (g cm ⁻³)		
	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean
Rajban C ₆	5.68	5.83	5.76	0.43	0.36	0.39	1.40	1.43	1.41
Rajban C ₇	5.21	6.05	5.63	0.42	0.39	0.41	1.59	1.68	1.64
Kukron C ₁₄	5.15	5.34	5.25	0.48	0.41	0.44	0.81	0.86	0.84
Rajban C ₁₀	5.18	6.79	5.99	0.5	0.28	0.39	1.03	1.10	1.06
Kukron C ₁₅	6.53	6.89	6.71	0.29	0.23	0.26	0.78	1.55	1.17
Gorakhpur C ₇	6.50	6.75	6.63	0.26	0.21	0.24	1.20	1.28	1.24
Lai C ₂₈	6.06	6.62	6.34	0.28	0.25	0.26	1.15	1.56	1.36
Mean	5.76	6.32		0.38	0.30		1.14	1.35	
Compartment (C)		NS			0.12			NS	
Soil Depth (D)		0.48			0.05			0.24	
(C*D)		NS			NS			NS	

4.9.2 Soil organic carbon and soil carbon fractions (labile and non-labile)

The soil organic condition was maximum (1.68 %) in soil under kukron C₁₄, which however remained statistically identical to Rajban C₁₀, Kukron C₁₅ and Gorakhpur C₇. The minimum soil organic carbon (0.40 %) was noticed in Rajban C₇, which remained statistically at par with the compartments- Rajban C₆ and Lai C₂₈. Similar trend was recorded similar in respect of labile carbon (%) and non-labile carbon (%) for different Compartments.

A similar trend along soil depth was also reported for labile carbon fractions for their sensitivity to management by Culman *et al.* (2012), Guimaraes *et al.* (2013) and Geraei *et al.* 2016.

Table 50 Fractions of soil carbon (%) under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Soil carbon (%)			Labile Carbon (%)			Non-Labile Carbon (%)		
	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean
Rajban C ₆	0.79	0.53	0.66	0.16	0.14	0.15	0.28	0.15	0.22
Rajban C ₇	0.45	0.35	0.40	0.17	0.10	0.14	0.19	0.10	0.15
Kukron C ₁₄	1.95	1.4	1.68	0.35	0.30	0.33	0.42	0.38	0.40
Rajban C ₁₀	1.60	1.36	1.48	0.37	0.26	0.32	0.40	0.31	0.36
Kukron C ₁₅	1.42	1.39	1.41	0.34	0.22	0.28	0.48	0.22	0.35
Gorakhpur C ₇	1.41	1.31	1.36	0.31	0.22	0.27	0.36	0.30	0.33
Lai C ₂₈	0.8	0.75	0.78	0.24	0.11	0.18	0.25	0.16	0.21
Mean	1.20	1.01		0.28	0.19		0.34	0.23	
Compartment (C)		0.45			0.14			0.13	
Soil Depth (D)		0.21			0.08			0.06	
(C*D)		NS			NS			NS	

4.9.3 Available Nitrogen (kg ha⁻¹), Phosphorus (kg ha⁻¹) and Potassium (kg ha⁻¹)

Data presented in the Table 51 evinced that available N, P and K was influenced significantly due to compartmental and soil depth effect. Irrespective of compartment, the level of available N, P and K declined significantly from 10-20 to 20-40 cm soil depth. Irrespective of soil depth, maximum available N (404.47 Kg ha⁻¹) was recorded in the compartment Kukron C₁₄, which was found to be significantly at par with Rajban C₁₀, Kukron C₁₅ and Gorakhpur C₇. The minimum level of available N (2.55.93 Kg ha⁻¹) was recorded in Rajban C₇, which remained statistically at par with Rajban C₆ and Lai C₂₈. The level of available P and K in respect of different compartments followed the same trend as that of available N. The interaction between compartment and soil depth failed to exercise significant influence on the level of available N, P and K.

Table 51 Soil available N, P and K under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Available N (kg ha ⁻¹)			Available P (kg ha ⁻¹)			Available K (kg ha ⁻¹)		
	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean
Rajban C ₆	294.24	260.01	277.13	27.26	26.05	26.65	249.77	216.94	233.36
Rajban C ₇	286.91	224.94	255.93	27.15	24.32	25.73	239.92	216.66	228.29
Kukron C ₁₄	415.95	392.99	404.47	47.08	44.28	45.68	450.63	405.40	428.02
Rajban C ₁₀	386.29	392.00	389.15	44.46	43.2	43.83	401.76	391.23	396.50
Kukron C ₁₅	420.08	310.67	365.38	43.65	37.06	40.36	369.02	356.09	362.56
Gorakhpur C ₇	364.89	334.67	349.78	46.14	23.7	34.92	353.22	248.43	300.83
Lai C ₂₈	287.36	274.40	280.88	32.56	26.77	29.66	253.44	242.87	248.16
Mean	350.82	312.81		38.33	32.20		331.11	296.80	
Compartment (C)		61.49			7.70			35.91	
Soil Depth (D)		32.87			4.12			19.2	
(C*D)		NS			NS			NS	

4.9.4 Soil micronutrients (Zn, Fe, B, Cu and S)

It is evident from the data presented in the Table 52 that the level of the micronutrients Zn, Fe and B were significantly influenced due to the average effect of depth only. The level of all these micronutrients declined significantly from D₁ (0-20 cm) to D₂ (20-40 cm).

Table 52 Soil micronutrient (Zn, Fe and B) under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Zn (kg ha ⁻¹)			Fe (kg ha ⁻¹)			B (kg ha ⁻¹)		
	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean
Rajban C ₆	6.78	6.49	6.63	57.35	45.77	51.56	0.35	0.33	0.34
Rajban C ₇	7.32	6.66	6.99	51.97	37.02	44.50	0.32	0.26	0.29
Kukron C ₁₄	7.01	6.08	6.55	74.95	38.68	56.81	0.37	0.29	0.33
Rajban C ₁₀	7.56	5.57	6.57	82.31	78.86	80.58	0.47	0.11	0.29
Kukron C ₁₅	5.76	5.12	5.44	76.51	63.98	70.24	0.12	0.11	0.11
Gorakhpur C ₇	6.01	5.19	5.60	69.66	69.62	69.64	0.16	0.14	0.15
Lai C ₂₈	5.31	5.15	5.23	49.03	54.6	51.82	0.17	0.13	0.15
Mean	6.54	5.75		57.35	45.77		0.28	0.20	
Compartment (C)		NS			NS			NS	
Soil Depth (D)		0.48			0.02			0.08	
(C*D)		NS			NS			NS	

The status of Cu and S under different Sal compartments of Paonta Sal Working Circle in the Table 53. It is evident from the depicted table that Cu varied significantly due to the depth only, whereas, the level of S varied significantly due to compartmental as well as depth effect. The level of both Cu and S declined from D₁ (0-20 cm) to D₂ (20-40 cm), respectively. The maximum level of S (14.831 ha) was recorded in Kukron C₁₄, which was found to be significantly higher than the S levels under all other compartments. The level of S under different compartments followed the order: Kukron C₁₄> Rajban C₇> Rajban C₆> Rajban C₁₀> Lai C₂₈> Kukron C₁₅> Gorakhpur C₇.

Table 53 Soil micro nutrient (Cu and S) in soil micro nutrients of soil under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartments	Cu (kg ha ⁻¹)			S (kg ha ⁻¹)		
	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean	D ₁ (0-20 cm)	D ₂ (20-40 cm)	Mean
Rajban C ₆	2.49	2.15	2.32	12.31	11.83	12.07
Rajban C ₇	2.41	2.21	2.31	12.87	12.48	12.67
Kukron C ₁₄	2.22	2.19	2.21	15.27	14.38	14.83
Rajban C ₁₀	3.02	2.06	2.54	12.09	10.15	11.12
Kukron C ₁₅	1.80	1.37	1.58	9.82	8.78	9.30
Gorakhpur C ₇	1.79	1.68	1.74	9.31	8.85	9.08
Lai C ₂₈	1.64	1.54	1.59	12.51	10.43	11.47
Mean	2.20	1.88		12.03	10.98	
Compartment (C)		NS			2.13	
Soil Depth (D)		0.24			1.14	
(C*D)		NS			NS	

4.9.5 Soil depth

Table 54 illustrates the soil depth (cm) of several soil horizons in different compartments. The maximum humus depth (3.91cm) was recorded for Kukron C₁₄, followed by Rajban C₁₀ (3.29 cm), while the least humus depth (2.25 cm) was indicated for Rajban C₇. Similarly, soil depth varied with the compartments for soil horizons O, A, B, and C. The highest soil depth in Kukron C₁₄ varied from 35.60 cm in the O horizon to 98.60 cm in the C horizon, whereas the lowest soil depth in Rajban C₆ ranged from 12.40 cm in the O horizon to 72.40 cm in the C horizon.

Table 54 Soil Depth (cm) of different soil horizons under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Soil Depth (cm)	Compartments						
	Rajban C ₆	Rajban C ₇	Kukron C ₁₄	Rajban C ₁₀	Kukron C ₁₅	Gorakhpur C ₇	Lai C ₂₈
	D(cm)	D(cm)	D(cm)	D(cm)	D(cm)	D(cm)	D(cm)
Humus	2.31	2.25	2.91	2.29	3.09	2.84	2.78
O	12.40	12.60	35.60	3.70	3.20	3.50	3.60
A	17.60	13.50	52.50	48.50	46.70	40.50	44.60
B	32.80	35.80	80.10	63.80	65.80	70.70	61.70
C	72.40	76.40	98.60	75.90	86.50	80.40	79.90

4.9.6 Soil quality index

The results pertaining to the Soil quality index of different compartments is presented in Table 55. Soil quality index was developed by taking into account all of the soil physicochemical characteristics investigated. Soil quality indexes followed the order: Kukron C₁₄ (0.87)> Rajban C₁₀ (0.85)> Kukron C₁₅ (0.78)> Gorakhpur C₇ (0.70)> Lai C₂₈ (0.58)> Rajban C₆ (0.56)> Rajban C₇ (0.53). Soil quality index was found to be higher in Kukron C₁₄, indicating that continual nutrient input via leaf litter and detritus biomass has influenced overall soil quality. Soil quality is the ability of soil to perform within natural or managed ecosystem limits in order to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen *et al.*, 1997).

Table 55 Soil quality index under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Compartment	pH	E _c (dSm-1)	Bulk density (g cm-3)	N (kg ha-1)	P (kg ha-1)	K (kg ha-1)	Zn (kg ha-1)	Fe (kg ha-1)	B (kg ha-1)	Organic carbon (%)	Cu(kg ha-1)	Si(kg ha-1)	SQI
Rajban C ₆	5.76	0.39	1.41	277.13	26.65	233.36	6.63	51.56	0.34	0.66	2.32	12.07	0.56
Rajban C ₇	5.63	0.41	1.64	255.93	25.73	228.29	6.99	44.50	0.29	0.40	2.31	12.67	0.53
Kukron C ₁₄	5.25	0.44	0.84	404.47	45.68	428.02	6.55	56.81	0.33	1.68	2.21	14.83	0.87
Rajban C ₁₀	5.99	0.39	1.06	389.15	43.83	396.50	6.57	80.58	0.29	1.48	2.54	11.12	0.85
Kukron C ₁₅	6.71	0.26	1.17	365.38	40.36	362.56	5.44	70.24	0.11	1.41	1.58	9.30	0.78
Gorakhpur C ₇	6.63	0.24	1.24	349.78	34.92	300.83	5.60	69.64	0.15	1.36	1.74	9.08	0.70
Lai C ₂₈	6.34	0.26	1.36	280.88	29.66	248.16	5.23	51.82	0.15	0.78	1.59	11.47	0.58

Soil pH in the present study increased with soil depth. The availability of many plant nutrients in the soil changes as a result of reactions in the soil, which are largely controlled by soil pH. Similar finding have been reported by Marasini, (2003), Bashyal (2005) and Acharyar and Shrestha (2012). This might be due to high concentration of high valence ions like Fe, which will tend to displace those with lower valences such as H⁺; thus, when this H⁺ is displaced into the soil. And rapid uptake of basic nutrients (K⁺, Ca²⁺, Mg²⁺) by the plant root system, causing an increase in pH levels (Ghehi *et al.*, 2012). Cation exchange capacity of the soil was low in this study site and total nitrogen, phosphorus and potassium decreased with depth. This trend in total nitrogen may be due to the level of organic matter in topsoils and its decomposition (De Moraes *et al.*, 1999) Organic carbon decreased with depth, implying that there were high organic carbon concentrations on topsoils. This might have occurred because of high organic matter deposition on top soils thus more organic carbon due to decomposition. Bulk density of the study site increased with soil depth. This is in agreement with the findings of (Ghehi *et al.*, 2012) Bulk density is dependent on soil texture and the densities of soil mineral (silt, sand and clay) and organic matter particles as well as their packing arrangement. It increases with depth since subsurface layers have reduced organic matter, aggregation and root penetration. High bulk density is an indicator of low porosity and compaction, which may cause restrictions to root growth and poor movement of air and water through the soil. Present study is in close conformity with values reported by Kongkham *et al.* (2021) in four different sites, viz. Shuduwala, Manduwala, Bhawala, and Tilwari of Shivalik foothills Dehradun Forest Region of Uttarakhand. The availability of many plant nutrients in the soil changes because of reactions in the soil, which are largely

4.10 REGRESSION EQUATIONS

Table 56 Linear and non-linear allometric equations for estimation of Volume, Total biomass and carbon (Mg C ha⁻¹) in *Shorea robusta* trees based on diameter over bark, height and density variables

Diameter	Dependent (X)	Independent (Y)	Regression type	Best fitted regression equation	R ²	
Diameter Over bark	Volume	Density	Linear	$V = -6.55 + 0.082 N$	0.889	
			Power	$V = 0.030 N^{1.160}$	0.919	
			Growth	$\ln V = \ln (-1.721) + (0.062N)$	0.930	
			Quadratic	$V = 0.336 - 0.017 N + 0.002N^2$	0.973	
		DBH	Linear	$V = -2.109 + 0.079 D$	0.943	
			Power	$V = -2.706D^{0.058}$	0.978	
			Exponential	$V = 0.067e^{0.058 D}$	0.910	
			Quadratic	$V = 0.074 + 0.001 D - 0.018 D^2$	0.985	
		Height	Linear	$V = -2.397 + 0.188H$	0.909	
			Growth	$\ln V = \ln (-3.535) + (0.165H)$	0.935	
			Power	$V = 0.0001H^{2.936}$	0.669	
			Quadratic	$V = 3.319 + 0.017H - 0.469H^2$	0.851	
		Total biomass	Density	Linear	$TB = 11.359 + 0.422N$	0.878
				Log linear	$TB = -0.165 + 7.705 \ln N$	0.830
				Power	$TB = 6.428N^{0.400}$	0.865
				Quadratic	$TB = 8.694 + 0.688N + 0.005N^2$	0.901
	DBH		Linear	$TB = 4.644 + 0.393D$.861	
			Log linear	$TB = -46.717 + 18.490 \ln D$.915	
			Power	$TB = 8.894D^{0.019}$	0.875	
			Quadratic	$TB = -8.775 + 0.992D - 0.006D^2$	0.919	
	Height		Linear	$TB = -2.397 + 1.188H$	0.988	
			Power	$TB = 0.806H^{1.092}$	0.995	
			Growth	$\ln TB = \ln (1.773) + (0.060H)$	0.988	
			Quadratic	$TB = 3.319 + 0.531H + 0.017H^2$	0.994	
	Carbon		DBH	Linear	$C = 2.206 + 0.187D$	0.861
				Log linear	$C = -22.191 + 8.783 \ln D$	0.915
				Power	$C = 0.318D^{0.920}$	0.875
				Quadratic	$C = -4.169 - 0.471D + 0.003D^2$	0.919
		Height	Linear	$C = -1.138 + 0.564H$	0.988	
			Power	$C = 0.383H^{1.093}$	0.995	
			Exponential	$C = 2.797e^{0.060H}$	0.988	
			Quadratic	$C = 1.573 + 0.008H + 12.509H^2$	0.994	
		Density	linear	$C = 5.396 + 0.200N$	0.878	
			Power	$C = 3.053N^{0.400}$	0.865	
			Log linear	$C = -0.078 + 3.660 \ln N$	0.798	
			Quadratic	$C = 4.130 - 0.002N + 0.327N^2$	0.901	

D = diameter at breast height (cm) H= tree Height (m), V= Tree Volume, TB= Total biomass and C=Carbon

* Significant at 5% level of significance.

controlled by soil pH. The soil pH was more acidic in undisturbed forest stand than in disturbed forest stand. The nitrogen concentration varied substantially across all compartments. Nitrogen is typically found in the soil as nitrates, which are particularly mobile and may move easily with precipitation (Gupta and Sharma, 2008). The higher range of soil pH, bulk density, organic carbon, available nitrogen, phosphorus, and potassium and calcium in the present study concluded that soil enrichment could be due to differences in species-site interaction and differential nutrient uptake (Marasini, 2003; Paudel and Sah, 2003; Kumar and Kumar, 2022).

4.10.1.1 Regression equations for diameter over bark

The linear and non-linear relationships of Volume with diameter over bark, height and tree density, each taken independently, resulted in highly significant \bar{R}^2 (adjusted R^2) results (Table 56), where Quadratic function showed highest \bar{R}^2 (0.973) for tree volume with density followed by growth function (0.930). In contrast, linear function depicted lowest \bar{R}^2 (0.889). In case of tree Height taken as predictor variable, Quadratic function showed highest \bar{R}^2 (0.972) followed by Growth (0.930) and Power function (0.919). While, linear function reported minimum value for \bar{R}^2 (0.12).

For dbh, significant \bar{R}^2 was reported with Quadratic function (0.985) followed by Power function (0.919) While, linear function reported minimum value for \bar{R}^2 (0.887).

The linear and non-linear relationships of total biomass with diameter over bark, height and density each taken independently showed significant results (Table 56), where Quadratic function had highest \bar{R}^2 (0.901) for density followed by log linear (0.915). Whereas, log linear function depicted lowest \bar{R}^2 (0.830) for tree volume with density. In case of dbh, taken as predictor variable, Quadratic function showed highest \bar{R}^2 (0.919) followed by log linear function (0.915). While, in case of height, Quadratic linear function reported maximum value for \bar{R}^2 (0.994). However, in case of linear and growth function (0.988) showed minimum significant \bar{R}^2 result.

The linear and non-linear relationships of carbon with diameter over bark, height and tree density each taken independently showed significant results (Table 56), whereas, Quadratic function had highest \bar{R}^2 (0.919) for tree carbon with density followed by log linear function with value of \bar{R}^2 (0.915). However, linear function depicted lowest \bar{R}^2 (0.861). In case of tree Height taken as predictor variable, Quadratic function showed highest \bar{R}^2 (0.994)

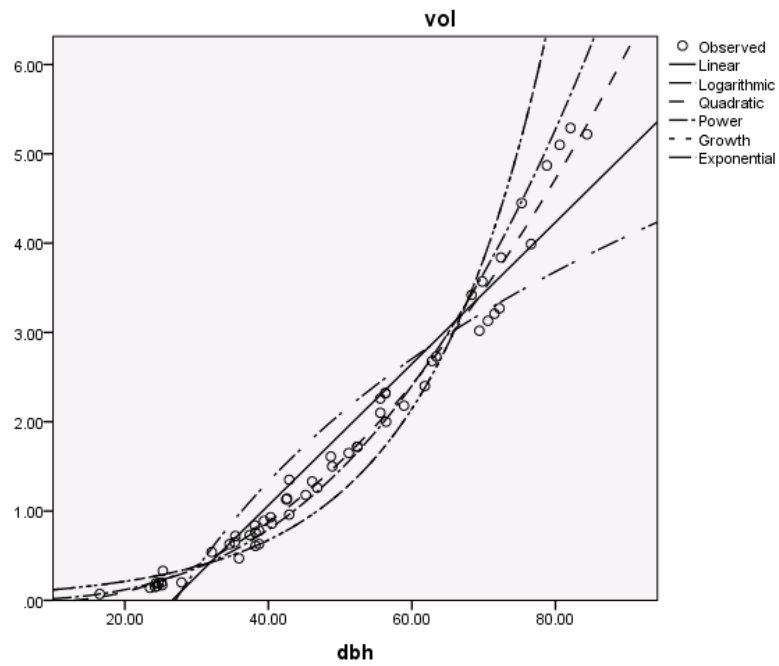


Fig. 4. Relationship between volume and diameter over bark

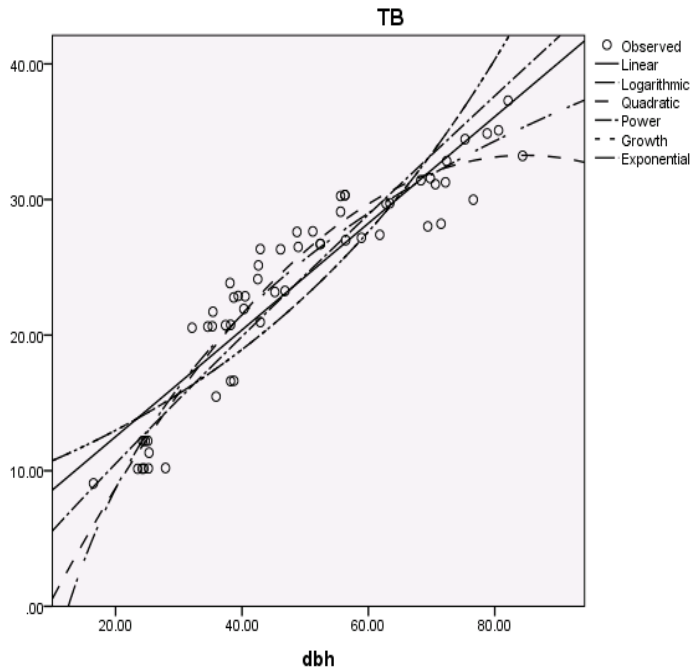


Fig. 5. Relationship between total biomass and diameter over bark

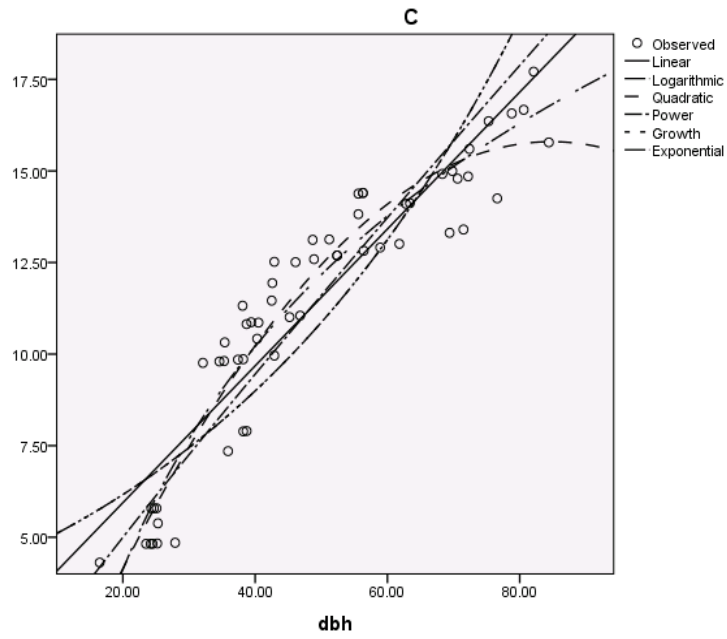


Fig. 6. Relationship between carbon and diameter over bark

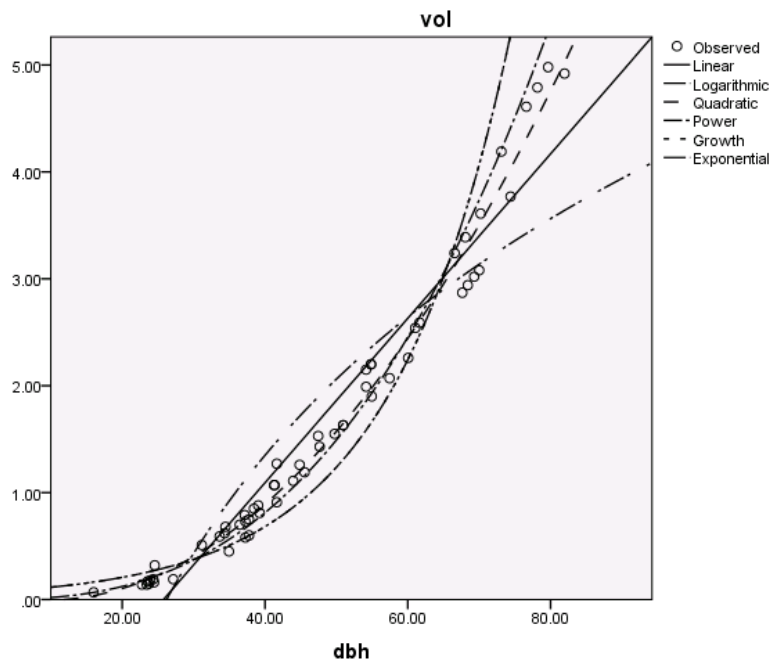


Fig. 7. Relationship between volume and Diameter under bark

followed by Power function value of \bar{R}^2 (0.995). Whereas, linear function reported minimum value for \bar{R}^2 (0.988). While, in case of density, Quadratic function reported maximum value for \bar{R}^2 (0.901). However, in case of log linear function (0.798) showed minimum significant \bar{R}^2 result.

Table 57 Linear and non-linear allometric equations for estimation of Volume, Total biomass and carbon (Mg C ha⁻¹) in *Shorea robusta* trees based on diameter under bark, under bark, height and density variables

Diameter	Dependent (X)	Independent (Y)	Regression type	Best fitted regression equation	R ²
Diameter under bark	Volume	DBH	linear	$V = -1.984 + 0.077D$	0.943
			Power	$V = 0.001D^{2.728}$	0.975
			Growth	$\ln V = \ln(-2.762) + (0.060D)$	0.910
			Quadratic	$V = 0.077 - 0.018D + 0.001D^2$	0.985
		Height	linear	$V = -2.259 + 0.178H$	0.878
			Power	$V = 0.001H^{2.934}$	0.865
			Growth	$\ln V = \ln(-3.586) + (0.165H)$	0.798
			Quadratic	$V = 3.114 - 0.440H + 0.016H^2$	0.901
		Density	linear	$V = -0.615 + 0.077dbh$	0.890
			Power	$V = 0.029H^{1.159}$	0.919
			Growth	$\ln V = \ln(3.695) + (0.140H)$	0.929
			Quadratic	$V = 0.312 - 0.016H + 0.002H^2$	0.973
	Total biomass	DBH	linear	$TB = -3.318 + 0.131D$	0.938
			Power	$TB = 0.001D^{2.630}$	0.907
			Growth	$\ln TB = \ln(-2.064) + (2.829D)$	0.935
			Quadratic	$TB = 0.041 - 0.002D + 0.023D^2$	0.871
		Height	linear	$TB = -3.861 + 0.306H$	0.682
			Power	$TB = 0.001H^{2.829}$	0.907
			Growth	$\ln TB = \ln(-2.881) + (0.1599H)$	0.935
			Quadratic	$TB = 5.524 - 0.774H + 0.027H^2$	0.871
		Density	linear	$TB = -0.988 + 0.131N$	0.887
			Power	$TB = 0.59N^{1.116}$	0.915
			Growth	$\ln TB = \ln(-1.129) + (0.060N)$	0.929
			Quadratic	$TB = 0.546 - 0.022N + 0.003N^2$	0.964
	Carbon	DBH	linear	$C = -1.576 + 0.062D$	0.938
			Power	$C = 0.001D^{2.622}$	0.830
			Exponential	$C = 0.060e^{0.057D}$	0.912
			Quadratic	$C = 0.023 - 0.011D + 0.001D^2$	0.977
		Height	linear	$C = -1.833 + 0.145H$	0.682
			Power	$C = 0.001H^{2.15}$	0.871
			Exponential	$C = 0.027e^{0.159H}$	0.905
			Quadratic	$C = 2.635 - 0.013H + 0.369H^2$	0.935
		Density	Linear	$C = -0.489 + 0.062N$	0.887
			Power	$C = 0.028N^{1.112}$	0.965
			Exponential	$C = 0.155e^{0.060N}$	0.930
			Quadratic	$C = 0.261 - 0.011N + 10.001N^2$	0.914

D = diameter at breast height (cm) H= tree Height (m), V= Tree Volume, TB= Total biomass and C=Carbon

* Significant at 5% level of significance.

4.10.1.2 Regression equations for diameter under bark

The linear and non-linear relationships of Volume with diameter under bark, height and tree density, each taken independently, resulted in highly significant \bar{R}^2 (adjusted R^2) results (Table 57), where Quadratic function showed highest \bar{R}^2 (0.985) for tree volume with dbh followed by growth function (0.910). In contrast, linear function depicted lowest \bar{R}^2 (0.943). In case of tree Height taken as predictor variable, Quadratic function showed highest \bar{R}^2 (0.901) followed by linear function (0.878). While, growth function reported minimum value for \bar{R}^2 (0.798). For density, significant \bar{R}^2 was reported with Quadratic function (0.973) followed by growth function (0.919). While, linear function reported minimum value for \bar{R}^2 (0.890).

The linear and non-linear relationships of total biomass with diameter under bark, height and density each taken independently showed significant results (Table 57), linear function had highest \bar{R}^2 (0.938) for dbh followed by growth function (0.935). Whereas, quadratic function depicted lowest \bar{R}^2 (0.871) for tree biomass with dbh. In case of height, taken as predictor variable, growth function showed highest \bar{R}^2 (0.935) followed by power function (0.907) and lowest value was recorded for quadratic function (0.871). While, in case of density, Quadratic linear function reported maximum value for \bar{R}^2 (0.964). However, in case of linear function (0.887) showed minimum significant \bar{R}^2 result.

The linear and non-linear relationships of carbon with diameter over bark, height and tree density each taken independently showed significant results (Table 57), where, Quadratic function had highest \bar{R}^2 (0.977) for tree carbon with dbh followed by linear function with value of \bar{R}^2 (0.938). However, exponential function depicted lowest \bar{R}^2 (0.912). In case of tree Height taken as predictor variable, Quadratic function showed highest \bar{R}^2 (0.935) followed by exponential function with value of \bar{R}^2 (0.905). Whereas, linear function reported minimum value for \bar{R}^2 (0.682). While, in case of density, power function reported maximum value for \bar{R}^2 (0.965). followed by exponential function with value of \bar{R}^2 (0.930). However, linear function (0.887) showed minimum significant \bar{R}^2 result.

4.10.2 Two variable (dbh and tree height) based regression equations.

Multilinear regression models for predicting Volume, total biomass and carbon density (Mg ha^{-1}) of *S. robusta* over and under bark with the help of two independent variables DBH and height have been demonstrated in the Table 58. The table reveals that all

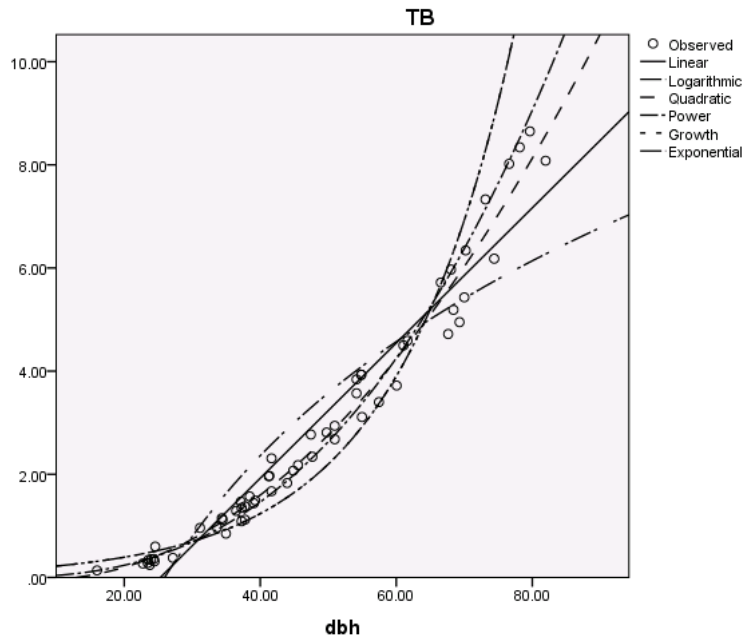


Fig. 8. Relationship between TB and Diameter under bark

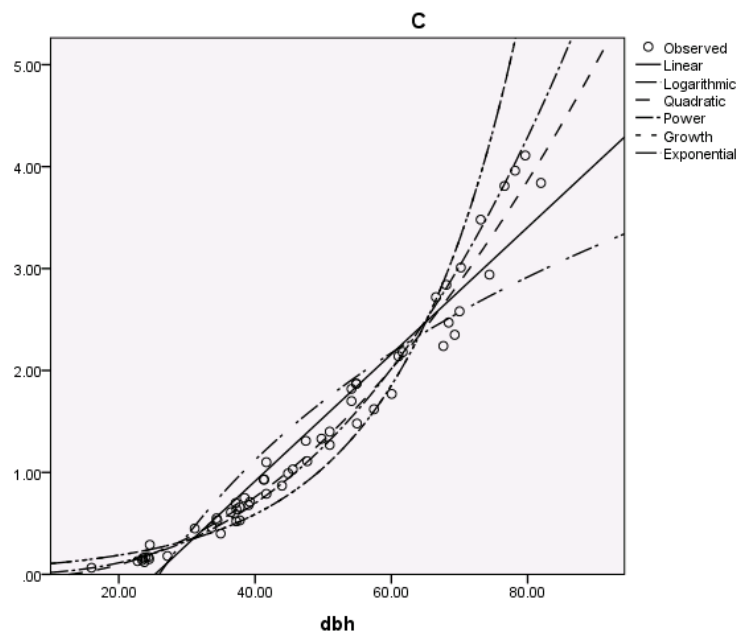


Fig. 9. Relationship between Carbon and Diameter under bark

the traits viz., volume, total biomass and carbon density (Mg ha^{-1}) can be predicted with a degree of accuracy ($R^2 = 0.97$) in both the Cases over bark dbh and under bark dbh.

A perusal of data in Table 58 revealed that linear relationships of Volume, total biomass and carbon with diameter over bark, height collectively, resulted in highly significant \bar{R}^2 (adjusted R^2) results.

4.10.2.1 Regression equations for diameter over bark

The results pertaining to linear relationships of Volume with diameter over bark and height collectively (Table 58), showed highly significant \bar{R}^2 (0.976). In case of total biomass with diameter over bark and tree height taken as predictor variable together showed highest \bar{R}^2 (0.972) whereas, for carbon significant relationship with maximum value of \bar{R}^2 (0.971) were reported.

4.10.2.2 Regression equations for diameter over bark

The data in Table 58 demonstrated significant linear relationships of volume with diameter at breast height under bark and height taken collectively, with the results indicating that the linear function was strong with $\bar{R}^2 = 0.975$. Furthermore, total biomass with diameter under bark and tree height as predictor variables exhibited the highest \bar{R}^2 (0.971), while carbon significant relationship with significant value of \bar{R}^2 was 0.970.

Table 58 Multi-linear allometric equations for estimation of volume, total biomass and carbon in *Shorea robusta* trees based on diameter over bark, under bark and height variables

	Independent (X)	Dependent (Y)	Regression type	Best fitted regression equation	R^2
Diameter over bark	dbh and height	Volume	linear	$V = 0.045(D) + 0.093(H) - 1.804$	0.976
		Total biomass	linear	$TB = 0.955(D) + 0.093(H) - 1.804$	0.972
		Carbon	linear	$C = 0.454(D) + 0.044(H) - 0.87$	0.971
Diameter under bark	dbh and height	Volume	linear	$V = 0.043(D) + 0.091(H) - 1.698$	0.975
		Total biomass	linear	$TB = 0.057(D) + 0.149(H) - 2.935$	0.971
		Carbon	linear	$C = 0.027(D) + 0.071(H) - 1.393$	0.970

D = Diameter at breast height (cm) H= Tree height (m), V= Tree volume, TB= Total biomass and C= Carbon * Significant at 5% level of significance.

The non-linear and linear relationships of Volume, total biomass and carbon with diameter over bark and under bark, height and tree density, each taken independently, resulted in highly significant \bar{R}^2 (adjusted R^2) results.

Data presented in the Table 56 reveals that volume of *S. robusta* can be predicted with a high degree of accuracy using density, dbh over bark and height as an independent variable. Volume of *S. robusta* can be best predicted using density ($V = 0.336 - 0.017N + 0.002N^2$; $R^2 = 0.973$) as independent variable using quadratic function. Similarly, Volume can be predicted using dbh over bark in quadratic function using ($V = 0.074 + 0.001D + 0.018D^2$; $R^2 = 0.985$). However, the best Volume prediction using height as independent variable while using Growth function of $\ln V = (-3.535) + (0.165H)$; $R^2 = 0.935$). It is evident from the data presented in the Table 56 that total biomass of the *S. robusta* can be predicted using density, dbh and height as independent variable using any type of regression function. However, the best regression fit ($R^2 = 0.99$) of total biomass was observed with height and independent variable in power and quadratic functions. Similar to total biomass, carbon content of *S. robusta* can be predicted with fairly high degree of prediction but best equation of carbon content of *S. robusta* (Mg ha^{-1}) is with total height as independent variable in power function ($C = 0.383H^{1.093}$; $R^2 = 0.995$). Data in Table 56 the presents the volume, total bromass and carbon content of *S. robusta* on Mg ha^{-1} using DBH, height and density an independent variables using linear, power, growth and quadratic function. With a reasonable accuracy. The best prediction of volume Mg ha^{-1} ($R^2 = 0.97$) is With DBH ($V = 0.077 - 0.018D + 0.001D^2$; $R^2 = 0.985$) followed by density ($V = 0.312 - 0.016H + 0.002H^2$, $R^2 = 0.973$) but both in quadratic function. Total biomass (Mg ha^{-1}) can the predicted with a good degree of success using DBH, height and density variable in different form of regression type. The best prediction equation of total biomass with DBH ($TB = -3.318 + 0.131D$; $R^2 = 0.938$); height ($\ln TB = \ln(-2.881 + 0.1599H)$; $R^2 = 0.935$), desity ($TB = 0.546 - 0.022N + 0.03N^2$; $R^2 = 0.964$) in power, growth and quadratic regression function, respectively.

The results in Table 56 reveals that carbon contents (Mg ha^{-1}) of *S. robusta* can be predicted accurately with the help of DBH, height and density as independent variable. The carbon content can be predicted with DBH ($C = 0.023 - 0.011D + 0.001 D^2$; $R^2 = 0.977$) with highest accuracy using quadratic regression equation. Current observation best prediction equation of volume over bark is within range with the study conducted by Subedi (2018) who estimated the timber volume of Sal and selected model for total over bark stem volume as $\ln V = -8.04674 + 2.26641 \ln \text{DBH}$ with R^2 of 0.92 and standard error of 0.18. Similarly, the selected models for over bark volume up to 10 and 20 cm top diameter have R^2 of 0.82 and 0.79 and standard errors of 0.35 and 0.42, respectively. Similiarly, Paudel *et al.* (2020) developed carbon stock models based on DBH and total height. Regression model with

natural logarithm of DBH² and total tree height (i.e. log transformed polynomial equation) was best fitted for estimation of carbon stock per tree in different crown cover class with adjusted R²>0.99.

4.11 Correlation studies

The correlation relationship between the Tree, Shrubs and herb carbon density and various diversity indices have been depicted through Table 59 and graphically in Fig. 10.

The Shrub carbon and Shannon diversity index (shrub) were shown to be highly and positively correlated (Table 59). Further, Simpson Dominance index (tree) have strong positive relationship with Shannon diversity index (tree), Meanwhile, SHT was negatively correlated with Margalef Index of species richness(shrub), whereas, Pielou Equitability (Ep) index (Tree) was positively correlated with SIH (herb), Shannon diversity index (herb), Margalef Index of species richness(herb). Simpson Dominance index (Shrub) was highly correlated with Pielou Equitability (Ep) index (shrub). Likewise, Simpson Dominance index (herb) had a strongest positive association with Shannon diversity index (herb) and Pielou Equitability (Ep) index (herb). SHH was positively correlated with MH and EH. Also, Positive association between MH and EH was reported.

Table 59 Correlation matrix between tree carbon, shrub carbon, herb carbon and diversity indices [Simpson Dominance index, Shannon diversity index, Margalef Index of species richness (MI) and Pielou Equitability (Ep) index] of trees shrubs and herbs among different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

	TC	SC	HC	SIT	SHT	MT	ET	SIS	SHS	MS	ES	SIH	SHH	MH	EH
TC	1														
SC	0.14	1													
HC	-0.91	0.17	1												
SIT	-0.24	-0.65	0.03	1											
SHT	-0.14	-0.40	-0.06	0.86*	1										
MT	-0.08	0.08	-0.04	0.44	0.82*	1									
ET	-0.16	-0.75	0.04	0.82*	0.40	-0.19	1								
SIS	0.35	0.70	-0.21	-0.19	0.19	0.59	-0.56	1							
SHS	0.32	0.78*	-0.15	-0.32	0.05	0.50	-0.64	0.98***	1						
MS	-0.05	0.74	0.23	-0.84	-0.77*	-0.38	-0.68	0.27	0.42	1					
ES	0.41	0.54	-0.31	-0.02	0.37	0.70	-0.44	0.97	0.98**	0.03	1				
SIH	-0.54	-0.45	0.56	0.43	0.02	-0.43	0.82*	-0.60	-0.60	-0.27	-0.59	1			
SHH	-0.42	-0.50	0.43	0.55	0.15	-0.34	0.85*	-0.52	-0.55	-0.40	-0.48	1.00***	1		
MH	-0.34	-0.62	0.31	0.62	0.22	-0.32	0.90**	-0.56	-0.61	-0.51	-0.49	0.98*	0.99***	1	
EH	-0.48	-0.14	0.63	0.05	-0.25	-0.49	0.43	-0.39	-0.35	0.03	-0.43	0.87*	0.83*	0.77*	1

TB=Tree carbon SC=Shrub carbon HC=Herb carbon SIT=Simpson Dominance index(Tree) SHT=Shannon diversity index (tree) MT= Margalef Index of species richness(tree) ET=Pielou Equitability (Ep) index(Tree) SIS=Simpson Dominance index (Shrub) SHS=Shannon diversity index (shrub) MS=Margalef Index of species richness(shrub) ES=Pielou Equitability (Ep) index(shrub) SIH= Simpson Dominance index (herb) SHH=Shannon diversity index (herb) MH=Margalef Index of species richness(herb) EH= Pielou Equitability (Ep) index(herb)

* Correlation is significant at the 0.05 level (2-tailed).
 ** Correlation is significant at the 0.01 level (2-tailed).
 *** Correlation is significant at the 0.001 level (2-tailed).

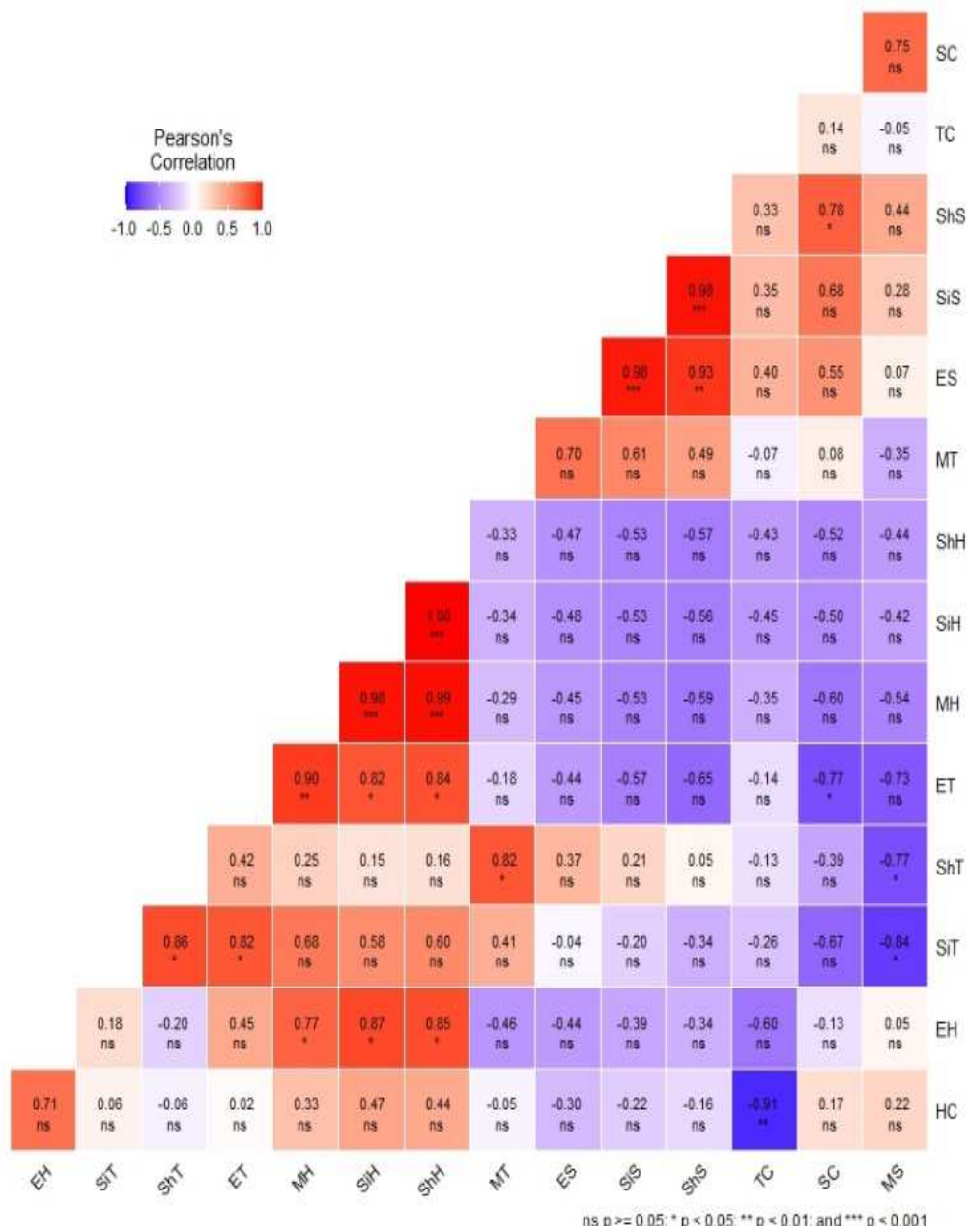


Fig. 10 Correlation matrix between tree carbon, shrub carbon, herb carbon and diversity indices.

Table 60 Correlation matrix between soil physico-chemical characteristics and diversity indices [Simpson Dominance index, Shannon diversity index, Margalef Index of species richness (MI) and Pielou Equitability (Ep) index] of trees, shrubs and herbs among different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

	BD	SOC	N	P	K	Zn	Fe	B	Cu	S	SIT	SHT	MT	ET	SIS	SHS	MS	ES	SIH	SHH	MH	EH	
BD	1																						
SOC	-0.91**	1																					
N	-0.94**	0.98***	1																				
P	-0.94**	0.95***	0.98***	1																			
K	-0.94**	0.92	0.97***	0.99***	1																		
Zn	0.11	-0.29	-0.09	-0.08	0.01	1																	
Fe	-0.59	0.81*	0.76*	0.72	0.67	-0.27	1																
B	-0.06	-0.24	-0.04	-0.02	0.06	0.92**	-0.31	1															
Cu	-0.04	-0.13	0.05	0.07	0.13	0.93**	-0.02	0.91**	1														
S	-0.18	-0.19	-0.02	0.05	0.13	0.64	-0.56	0.78*	0.55	1													
SIT	0.50	-0.67	-0.69	-0.61	-0.59	-0.01	-0.88**	0.06	-0.17	0.47	1												
SHT	0.30	-0.45	-0.51	-0.41	-0.43	-0.34	-0.56	-0.20	-0.36	0.25	0.86*	1											
MT	0.11	-0.12	-0.22	-0.12	-0.18	-0.62	-0.03	-0.49	-0.48	-0.18	0.44	0.82*	1										
ET	0.45	-0.67	-0.61	-0.59	-0.53	0.43	-0.93**	0.46	0.19	0.68	0.82*	0.40	-0.19	1									
SIS	-0.08	0.05	0.07	0.18	0.16	-0.14	0.33	-0.10	0.05	-0.17	-0.19	0.19	0.59	-0.56	1								
SHS	-0.08	0.10	0.12	0.21	0.19	-0.12	0.42	-0.12	0.07	-0.26	-0.32	0.05	0.50	-0.64	0.98***	1							
MS	-0.05	0.33	0.33	0.29	0.28	0.10	0.68	-0.15	0.16	-0.59	-0.84*	-0.77*	-0.38	-0.68	0.27	0.42	1						
ES	-0.13	0.03	0.05	0.16	0.14	-0.21	0.21	-0.08	-0.01	-0.03	-0.02	0.37	0.70	-0.44	0.98***	0.93**	0.03	1					
SIH	0.70	-0.77	-0.77*	-0.80	-0.77*	0.45	-0.72	0.40	0.25	0.24	0.43	0.02	-0.43	0.82*	-0.60	-0.60	-0.27	-0.59	1				
SHH	0.67	-0.82*	-0.77*	-0.82*	-0.76*	0.48	-0.81*	0.48	0.28	0.39	0.55	0.15	-0.34	0.84*	-0.52	-0.55	-0.40	-0.48	1.00***	1			
MH	0.60	-0.78	-0.72	-0.75	-0.70	0.45	-0.88	0.48	0.23	0.48	0.62	0.22	-0.32	0.90**	-0.56	-0.61	-0.51	-0.49	0.98***	0.99***	1		
EH	0.59	-0.64	-0.59	-0.79*	-0.76*	0.39	-0.42	0.38	0.28	-0.01	0.05	-0.25	-0.49	0.43	-0.39	-0.35	0.03	-0.43	0.87*	0.83*	0.77*	1	

BD= Bulk density SOC=Soil organic carbon N=Nitrogen P=Phosphorus K=Potassium Zn=Zinc Fe=Iron B=Boron C=Copper S=Sulphur SIT=Simpson Dominance index(Tree) SHT=Shannon diversity index (tree) MT= Margalef Index of species richness(tree) ET=Pielou Equitability (Ep) index(Tree) SIS=Simpson Dominance index (Shrub) SHS=Shannon diversity index (shrub) MS=Margalef Index of species richness(shrub) ES=Pielou Equitability (Ep) index(shrub) SIH= Simpson Dominance index (herb) SHH=Shannon diversity index (herb) MH=Margalef Index of species richness(herb) EH= Pielou Equitability (Ep) index(herb)

* Correlation is significant at the 0.05 level (2-tailed)
 ** Correlation is significant at the 0.01 level (2-tailed)
 *** Correlation is significant at the 0.001 level (2-tailed)

The correlation between the various physico-chemical characteristics and biodiversity indices of sal compartments Paonta Sahib Forest Range has been depicted through Table 60 and Fig. 11.

Among several soil parameters, bulk density was shown to be significantly and negatively connected to soil organic carbon, nitrogen, phosphorus and potassium availability (Table 60). SOC had a considerably positive relationship with N and P, while, negative correlation was observed for Shannon diversity index (herb). The available N had a significant positive relationship with P and K, however, negative association with Shannon diversity index (herb) and Simpson Dominance index (herb). Phosphorus had significantly strong correlation with K and it was negatively related with SHH and Pielou Equitability (Ep) index (herb). Zinc had a positive connected with Boron and Copper. Furthermore, K demonstrated considerably negative relationship with Simpson Dominance index (herb), SHH and EH. Meanwhile, iron showed significantly negative correlation with Shannon diversity index (tree), Pielou Equitability (Ep) index (Tree) and SHH. B was positively related to Cu and S. Although, Simpson Dominance index (Tree) was positively associated with Margalef Index of species richness (tree) but remained negatively related to Margalef Index of species richness (shrub). Additionally, ET demonstrated a highly significant positive correlation with SIT, SHH and Margalef Index of species richness (herb). Simpson Dominance index (Shrub) was associated with a positive relationship with Shannon diversity index (shrub), Margalef Index of species richness (shrub) and Pielou Equitability (Ep) index (shrub). In addition, SHS and ES were positively correlated. The strongest positive association was being observed for SIH and SHH (Table 60) as well as with MH and EH. SHH was correlated positively with MH and EH. While, negative correlation was observed between MH and EH.

Positive correlation was found between the volume, total biomass, and basal area of tree species and C stock. The R^2 value for Banka range was 0.92 (volume with C stock), 1 (total biomass with C stock) and 0.65 (basal area with C stock). (Biswas *et al.*, 2021). A strong positive correlation was also established at Bounsi range with an R^2 value of 1. Correlation revealed that soil moisture content was negatively correlated with clay content in the disturbed plot, whereas they were positively correlated with each other in the undisturbed site. Soil organic carbon and soil nitrogen content were positively correlated with each other in both the study sites.

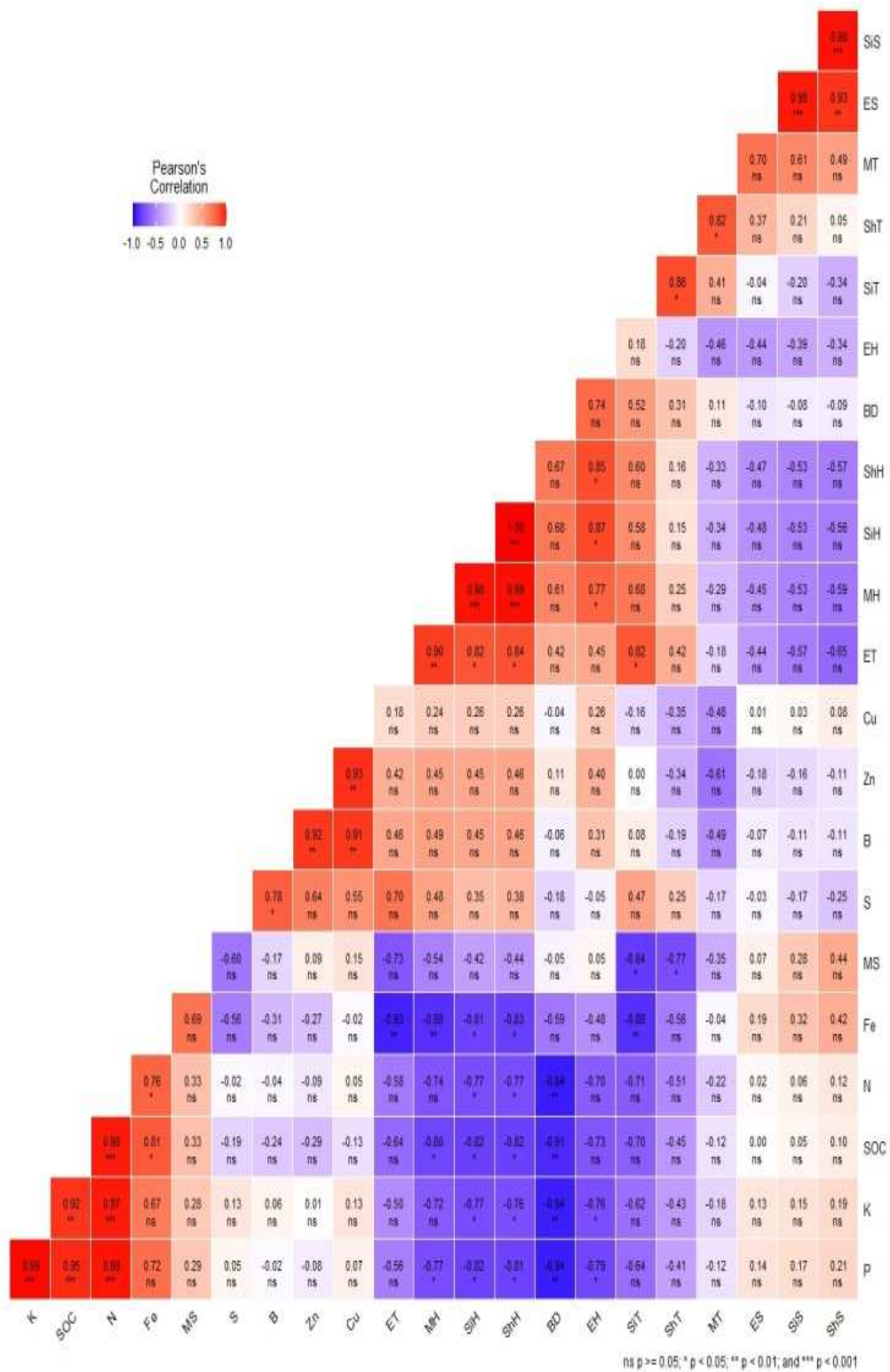


Fig. 11 Correlation matrix between soil physico-chemical characteristics and diversity indices.

Table 61 Correlation matrix between tree height, tree volume, tree biomass, shrub biomass, herb biomass and soil horizons among different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh.

	SH	TH	TV	TB	SB	HB
SH	1					
TH	0.49	1				
TV	0.63	0.57	1			
TB	0.62	0.58	1.00*	1		
SB	0.48	0.32	0.12	0.13	1	
HB	-0.85*	-0.45	-0.92**	-0.91**	0.18	1

SH=Soil horizon TH=Tree height TV=Tree volume TB=Tree biomass SB=Shrub biomass HB=Herb biomass

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

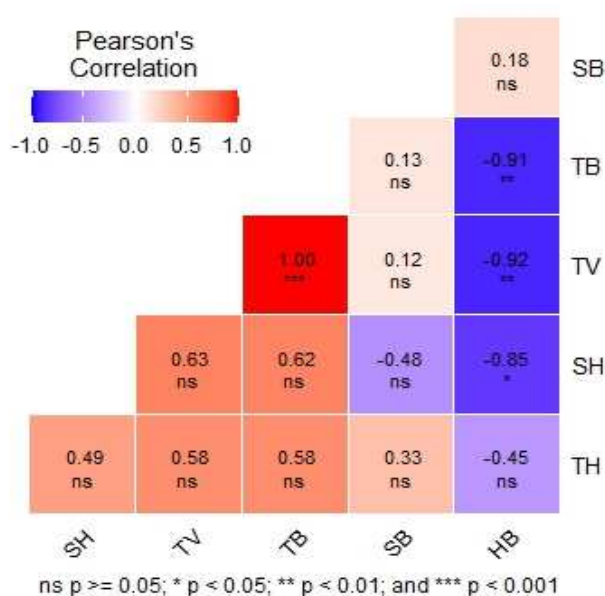


Fig. 12 Correlation matrix between tree height, tree volume, tree biomass, shrub biomass, herb biomass and soil horizons.

The relationship between the depth of the soil horizon and tree height, tree volume, tree biomass, shrub biomass and herb biomass have been depicted in Table 61 and Fig 12.

The Tree volume was shown to be highly and positively correlated with tree biomass (Table 61). Meanwhile, TV was negatively correlated with Herb biomass. Whereas, TB had a considerably negative relationship with HB. While, the soil horizon was significantly and negatively correlated with HB.

Table 62 Correlation matrix between tree height, tree volume, tree biomass and soil quality index among different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

	TH	TV	TB	SB	HB	SQI
TH	1					
TV	0.58	1				
TB	0.58	1.00 **	1			
SB	0.33	0.12	0.13	1		
HB	-0.45	-0.92**	-0.91 **	0.18	1	
SQI	0.94**	0.82*	0.82 **	0.31	-0.67	1

TH =Tree Height V=Volume TB=Total Biomass SQI=Soil Quality Index

The data presented in Table 62 shows the correlation matrix between tree height, tree volume and tree biomass and soil quality index among different compartments, where, tree height revealed strong positive correlation with SQI. Further, volume strongest relationship with total biomass and SQI. While, it was negatively related to herb biomass. Similarly, TB was positively correlated with SQI whereas negatively correlated to herb biomass.

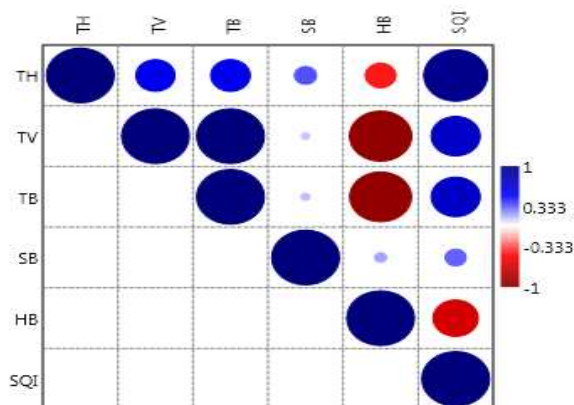


Fig. 13 Correlation matrix between tree height, tree volume, tree biomass and soil quality index.

Soil quality index (SQI) measures the soil physical and chemical properties into a single parameter that could be used as an indicator of overall forest soil quality that may includes Soil bulk density, total organic C and N, electrical conductivity, pH, plant-available nutrients, and other factors influencing soil ecological functions and quality. The present study showed strongest positive correlation of SQI with SOC, N, P and K, tree height and tree biomass. Therefore, has a significant impact on tree height and biomass. However,

Ramachandran *et al.* (2016) revealed that SQI varied from low SQI values in degraded soil to high values in non-degraded soil (0.09) owing to anthropogenic activities and environmental conditions. Chandel *et al.* (2018) also reported highest Soil quality index under the land use forest (0.80) followed by grasses (0.79), horticulture (0.78), cultivated (0.75), and bare (0.67). Shahid *et al.* (2013) assessed the soil quality index (SQI), where, SQI varied from 1.46 in the control plot to 3.78 in NPK+FYM plot.

Table 63 Correlation matrix between tree carbon, shrub carbon, herb carbon and soil physico-chemical characteristics among different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

	TC	SC	HC	BD	SOC	N	P	K	Zn	Fe	B	Cu	S
TC	1												
SC	0.14	1											
HC	-0.91**	0.17	1										
BD	-0.78*	-0.1	0.75	1									
SOC	0.52	0.23	-0.52	-0.91**	1								
N	0.66	0.27	-0.61	-0.94**	0.98**	1							
P	0.74	0.29	-0.7	-0.94**	0.95**	0.98**	1						
K	0.78*	0.26	-0.74	-0.94**	0.92**	0.97**	0.99**	1					
Zn	0.28	0.14	-0.04	0.11	-0.29	-0.09	-0.08	0.01	1				
Fe	0.21	0.70	-0.06	-0.59	0.81*	0.76*	0.72	0.67	-0.27	1			
B	0.45	0.04	-0.19	-0.06	-0.24	-0.04	-0.02	0.06	0.92**	-0.31	1		
Cu	0.36	0.39	-0.03	-0.04	-0.13	0.05	0.07	0.13	0.93**	-0.02	0.91**	1	
S	0.58	-0.39	-0.55	-0.18	-0.19	-0.02	0.05	0.13	0.64	-0.56	0.78*	0.55	1

TB= Tree carbon SC= Shrub carbon HC= Herb carbon BD= Bulk density SOC=Soil organic carbon N=Nitrogen P=Phosphorus K=Potassium Zn=Zinc Fe=Iron B=Boron C=Copper S= Sulphur

- * Correlation is significant at the 0.05 level (2-tailed)
- ** Correlation is significant at the 0.01 level (2-tailed)
- *** Correlation is significant at the 0.001 level (2-tailed)

The correlation between the tree carbon, shrub carbon, herb carbon with different physio-chemical characteristics have been depicted in Table 63 and Figure 14.

Tree carbon was adversely associated with Herb carbon and bulk density and positively correlated with Potassium (Table 63). Whereas, negative association between BD and soil organic carbon, available Nitrogen, Phosphorus and K was detected. However, SOC

Table 64 Correlation matrix between soil physico-chemical characteristics and soil quality index among different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

	EC	pH	BD	SOC	N	P	K	Zn	Fe	B	Cu	S	SQI
EC	1												
pH	0.95**	1											
BD	-0.13	0.12	1										
SOC	-0.15	0.21	-0.91**	1									
N	0.06	0.02	-0.95**	0.98**	1								
P	0.11	-0.03	-0.94**	0.95**	0.98**	1							
K	0.20	-0.12	-0.94**	0.92**	0.98**	0.99**	1						
Zn	0.93**	-0.83*	0.11	-0.29	-0.09	-0.08	0.01	1					
Fe	-0.30	0.48	-0.59	0.81*	0.76*	0.72	0.67	-0.27	1				
B	0.95**	-0.92**	-0.06	-0.24	-0.04	-0.02	0.06	0.92**	-0.31	1			
Cu	0.89**	-0.76*	-0.04	-0.13	0.05	0.07	0.13	0.93**	-0.02	-0.91**	1		
S	0.84*	-0.96**	-0.18	-0.19	-0.02	0.05	0.13	0.64	-0.57	-0.70*	0.55	1	
SQI	0.12	-0.03	-0.94**	0.95**	0.99**	0.99**	0.99**	-0.04	0.74	0.01	0.11	0.03	1

EC= Electrical Conductivity BD= Bulk Density SOC= Soil organic carbon N=Available Nitrogen P= Available Phosphorus K= Available Potassium Zn=Zinc Fe=Iron B=Boron Cu=Copper S=Sulphur SQI=Site Quality Index

The results pertaining to the Correlation matrix between soil physico-chemical characteristics and soil quality index among different compartments are shown in Table 64. Electrical Conductivity was negatively associated with pH while positive relationship was reported with zinc, boron, copper and sulphur, contrarily, pH had negative association with zinc, boron and copper. However, bulk density showed negative correlation between soil organic carbon, available nitrogen, phosphorus and potassium. SOC was associated with a strong positive relationship with N, P, K and Iron. In addition, N had highly positive correlation with P, K and Fe. P showed strongest correlation with K., although, P and K were highly correlated with N. Meanwhile, Zn had positive association with Boron and Copper. B was shown to be negatively associated to Cu and Sulphur. Furthermore, BD was negatively related to SQI, whereas, SQI showed strongest positive correlation with SOC, N, P and K.

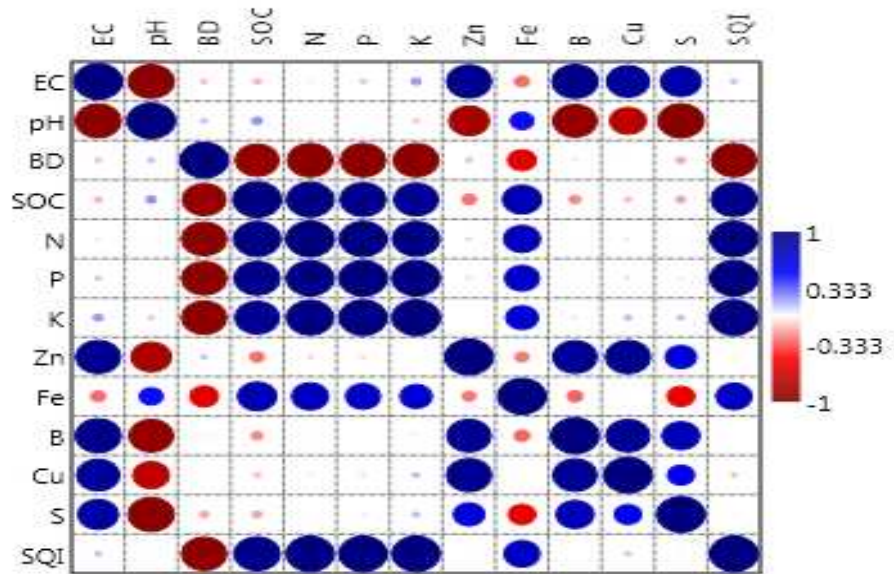


Fig. 15 Correlation matrix between soil physico-chemical characteristics and soil quality index

4.11 PRINCIPAL COMPONENT ANALYSIS

Principal component analysis (PCA) was utilized to illustrate the variations in the stand characteristics, biomass and carbon stock, soil physico-chemical characteristics and diversity indices of trees shrubs and herbs among different compartments of Sal Working Circle. PCA is a useful statistical approach that reduces the large number of variables into a few variables called principal components (PCs) that describe the greatest variance in the data analyzed. In the present study PCA reduced the studied thirty one characters into four Principal components namely PC1 PC2 PC3 and PC4 which had eigen value greater than one i.e., 13.52, 6.98, 5.06 and 4.16 respectively and accounted for 95.85 per cent of total variability (Table 65, Fig. 16). In contrast, other PCs had eigen value smaller than one hence not considered for further interpretation because of “Guttman’s lower bond principle” according to which the eigen values less than unity should be ignored. The data of all the four PCs has been presented in Table 65 and PC1vs. PC2 biplot was generated and shown in Fig.17. Among the PCs, PC1 contributed for majority of the variation i.e., 43.62 per cent followed by PC2 (22.52), PC3 (16.33) and PC4 (13.41), respectively.

In Table 65, PC1 was positively strongly associated with Phosphorus (0.95), Potassium (0.94), Nitrogen (0.92) and soil organic carbon (0.90) and negatively associated with Simpson (Herb) (-0.91), Shannon (Herb) (-0.90), Margalef (Herb) (-0.87) and Bulk density (-

0.87). PC2, which accounted for 22.52 per cent of total variation i.e., 43.62 per cent, was positively strongly associated with Sulphur (0.91), Soil horizon (0.66), Equitability (Tree) (0.65) and Soil organic carbon (0.90) and negatively associated with Herb biomass (-0.66), Herb carbon (-0.66), Shrub biomass (-0.62) and Shrub carbon (-0.62). PC3, which accounted for 16.33 per cent of total variation i.e., was positively correlated with Copper (0.69), Zinc (0.68), Margalef (Shrub) (0.59) and negatively associated with Margalef (Tree) (-0.87) and Shannon (Tree) (-0.86). In case of PC4, which accounted for 22.52 per cent of total variation i.e., 43.62 per cent, was positively weakest association with Equitability (Shrub) (0.71), Simpson (Shrub) (0.71) and Shannon (Shrub) (0.67) and negatively associated with Soil horizon (-0.43), Soil organic carbon (-0.42) and Nitrogen (-0.29).

In conformity with our findings, Kumar and Saikia (2020) formed three principal components (PCs) based on Eigen value, have been, and the interpretations of PCs were based on the most strongly correlated variables. The first PC had a moderately positive correlation with associated tree species density (0.70) and species richness (0.70). In the first PC, increased associated tree species density and species richness suggested that these two variables were strongly correlated and if one increases, then the remaining one tends to increase as well. Sal tree density (-0.71) had a strong negative correlation with associated tree density in the second PC, i.e., increasing associated tree density in the studied forest stands decrease the Sal tree density. The highest component load recorded in Sal density (0.68) and disturbance index (0.71) in the third PC, and both were in opposite directions. Principal Component Analysis (PCA) based multivariate analyses contribute to understanding the influence of anthropogenic or ecological pressure on vegetation structure in forests (Zamprogno *et al.*, 2016). PCA approach was also applied to study the impact of anthropogenic disturbances in tropical forests of Brazil's (Barlow *et al.* 2016), and it is used to reduce the dimensionality of sampling datasets (Jolliffe and Cadima 2016). In the first PC, extended associated tree species density and species richness found that these two parameters were closely correlated, and if one increases, the other parameters appear to increase as well. PCA was applied to the factors of variance that explain the groupings correlation coefficients, and range from -0.06 to 0.71 on a scale of -1.0 to 0 to 1, which described a moderately strong statistical grouping (Rogers, 2002).

Table 65 Principal Component Analysis for stand characteristics, biomass and carbon stock, soil physico-chemical characteristics and diversity indices (Simpson Dominance index, Shannon diversity index, Margalef Index of species richness (MI) and Pielou Equitability (Ep) index) of trees shrubs and herbs among different compartments of Sal Working Circle of Paonta Forest Division, Himachal Pradesh

Components	Total Variance		
	Eigen value	% of Variance	Cumulative variance (%)
PC1	13.52	43.62	43.62
PC2	6.98	22.52	66.15
PC3	5.06	16.33	82.48
PC4	4.16	13.41	95.89

Table 66 Percentage of variance explained by PC under different compartments in Sal Working Circle of Paonta Forest Division, Himachal Pradesh.

Component Matrix				
	Component			
	PC 1	PC 2	PC3	PC 4
Phosphorus	0.95	0.20		-0.18
Potassium	0.94	0.28	0.12	-0.15
Nitrogen	0.92	0.17	0.18	-0.29
Simpson(Herb)	-0.91	0.20	0.36	-
Shannon(Herb)	-0.90	0.32	0.25	0.11
Soil organic carbon	0.90	-	-	-0.42
Margalef(Herb)	-0.87	0.44	0.16	-
Bulk density	-0.87	-0.36	-	0.21
Tree height	0.83	0.15	0.39	-0.27
Iron	0.79	-0.49	0.26	-0.19
Equitability (Tree)	-0.75	0.65	-	-
Tree carbon	0.73	0.58	-	0.34
Tree biomass	0.73	0.58	-	0.34
Tree volume	0.73	0.58	-	0.33
Equitability(Herb)	-0.72	-	0.55	-
Simpson(Tree)	-0.66	0.37	-0.60	0.15
Sulphur	-	0.91	-	0.38
Soil horizon	0.52	0.66	-0.27	-0.43
Herb biomass	-0.65	-0.66	0.29	-
Herb carbon	-0.65	-0.66	0.30	-
Shrub biomass	0.48	-0.62	0.36	0.49
Shrub carbon	0.49	-0.62	0.35	0.49
Boron	-0.10	0.61	0.54	0.54
Margalef(Shrub)	0.39	-0.59	0.59	-
Margalef(Tree)	-	-0.34	-0.87	0.27
Shannon(Tree)	-0.36	0.11	-0.86	0.24
Copper	-	0.32	0.69	0.59
Zinc	-0.16	0.46	0.68	0.49
Simpson(Shrub)	0.45	-0.41	-0.31	0.71
Equitability(Shrub)	0.42	-0.27	-0.47	0.71
Shannon(Shrub)	0.49	-0.49	-0.19	0.67
<i>Extraction Method: Principal Component Analysis.</i>				
<i>a. 4 components extracted.</i>				

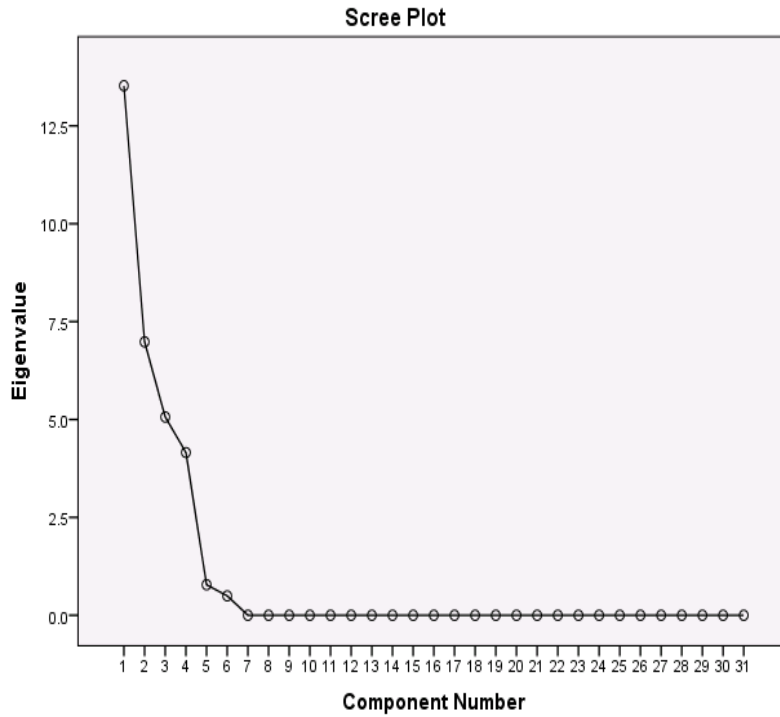


Fig. 16 The Scree plot of stand characteristics, biomass and carbon stock, soil physico-chemical characteristics and diversity indices of trees, shrubs and herbs among different compartments of Sal Working Circle.

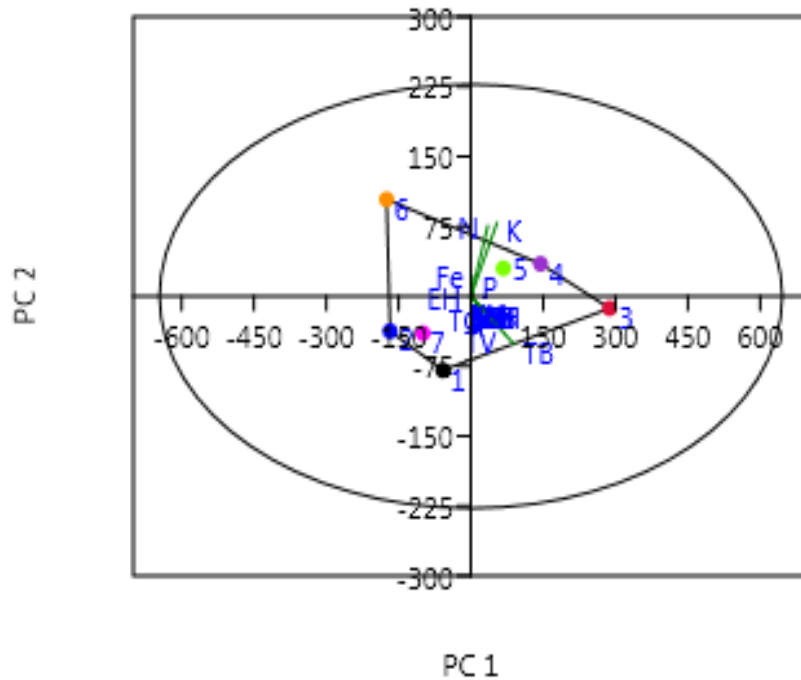


Fig. 17 Biplot of stand characteristics, biomass and carbon stock, soil physico-chemical characteristics and diversity indices of trees, shrubs and herbs for first two principal components.

Chapter-5

SUMMARY AND CONCLUSION

The present investigation entitled “**Inter compartmental variations in floristic composition, biomass productivity and soil physico-chemical characteristics of Sal forest in Himachal Pradesh**” was conducted during the year 2019-2021. Field investigation was carried out in seven compartments viz., Rajban C₆, Rajban C₇, Gorakhpur C₇, Rajban C₁₀, Kukron C₁₄, Kukron C₁₅ and Lai C₂₈ of sal working circle in Paonta Sahib in Himachal Pradesh. One way ANOVA technique was used to analyse various traits viz., growth, stand characteristics and biomass production, etc. Each compartment was considered as treatment. Two way ANOVA was used for analysing the soil for various physico-chemical characteristics.

These experiments were carried out at different compartments studied during the research period. The plot size in each treatment combination was 31.62m×31.62m for tree biomass estimation. 5m×5m sub-plot for shrubs, 1m×1m sub-plot for herbs and 2m×2m sub-plots for shrub regeneration assessment were used. Data on phyto-sociological attributes (like total number of species, tree shrub and herb basal area, per cent frequency and IVI), stand structure, natural regeneration and soil physico-chemical properties. Soil samples were collected from two different soil depths viz., (i) “upper” (0-20 cm), (ii) “lower” (20-40 cm) for assessing the physical and chemical properties in all the selected compartments. Humus samples were also collected and humus depth was recorded using measuring scale. The soil tests were conducted at the Laboratory of Department of Silviculture and Agroforestry, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Naini, Solan (H.P.). Soil attributes were determined and the same were used to prepare inventory on soil carbon density, carbon pool and soil quality index. The data was collected, analyzed and interpreted based on standard laboratory and statistical procedure. The salient findings of these experiments are summarized as follows:

Floristic composition, phyto-sociology and diversity indices

The study of various phyto-sociological attributes revealed that different compartments of Sal Working Circle of Paonta Forest Division constituted 33 genera with 34 species belonging to 26 families.

In Rajban C₆, 6 tree species, 10 shrubs, and 10 herbs were identified. Likewise, Rajban C₇ had 6 tree species, 10 shrub species and 10 herb species. Kukron C₁₄ contained 6 tree species, 9 shrub species and 9 herb species, whereas, Rajban C₁₀ comprised 11 shrub species and 8 herb species. In addition, 7 tree species, 11 shrub species and 8 herb species were documented in Kukron C₁₅. 6 tree species, 10 shrub species and 8 herb species were identified in Gorakhpur C₇. Lastly, Lai C₂₈ included 9 tree species, 8 shrub species and 9 herb species, respectively.

In Rajban C₆, *Shorea robusta* was the dominant species, with the highest relative density (47.57 %), relative basal area (83.87 %) and IVI (152.50), *Cassia fistula*, on the other hand, exhibited the lowest relative density (3.88 %), relative basal area (0.60 %) and IVI (15.01). The most dominant shrub species in Rajban C₆ was *Ardisia solanacea*, which had the highest relative density (47.38 %), relative frequency (14.29 %), relative basal area (24.94 %) and IVI (86.61). The compartment was dominated by *Apluda mutica* with maximum relative density of 14.33 per cent, relative frequency of 12.17 per cent, relative basal area of 28.66 per cent and IVI value of 55.14.

Rajban C₇ was dominated by *S. robusta* with maximum value for relative density (41.00 %), relative basal area (75.86 %) and IVI (137.91). *C. fistula*, on the other hand, exhibited the lowest relative density (4.00 %), relative basal area (0.70 %) and IVI (15.23). The under-storey vegetation of Rajban C₇ was extensively dominated *A. solanacea*, which had the highest relative density (53.20 %), relative frequency (14.49 %), relative basal area (25.23 %), and IVI (92.92). Among herbs, Rajban C₇ was dominated by *Digitaria sanguinalis* with maximum value for relative density (14.64 %), relative frequency (10.73%), relative basal area (36.5 %) and IVI value of 61.95.

In Kukron C₁₄, *S. robusta* was again dominant species having maximum highest value of relative density (45.54 %), relative frequency (22.22 %), relative basal area (83.59 %) and IVI value of 153.35. *C. fistula* had the minimum value for relative density (7.38 %), relative frequency (11.11 %), relative basal area (0.84 %) and IVI (19.32). *A. solanacea* was the most dominating shrub species with maximum value of relative density (53.79 %), relative frequency (15.04 %), relative basal area (30.08 %) and IVI (99.63). In herb species, Kukron C₁₄ was dominated by *Apluda mutica* with maximum relative density of 18.30 per cent, relative basal area of 28.05 per cent and IVI value of 58.68.

The phyto-sociological parameters of trees, shrubs, and herbs in Rajban C₁₀ revealed that *S. robusta* was the most dominant tree species in Rajban C₁₀, with the maximum value for relative density (54.17 %), relative basal area (81.37 %) and IVI value of 156.59. On the other hand, it presented the lowest relative density (5.00 %), relative frequency (10.53 %), relative basal area (1.46 %) and IVI values (16.99). *A. solanacea* dominated the understory vegetation of Rajban C₁₀, with a maximum relative density of 38.75 per cent, relative frequency of 13.16, relative basal area of 20.44 per cent and IVI of 72.35. Among herb species, Rajban C₁₀, with maximum relative density of 19.42 per cent, relative basal area of 29.41 per cent and IVI value of 61.30 was reported in *A. mutica*.

S. robusta was the dominant tree species in Kukron C₁₅, with the maximum overall relative density (52.94 %), relative frequency (21.05 %), relative basal area (77.94 %) and IVI value of 151.94, *Ficus palmata* had the minimum density (2.52 %), relative basal area (0.80 %) and IVI values (13.35). *A. solanacea*, with maximum relative density of 40.98 per cent, relative frequency of 12.90 per cent, relative basal area of 23.13 per cent, and IVI of 74.53, dominated the under-storey vegetation of Kukron C₁₅ extensively. In the case of herb species, *A. mutica* had the maximum relative density of 21.07 per cent, relative frequency of 12.63 per cent, relative basal area of 53.11 per cent and IVI value of 86.81.

S. robusta was documented with highest value for relative density (49.61 %), relative basal area (56.05 %) and IVI value of 126.72 in Gorakhpur C₇. *C. fistula* had the lowest relative density (3.10 %), relative frequency (10.53 %), relative basal area (0.96 %) and IVI values (14.59). The most dominant shrub species in Gorakhpur C₇ was *A. solanacea*, which had the maximum relative density (58.67 %), relative frequency (14.71 %), relative basal area (36.60 %) and IVI (109.98). In case of herb species inside of Gorakhpur C₇, the compartment was dominated by *D. paniculata* with maximum relative density of 18.91 per cent, relative frequency of 13.24 per cent, relative basal area of 34.44 per cent and IVI value of 66.59.

In Lai C₂₈, *S. robusta* was documented with highest value for relative density (45.59 %), relative frequency (16.67 %), relative basal area (76.70 %) and IVI value of 135.96. The most dominant shrub species in Lai C₂₈ was *A. solanacea*, which had the maximum relative density (42.93 %), relative frequency (16.52 %), relative basal area (19.69 %), and IVI (79.14). In case of herb species, inside of Lai C₂₈, *A. mutica* had the maximum relative density of 17.38 per cent, relative basal area of 27.77 per cent and IVI value of 56.79.

The Shannon Index of diversity (H') for trees ranged between 1.83(Lai C₂₈) to 1.44 (Gorakhpur C₇), for shrub 2.02 (Kukron C₁₄) to 1.56 (Gorakhpur C₇), and for herbs 2.28 (Rajban C₆) to 2.02 (Kukron C₁₄, Kukron C₁₅). Simpson Index of diversity (D) ranged for trees between 0.75 (Rajban C₇) to 0.67 (Kukron C₁₄), for shrub 0.81 (Kukron C₁₄) to 0.63 (Gorakhpur C₇) and for herbs 0.89 (Rajban C₆, Rajban C₇) to 0.86 (Kukron C₁₄, Gorakhpur C₇), Simpson Index of dominance (Cd) for trees ranged between 0.33 (Kukron C₁₄) to 0.23 (Lai C₂₈) for shrub 0.37 (Gorakhpur C₇) to 0.19 (Kukron C₁₄), and for herbs 0.14 (Kukron C₁₄, Kukron C₁₅) to 0.11 (Rajban C₆, Rajban C₇). Pielou's Equitability (Eq) varied between 0.88 (Rajban C₇) to 0.75 (Kukron C₁₄) for trees, 0.84 (Kukron C₁₄, Lai C₂₈) to 0.68 (Gorakhpur C₇) for shrub and 0.99 (Rajban C₆) to 0.97 (Rajban C₁₀, Kukron C₁₄, Kukron C₁₅ and Lai C₂₈) for herbs respectively; Margalef's Index of richness (MI) ranged for trees between 1.43 (Lai C₂₈) to 0.87 (Rajban C₁₀, Gorakhpur C₇), for shrub 1.08 (Kukron C₁₅) to 0.89 (Lai C₂₈) and for herbs 0.74(Rajban C₆, Rajban C₇) to 0.59 (Kukron C₁₄) , respectively.

The similarity index of trees in different compartments ranged from 0.67 to 1.00. Rajban C₆ and Rajban C₇ had the maximum similarity index (1.00) with Kukron C₁₄ and Gorakhpur C₇ while minimum value for similarity index (0.67) was reported with Lai C₂₈. Similarly, Kukron C₁₄ had the maximum similarity index (1.00) with Gorakhpur C₇. On the other hand, for tree species Rajban C₆, Rajban C₇, Kukron C₁₄ and Rajban C₁₀ reported minimum value for similarity index (0.67) with Lai C₂₈. For shrub species, Rajban C₆ had the maximum similarity index (1.00) with Rajban C₇. Maximum similarity index of 0.95 was reported in Rajban C₇ with Kukron C₁₄ and minimum value for similarity index (0.76) was reported with Kukron C₁₅. Furthermore, Kukron C₁₄ showed maximum similarity index of 0.90 with Rajban C₁₀. In respect of herb species, Rajban C₆ had the maximum similarity index (1.00) with Rajban C₇. Lai C₂₈ showed minimum similarity index (0.82) with Rajban C₁₀, Kukron C₁₅ and Gorakhpur C₇.

On the other hand, for tree species, Rajban C₆ reported minimum value for dissimilarity index (0.00) with Rajban C₇. Similarly, Kukron C₁₄ reported minimum value of dissimilarity index (0.00) with Lai C₂₈. Gorakhpur C₇ and minimum value of dissimilarity index (0.00) was documented with Rajban C₆, Rajban C₇ and Kukron C₁₄. Whereas, maximum value was recorded by Rajban C₁₀ and Kukron C₁₅ with Rajban C₆, Rajban C₇ and Kukron C₁₄. In case of shrub species, Rajban C₆ recorded minimum value for dissimilarity index (0.00) with Rajban C₇. Kukron C₁₅ had the maximum dissimilarity index (0.24) with Rajban C₆ and Rajban C₇. In respect of herb species, Rajban C₆ reported minimum value for

dissimilarity index (0.00) with Rajban C₇, however, maximum value was recorded by Kukron C₁₅ (0.22) followed by Lai C₂₈ with Rajban C₁₀, Kukron C₁₅ and Gorakhpur C₇.

Stand characteristics

In Rajban C₆, total number of 257.50 individuals ha⁻¹ contributing the total volume of 155.86 m³ ha⁻¹, AGB of 124.24 Mg ha⁻¹, BGB of 56.89 Mg ha⁻¹, TB of 181.14 Mg ha⁻¹ and carbon stock of 86.04 Mg C ha⁻¹ were recorded in the compartment, the contribution for volume, AGB, BGB, TB and carbon stock follows the following order: *S. robusta*> *Terminalia tomentosa*> *Syzygium cuminii*> *Mallotus philippinensis*> *Cordia dichotoma*> *C. fistula*, respectively.

A total density of 250 N ha⁻¹, volume of 103.71 m³ ha⁻¹, AGB of 124.24 Mg ha⁻¹, BGB of 56.89 Mg ha⁻¹, TB of 181.14 Mg ha⁻¹ and carbon stock of 86.04 Mg C ha⁻¹ was recorded in Rajban C₇. Hence, the contribution for volume, AGB, BGB, TB and carbon stock follows the following order: *S. robusta*, *T. tomentosa*, *M. philippinensis*, *C. dichotoma*, *S. cuminii* and *C. fistula*, respectively.

Species-wise distribution of density, above ground biomass (AGB), belowground biomass (BGB), total biomass (TB) and carbon stock of trees in Kukron C₁₄, with a total density of 305.00 number ha⁻¹, volume of 277.88 m³ ha⁻¹, AGB of 343.96 Mg ha⁻¹, BGB of 143.39 Mg ha⁻¹, TB of 487.35 Mg ha⁻¹, and carbon stock of 232.66 Mg C ha⁻¹. The species wise contribution for volume, BGB, TB and carbon stock is arranged in following order: *S. robusta* > *T. tomentosa* > *M. philippinensis*, *Syzygium cuminii*>*C. dichotoma*>*C. fistula*, respectively.

The total tree density (300.00 N ha⁻¹), volume (209.19 m³ ha⁻¹), AGB (258.46 Mg ha⁻¹), BGB (112.74 Mg ha⁻¹), TB (371.20 Mg ha⁻¹) and carbon stock (176.32 Mg C ha⁻¹) was recorded in Rajban C₁₀. The maximum value for AGB, BGB, TB and carbon stock was displayed by *S. robusta* followed the order: *Terminalia tomentosa*> *Mallotus philippinensis*> *Ficus palmata*> *Callicarpa japonica*> *S. cuminii* > *C. dichotoma*.

The total density of 297.50 N ha⁻¹, volume of 182.48 m³ ha⁻¹, AGB of 222.86 Mg ha⁻¹, BGB of 94.98 Mg ha⁻¹, TB of 317.84 Mg ha⁻¹, and carbon stock of 152.58 Mg C ha⁻¹ was reported for Kukron C₁₅. The species wise contribution for volume, BGB, TB and carbon stock is arranged in following order; *S. robusta* > *T. tomentosa*> *M. philippinensis*> *S. cuminii*> *C. dichotoma*> *Cassia fistula*, respectively.

In Gorakhpur C₇, The total tree density of 322.50 N ha⁻¹, volume of 68.95 m³ ha⁻¹, AGB of 81.91Mg ha⁻¹, BGB of 41.98 Mg ha⁻¹, TB of 123.89 Mg ha⁻¹ and carbon stock of 58.85 Mg C ha⁻¹ was recorded. The species wise contribution for volume, BGB, TB and carbon stock is arranged in following order; *S. robusta* > *T. tomentosa* > *M. philippinensis* > *S. cuminii* > *C. dichotoma* > *C. fistula*, respectively.

The total density of 270.00 N ha⁻¹, volume of 131.39 m³ ha⁻¹, AGB of 163.71 Mg ha⁻¹, BGB of 72.60 Mg ha⁻¹, TB of 236.31 Mg ha⁻¹, and carbon stock of 112.25 Mg ha⁻¹ in Lai C₂₈. The species wise contribution for volume, AGB, BGB, TB and carbon stock is arranged in following order: *S. robusta* > *T. tomentosa* > *A. catachu* > *M. philippinensis* > *C. dichotoma*, respectively.

Population dynamics

The population dynamics (N ha⁻¹) reported for Kukron C₁₄ had maximum seedling density (6000 N ha⁻¹) and Rajban C₇ had the minimum seedling density (4625 N ha⁻¹). Rajban C₁₀, on the other hand, had the maximum recorded sapling density at 3063 number ha⁻¹ Rajban C₇ recorded the minimum reported sapling density (2000 N ha⁻¹). Pole density, the maximum value was recorded in Kukron C₁₄ (440 N ha⁻¹), whereas, Rajban C₇ recorded the minimum pole density (160 N ha⁻¹) Gorakhpur C₇ (323 N ha⁻¹) recorded maximum value of tree density and minimum tree density was recorded Rajban C₇ (250 N ha⁻¹).

Kukron C₁₄ had maximum seedling density (6000 N ha⁻¹) Rajban C₁₀, on the other hand, had the maximum recorded sapling density at 3063 N ha⁻¹ Pole density, the maximum value was recorded in Kukron C₁₄ (440 N ha⁻¹), Gorakhpur C₇ (323 N ha⁻¹) recorded maximum value of tree density.

Maximum average diameter (33.27 cm), basal area (1.19 m² ha⁻¹) and volume (277.88 m³ ha⁻¹) was recorded in Kukron C₁₄ and minimum diameter (20.27 cm), basal area (0.37 m² ha⁻¹) and volume (68.95 m³ ha⁻¹) was recorded in Gorakhpur C₇, further, maximum tree height (15.10 m) was recorded in Rajban C₁₀ and minimum tree height was recorded in Rajban C₇ (11.60 m).

Rajban C₁₀ had the highest shrub density (11,200.00 N ha⁻¹) and basal area (81,326.94 cm² ha⁻¹) while, Kukron C₁₄ had the lowest shrub density (5,540.00 ha⁻¹) and basal area (29,991.88 cm² ha⁻¹). Kukron C₁₄ (185,800.00 N ha⁻¹) had maximum herb density and basal area (212,444.10 cm² ha⁻¹) and Rajban C₆ has the lowest herb density (133,300.00 N ha⁻¹). Kukron C₁₅ has the smallest basal area (495.81 cm² ha⁻¹).

Biomass and carbon density

Maximum stem biomass ($199.32 \text{ Mg ha}^{-1}$), AGB ($343.96 \text{ Mg ha}^{-1}$), BGB ($143.39 \text{ Mg ha}^{-1}$) and TB ($487.35 \text{ Mg ha}^{-1}$) was recorded in compartment Kukron C₁₄ and minimum value for stem biomass AGB (81.91 Mg ha^{-1}), BGB (41.98 Mg ha^{-1}) and TB ($123.89 \text{ Mg ha}^{-1}$) was displayed by Gorakhpur C₇ which followed the trend: Kukron C₁₄>Rajban C₁₀>Kukron C₁₅>Rajban C₆>Lai C₂₈>Rajban C₇>Gorakhpur C₇.

Maximum value for above ground shrub biomass (1.25 Mg ha^{-1}) in Rajban C₁₀ and lowest value for above ground shrub biomass (0.70 Mg ha^{-1}) was recorded in Kukron C₁₄ maximum value of below ground shrub biomass (0.83 Mg ha^{-1}) was reported in Kukron C₁₅ the lowest value for below ground shrub biomass was recorded in Kukron C₁₄ (0.49 Mg ha^{-1}).

Gorakhpur C₇ reported maximum value for above ground herb biomass (4.58 Mg ha^{-1}) below ground herb biomass (2.98 Mg ha^{-1}) and total herb biomass (7.55 Mg ha^{-1}), while, lowest value for above ground herb biomass (2.68 Mg ha^{-1}), below ground herb biomass (1.73 Mg ha^{-1}) and total herb biomass (4.41 Mg ha^{-1}) was recorded in Kukron C₁₅.

Maximum Tree carbon density ($232.66 \text{ Mg C ha}^{-1}$) was recorded for Kukron C₁₄ and lowest tree carbon density ($58.85 \text{ Mg C ha}^{-1}$) in Gorakhpur C₇. Maximum shrub carbon density was present in Rajban C₁₀ ($0.98 \text{ Mg C ha}^{-1}$), whereas, Kukron C₁₄ ($0.56 \text{ Mg C ha}^{-1}$) had minimum value of shrub carbon density. Maximum value of herb carbon density was recorded in Gorakhpur C₇ ($3.59 \text{ Mg C ha}^{-1}$) and lowest value for herb carbon density was recorded in Kukron C₁₅ ($2.09 \text{ Mg C ha}^{-1}$). Maximum value total carbon density was recorded in Kukron C₁₄ ($234.26 \text{ Mg C ha}^{-1}$) and Gorakhpur C₇ ($63.09 \text{ Mg C ha}^{-1}$) had the lowest value for total carbon density.

Leaf litter biomass (5.35 Mg ha^{-1}), dead twig and branch biomass (0.85 Mg ha^{-1}), dead tree biomass (0.96 Mg ha^{-1}) and total detritus biomass presented maximum value (7.16 Mg ha^{-1}). For Kukron C₁₄ and minimum value of leaf litter biomass (3.99 Mg ha^{-1}), dead twig and branch biomass (0.31 Mg ha^{-1}), dead tree biomass (0.67 Mg ha^{-1}) and total detritus biomass (4.97 Mg ha^{-1}) was recorded in Rajban C₇.

Maximum value ($234.26 \text{ Mg C ha}^{-1}$) of vegetation carbon density, humus carbon density ($6.07 \text{ Mg C ha}^{-1}$) was recorded in Kukron C₁₄ and Gorakhpur C₇ ($63.09 \text{ Mg C ha}^{-1}$) had the lowest value for vegetation carbon density. Rajban C₆ had significantly minimum value ($3.92 \text{ Mg C ha}^{-1}$) for humus carbon density, maximum soil carbon density was revealed in Rajban C₆ ($71.19 \text{ Mg C ha}^{-1}$) lowest value for soil carbon density (45.61 Mg ha^{-1}) was

recorded for Lai C₂₈. Total carbon density [humus+soil (0-40 cm)] showed similar trend as soil carbon density. Total carbon density reported in Rajban C₆ (75.11 Mg C ha⁻¹) and Lai C₂₈ recorded minimum value for total carbon density (40.90 Mg C ha⁻¹). Detritus carbon density maximum value (3.40 Mg C ha⁻¹) in Kukron C₁₄ and minimum value for detritus carbon density (2.36 Mg C ha⁻¹) was recorded in Rajban C₇. Maximum ecosystem carbon density was recorded in Kukron C₁₄ (287.58 Mg C ha⁻¹) and the minimum ecosystem carbon density (164.20 Mg C ha⁻¹) and carbon stock (4,718.12 Mg C ha⁻¹) was shown in Gorakhpur C₇.

Regeneration status

Maximum recruits (6000 recruits ha⁻¹) and established regeneration (937.50 N ha⁻¹) were recorded in Kukron C₁₄, while minimum recruits (4625 recruits ha⁻¹) were reported in Gorakhpur C₇ and Rajban C₇ (562.50 individual ha⁻¹). Rajban C₁₀ had the maximum un-established regeneration (2437.50 N ha⁻¹), while, Rajban C₇ had the lowest un-established regeneration (1437.50 individual ha⁻¹). The establishment stocking per cent (38.80 %) was maximum in Rajban C₆ and minimum in Rajban C₇ (36.88 %). Maximum regeneration success (52.50 %) was observed in Kukron C₁₄ and minimum regeneration success (36.88 %) in the Rajban C₇. Maximum Seed fall (202.70 kg ha⁻¹) was recorded in Kukron C₁₄ and minimum Seed fall in Rajban C₇ (150.90 kg ha⁻¹).

Soil characteristics

Maximum value for Humus depth (3.91 cm) was recorded for Kukron C₁₄ and the minimum value was shown in Rajban C₇ (2.25 cm). The maximum value for soil pH was recorded for Kukron C₁₅ (6.71), while, the minimum value was recorded in Kukron C₁₄ (5.25). Maximum value of Electrical conductivity (0.44 dsm⁻¹) was recorded in Kukron C₁₄ and the lowest value was recorded for Gorakhpur C₇ (0.24 dsm⁻¹). The bulk density increased significantly with the increase in soil depths from 1.46 to 1.49 g cm⁻³.

Soil organic carbon per cent in Kukron C₁₄ had the maximum value (1.68 %), whereas, the minimum value of Soil organic carbon was noted in Rajban C₇ (0.40 %). the labile carbon was also found highest in Kukron C₁₄ (0.33 %) and the minimum value was reported in Rajban C₇ (0.14 %). In Kukron C₁₄, non-labile carbon was also found to be highest with the maximum value (0.40 %) the minimum value was reported in Rajban C₇ (0.15 %).

Kukron C₁₄ had the maximum value of available soil nitrogen (404.47 kg ha⁻¹), available phosphorus (45.68 kg ha⁻¹) and potassium (428.02 kg ha⁻¹), while, the minimum value available soil nitrogen (255.93 kg ha⁻¹), phosphorus (25.73 kg ha⁻¹) and potassium (228.29 kg ha⁻¹) was recorded for Rajban C₇.

The soil micro nutrients viz., Zn, Fe, B and Zn decreased significantly along the soil depth as 6.54 (0-20 cm) to 5.75 kg ha⁻¹ (20-40 cm), Fe from 57.35 (0-20 cm) to 45.77 kg ha⁻¹ (20-40 cm), B from 0.28 (0-20 cm) to 0.20 kg ha⁻¹ (20- 40 cm), Cu 2.20 (0-20 cm) to 1.88 kg ha⁻¹ (20-40 cm) and S from 12.03(0-20 cm) to 10.98 kg ha⁻¹ (20- 40 cm).

Correlation

N had highly positive correlation with P, K and Fe. P showed strongest correlation with K., although, P and K were highly correlated with N. Meanwhile, Zn had positive association with Boron and Copper. SQI showed strongest positive correlation with SOC, N, P and K. Tree height revealed strong positive correlation with Site Quality Index. Further, volume strongest relationship with Total Biomass and TB was positively correlated with SQI whereas negatively correlated to herb biomass. Tree volume was shown to be highly and positively correlated with tree biomass.

Soil quality index

Tree carbon was positively correlated with Potassium. SOC was associated with a strong positive relationship with N, P, K and Iron. While, P showed strongest correlation with K. Furthermore, N was highly positively correlated with P, K and Fe, although, P and K were highly correlated with N. Meanwhile, Zn had positive association with Boron and Copper. Among several soil parameters, bulk density was shown to be significantly and positively connected to Soil organic carbon, nitrogen, phosphorus and potassium availability. SOC had a good positive relationship with N and P.

The Shrub carbon and Shannon diversity index (shrub) were shown to be highly and positively correlated. Further, Simpson Dominance index (tree) strong relationship with Shannon diversity index (tree), Pielou Equitability (Ep) index (Tree) was positively correlated with SIH (herb), Shannon diversity index (herb), Margalef Index of species richness (herb). Simpson Dominance index (Shrub) was highly correlated with Pielou Equitability (Ep) index (shrub). Likewise, Simpson Dominance index (herb) had a strongest positive association with Shannon diversity index (herb) and Pielou Equitability (Ep) index

(herb). SHH was positively correlated. with MH and EH. Also, Positive association between MH and EH was reported.

Simpson Dominance index (Tree) was positively associated with Margalef Index of species richness (tree). ET demonstrated a highly significant positive correlation with SIT, SHH and Margalef Index of species richness(herb). Simpson Dominance index (Shrub) was associated with a positive relationship with Shannon diversity index (shrub), Margalef Index of species richness (shrub) and Pielou Equitability (Ep) index (shrub). In addition, SHS and ES were positively correlated. The strongest positive association was being observed for SIH and SHH as well as with MH and EH. SHH was correlated positively with MH and EH.

Principal component analysis

PCA reduced the studied thirty one characters into four Principal components namely PC1 PC2 PC3 and PC4 which had eigen value greater than one i.e., 13.52 6.98 5.06 and 4.16 respectively and accounted for 95.85 per cent of total variability. PC1 vs. PC2 bi-plot was generated. Among the PCs, PC1 contributed for majority of the variation i.e., 43.62 per cent followed by PC2 (22.52), PC3 (16.33) and PC4 (13.41), respectively.

CONCLUSION

In the present investigation, it was observed that the floristic composition of trees, shrubs and herbs are common among all the compartments of Sal forests, excepting Lai C₂₈. However, a lot of inter compartmental variation was observed for biomass and carbon density and thus it was recommended to impose optimum treatments, like density manipulation of mixture to create favourable environment for growth of Sal for realization of higher volume and carbon storage capacity from low yielding compartments of Gorakhpur C₇, Rajban C₇ and Lai C₂₈. All the compartments, excepting Gorakhpur C₇ exhibited characteristic reverse J-shaped curve indicating less anthropogenic/ biotic pressure. However, Gorakhpur C₇ compartment deserve due attention. The regeneration from the seeds was satisfactory in all the compartments, but its progression towards the establishment was checked due to heavy infestation of *Ardisia solanacea*, which needs to be controlled. Soil quality indices indicated inter compartment variation, which means that each compartment need individual attention in terms of floor management so that objective of the high biodiversity, biomass and carbon storage can be achieved, as it bears a strong positive relationship among different parameters.

LITERATURE CITED

- Acharya R and Shrestha BB. 2012. Physiochemical Characteristics of Soil of a Mixed *Shorea robusta* Forest in Rupandehi District, Nepal. *Journal of Natural History Museum***26**:155-162.
- Adhikari B, Kapkoti B, Lodhiyal N and Lodhiyal LS. 2018. Diversity of Herbs in some sal Forests in Shivalik Region of Central Himalaya. *Indian Journal of Non Timber Forest Products***25**: 41-45.
- Adhikari B, Kapkoti B, Lodhiyal N and Lodhiyal LS. 2017. Structure and regeneration of Sal (*Shorea robusta*) forests in Shivalik region of Kumaun Himalaya, India. *Indian Journal of Forestry***40**:1-8.
- Ayyappan N and Parthasarathy N. 1999. Biodiversity inventory of trees in a large-scale permanent plot of tropical evergreen forest at Varagalaiar, Anamalais, Western Ghats, India. *Biodiversity Conservation***8(11)**:1533-1554.
- Baishya R, Barik SK and Upadhaya K. 2009. Distribution pattern of aboveground biomass in natural and plantation forests of humid tropics in northeast India. *Tropical Ecology***50**: 295-304.
- Banik B, Deb D, Deb S and Datta BK. 2018. Assessment of Biomass and Carbon Stock in Sal (*Shorea robusta*) Forests under two management Regimes in Tripura, Northeast India. *Journal of Forest and Environmental Science***34**: 209-222.
- Barik SK, Pandey HN, Tripathi RS and Rao P. 1992. Microenvironmental variability and species diversity in tree fall gaps in a sub-tropical broad-leaved forest. *Vegetation* **103**: 31-40.
- Barlow J, Lennox GD, Ferreira J, Berenguer E, Lees AC, Mac NR and Parry L. 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature***535**:144-147.
- Bashyal S. 2005. Quantitative analysis and regeneration of *Shorea robusta* and *Terminalia alata* of tropical forest in Palpa district. M.Sc. Dissertation Submitted to Central Department of Botany, Tribhuvan University, Kathmandu, Nepal. 345pp.
- Basyal S, Lekhak HD and Devkota A. 2011. Regeneration of *Shorea robusta* Gaertn.f in tropical forest of Palpa district, central Nepal. *Scientific world***9(9)**: 53-56.
- Behera SK, Saha N, Mishra AK, Bargali SS, Behera MD and Tulia R. 2017. Aboveground biomass and carbon stock assessment in Indian tropical deciduous forest and relationship with stand structural attributes. *Ecological Engineering***99**: 513-524.
- Bhatnagar HP. 1965. Soils from different quality sal (*Shorea robusta*) forests of Uttar Pradesh. *Tropical Ecology***6**: 56-62.
- Bhatta SP. 2016. Carbon Stock and Regeneration Status of Community Managed Sal (*Shorea robusta* Gaertn.) Forests in Dadeldhura District, Western Nepal (Doctoral dissertation, Department of Botany).

- Bhattarai KP and Mandal TN. 2016. Effect of altitudinal variation on the soil characteristics in sal (*Shorea robusta*) forests of eastern Nepal. *Our Nature***14**: 30-38.
- Bisht APS. 1989. Microsite mosaic and under canopy vegetation dynamics of Sal communities in East and West Dehradun Forest Division. Ph.D. Thesis. Garhwal University, Srinagar, Garhwal, India. 209pp.
- Biswas S, Biswas A, Das A and Banerjee S. 2021. Phytosociological assessment and carbon stock estimation and valuation in the tropical dry deciduous forest of Bihar. *Ecofeminism and Climate Change***2**: 2-16.
- Bitterlich W. 1984. The relascope idea. Relative measurements in forestry. Commonwealth Agricultural Bureaux. 1098pp.
- Braun-Blanquet J. 1965. Plant Sociology (Pflanzensoziologie). *Tr. by GD Fuller. New York, Hafner publication.* 439p.
- Brown SA and Lugo AE. 1982. The Storage and Production of Organic Matter in Tropical Forests and their Role in the Global Carbon Cycle. *Biotropica***1**: 161-167.
- Cailliez F and Alder D. 1980. Forest volume estimation and yield prediction (Vol. 1). Food and agriculture Organization of the United Nations. 152pp.
- Cairns MA, Brown S, Helmer EH and Baumgardner GA. 1997. Root biomass allocation in the world's upland forests. *Oecologia***111**: 1–11. doi: 10.1007/s004420050201
- Chacko VJ. 1965. A manual on sampling techniques for forest surveys. *A manual on sampling techniques for forest surveys.* 172pp.
- Champion HG and Seth SK. 1968. A revised survey of the Forest Types of India. Manager of Publication, Govt. of India, New Delhi. 563pp.
- Champion HG and Seth SK. 1968. General Silviculture for India. Government of India, Delhi. 511pp.
- Chandel S, Hadda MS and Mahal AK. 2018. Soil quality assessment through minimum data set under different land uses of submontane Punjab. *Communications in Soil Science and Plant Analysis***49(6)**: 658-674.
- Chandra A, Naithani HB, Verma PK and Saxena J. 2022. Floristic assessment of forests of Banka district of Bihar, Eastern India. *International Journal of Ecology and Environmental Sciences***48**: 207-212.
- Chandrashekara UM and Ramakrishnan PS. 1993. Gap phase regeneration of tree species of differing successional status in a humid tropical forest of Kerala, India. *Journal of Bioscience***18**: 279-290.
- Chaturvedi AN and Khanna LS. 1982. Forest mensuration. International Book Distributors, Dehradun, India. 403pp.
- Chaubey OP and Jamaluddin. 1989. Impact of grazing closure on some ecological aspects of *Shorea robusta* natural forests with special reference to its regeneration in Madhya Pradesh. *Biome***4**: 29-33.

- Chaubey OP and Sharma A. 2013. Population structure and regeneration potential of Sal (*Shorea robusta*) and its associates in sal bearing forests of Satpura Tiger Reserve. *International Journal of Bio-Science and Bio-Technology***5**: 63-70.
- Chaudhury G, Darji CB, Basumatari M, Dutta G, Devi A and Bharadwaj N. 2022. Stand structure, biomass and carbon stock along disturbance gradients in differently managed tropical forests of Assam, northeast India. *Trees, Forests and People***9**:100-296.
- Chauhan DS, Dhanai CS, Singh B, Chauhan S, Todaria NP and Khalid MA. 2008. Regeneration and tree diversity in natural and planted forests in a terai-bhabhar forest in Katarniaghat Wildlife Sanctuary, India. *Tropical Ecology***49**: 53-67.
- Chauhan DS, Singh B, Chauhan S, Dhanai CS and Todaria NP. 2010. Regeneration and plant diversity of natural and planted sal (*Shorea robusta* Gaertn. F.) forests in the Terai-Bhabhar of Sohagibarwa Wildlife Sanctuary, India. *Journal of American Science***6(3)**: 32-45.
- Chauhan PS, Negi JDS, Singh L and Monhas RK. 2008. Regeneration status of Sal forests of Doon Valley. *Annals of Forestry***16**: 1781-1782.
- Chavan BL and Rasal GB. 2012. Carbon sequestration potential of young *Annona reticulate* and *Annona squamosa* from University Campus of Aurangabad. *International Journal of Physical and Social Sciences***2**:193-198.
- Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Folster H, Fromard F, Higuchi N and Kira T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia***145**: 87-99.
- Culman SW, Snapp SS, Freeman MA, Schipanski ME, Beniston J, Lal R, Drinkwater LE, Franzluebbers AJ, Glover JD, Grandy AS and Lee J. 2012. Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. *Soil Science Society of America Journal***76(2)**: 494-504.
- Dabral BG, Pant SP and Pharasi SC. 1980. Micro-climate of a regenerating *Shorea robusta* forest in West. *The Indian Forester***143**: 1-13.
- Dadhwal VK, Singh S and Patil P. 2009. Assessment of phytomass carbon pools in forest ecosystems in India. NNRMS Bulletin, Indian Institute of Remote Sensing, Dehradun, 41-47pp.
- Dar JA and Sundarapandian S. 2015. Variation of biomass and carbon pools with forest type in temperate forests of Kashmir Himalaya, India. *Environmental monitoring and assessment* **187**:1-17.
- Darji CB, Basumatari M, Dutta G, Devi A and Bharadwaj N. 2022. Stand structure, biomass and carbon stock along disturbance gradients in differently managed tropical forests of Assam, northeast India. *Trees, Forests and People***9**:1-13.
- Dash AK, Upadhyay VP and Patra HK. 2020. Floristic assessment of semi evergreen forests of a peripheral site in Hadagarh Sanctuary, Odisha, India. *International Journal of Biodiversity and Conservation***12**: 104-112.

- Deka J, Tripathi OP and Khan ML. 2012. High Dominance of *Shorea robusta* Gaertn.f in Alluvial Plain Kamrup Sal forest of Assam. *India International Journal of Ecosystem***2**: 67-73.
- Demoraes RM, Delitti WBC and Struffaldi DVY. 1999. Litterfall and Litter nutrient content in two Brazilian Tropical Forests. *Brazilian Journal of Botany***22**: 9-16.
- DeMoraes SJC and Lal R. 2009. Stratification ratio of soil organic matter pools as an indicator of carbon sequestration in a tillage chronosequence on a Brazilian Oxisol. *Soil and Tillage Research***103**(1): 46-56.
- Devi LS and Yadava PS. 2009. Aboveground biomass and net primary production of semi-evergreen tropical forest of Manipur, north-eastern India. *Journal of Forestry Research***20**: 151-155.
- Divakara BN. 2015. Floristic analysis, phytosociological studies and regeneration status of tree species in sal forests of Jharkhand, India, in XIV world forestry congress Durban, South Africa. [https:// www.researchgate.net/publication/286443392](https://www.researchgate.net/publication/286443392).
- doi:[10.1371/journal.pone.0094966](https://doi.org/10.1371/journal.pone.0094966)
- Dutta G and Devi A. 2013. Plant diversity and community structure in tropical moist deciduous sal (*Shorea robusta* Gaertn. f) Forest of Assam, northeast India. *Journal of Environment and Applied Bioresources***1**: 1-4.
- Ekta and Ray M. 2019. Study of soil organic carbon pool and its variation with depth in the tropical dry deciduous forest of Ranchi, Jharkhand, India. *International Journal of Scientific Engineering and Research***7**: 67-71.
- Fahey TJ, Woodbury PB, Battles JJ, Goodale CL, Hamburg SP, Ollinger SV and Woodall CW. 2010. Forest carbon storage: ecology, management, and policy. *Frontiers in Ecology and the Environment***8**: 245-252.
- FSI. 1996. Volume equations for forests of India, Nepal and Bhutan, Forest Survey of India, Ministry of Environment and Forests. Dehradun: Govt. of India- FSI. Volume Equations for Forester of India, Nepal and Bhutan. Ministry of Environment and Forests, Government of India, Dehradun. 1-249pp.
- FSI. 2021. <https://fsi.nic.in/forest-report-2021>
- Gautam KH and Devoe NN. 2006. Ecological and anthropogenic niches of sal (*Shorea robusta* Gaertn. f.) forest and prospects for multiple-product forest management-A review. *Forestry***79**(1): 81-101.
- Gautam KH. 1990. Regeneration Status of Sal (*Shorea robusta*) Forests in Nepal. Department of Forest Nepal, Kathmandu. 11pp.
- Gautam MK, Manhas RK and Tripathi AK. 2016. Patterns of diversity and regeneration in unmanaged moist deciduous forests in response to disturbance in Shiwalik Himalayas, India. *Journal of Asia-Pacific Biodiversity***9**(2): 144-151.
- Gautam TP and Mandal TN. 2016. Effect of disturbance on biomass, production and carbon dynamics in moist tropical forest of eastern Nepal. *Forest Ecosystems***3**: 11.

- Geraei DS, Hojati S, Landi A and Cano AF. 2016. Total and labile forms of soil organic carbon as affected by land use change in southwestern Iran. *Geoderma regional***7(1)**: 29-37.
- Ghehi G, Nemes NA, Verdoodt A, Van EE, Cornelis WM and Boeckx P. 2012. Nonparametric techniques for predicting soil bulk density of tropical rainforest top soils in Rwanda. *Soil Science Society of American Journal***76(4)**: 1172-1183.
- Gibbs HK, Brown S, Niles JO and Foley JA. 2007. Monitoring and estimating tropical forest carbon stocks: making REDD a reality. *Environmental Research Letters***2**: 1-13.
- Giril A, Aryal B, Bhattarai B, Ghimire SK, Shrestha K and Jha PK. 1999. Vegetation composition, biomass production and regeneration in *Shorea robusta* forests in the Royal Bardia National Park, Nepal. *Nepal Journal of Science and Technology***1**: 47-56.
- Gogoi A, Sahoo UK and Singh SL. 2017. Assessment of biomass and total carbon stock in a tropical wet evergreen rainforest of Eastern Himalaya along a disturbance gradient. *Journal of Plant Nutrition and Soil Science***4**: 1-8.
- Goldsmith FB, Harrison CM and Morton AJ. 1986. Description and analysis of vegetation. In: methods in plant ecology. (eds. Moore PD and SB Chapman) Blackwell Sciences Publication, London. 442pp.
- Gren IM and Zeleke AA. 2016. Policy design for forest carbon sequestration: A review of the literature. *Journal of Political Economy***70**: 128-136.
- Grote R. 2002. Foliage and branch biomass estimation of coniferous and deciduous tree species. *Silva Fennica***36**: 779-788.
- Guimaraes DV, Gonzaga MI, DaSilva TO, DaSilva TL, DaSilva DN and Matias MI. 2013. Soil organic matter pools and carbon fractions in soil under different land uses. *Soil and Tillage Research***126**:177-182.
- Gupta MK and Sharma SD. 2008. Effect of tree plantation on soil properties, profile morphology and productivity index I. Poplar in Uttarakhand. *Annals of Forestry***16(2)**: 209-224.
- Gupta RS. 1953. Studies in soils. Proceedings of All India *Shorea robusta* study tour and Symposium FRI, Dehradun. 28-29pp.
- Gupta SK and Sharma R. 1996. Biological oxidation of high strength nitrogenous waste water. *Water Research***30(3)**: 593-600. doi:10.1016/0043-1354(95)00172-7
- Hailemariam MB and Temam TD. 2018. The vegetation composition, structure and regeneration status of Gole Natural Forest, West Arsi Zone, Oromia Regional State, Ethiopia. *Journal of Agricultural science and Botany***2(2)**: 10-21.
- Hole RS. 1921. Regeneration of sal (*Shorea robusta*) forests. A study in economic ecology, Indian Forest Record, Silviculture (Old Series), 8(2): 435pp.
- Hoque AE, Islam AKM and Huq SMI. 2008. Seasonal variation of edaphic features of Madhupur Sal Forest, Bangladesh. *Ecoprint***15**: 7-14.

- Ilorkar VM and Khatri PK. 2003. Phytoso-ciological study of Navegaon National Park (Maharashtra). *Indian Forester***129(3)**: 377-387.
- International Panel on Climate Change (IPCC). 2007. Climate change: Scientific basis: IPCC fourth assessment report, Working Group I. Institute for Global Environmental Strategies (IGES).
- Jackson ML. 1973. Soil chemical analysis, pentice hall of India Pvt. Ltd., New Delhi, India**498**: 151-154.
- Jha CS and Singh JS. 1990. Composition and dynamics of dry tropical forest in relation to soil texture. *Journal of Vegetation Science***1(5)**: 609-614.
- Jolliffe IT and Cadima J. 2016. Principal component analysis: A review and recent developments. *Philosophical transactions of the royal society A: Mathematical, Physical and Engineering Sciences***374(2065)**: 20150202.
- Joshi B and Pant SC. 2014. Physico-chemical investigation of soil in some forests of Tarai, Kumaun Himalaya, Uttarakhand, India. *Range Management and Agroforestry***35**: 85-90.
- Joshi SM. 2015. Biomass and carbon stock assessment in moist deciduous forests of Doon Valley, Western Himalaya, India. *Taiwania***60**: 71-76.
- Joshi VC and Chandra N. 2020. Pattern of diversity and regeneration potential along altitudinal gradient in selected forest stands of Kumaun Himalaya. *Indian Forester***146**: 301-305.
- Karki D. 2002. Economic assessment of community forestry in inner terai of Nepal: A case study from Chitwan district. Asian Institute of Technology press, Thailand. 35pp.
- Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF and Schuman GE. 1997. Soil quality: A concept, definition, and framework for evaluation (a guest editorial). *Soil Science Society of America Journal***61(1)**: 4-10.
- Kaul ON, Srivastava PBL and Bora NKS. 1966. Diagnosis of mineral deficiencies in sal (*Shorea robusta*) seedlings. *Indian forester* **92**: 704-706.
- Kayastha BP. 1985. Silvics of the Trees of Nepal. Community Forestry Development Project, Kathmandu.
- Khan MAW and Gupta AC. 1960. Plant communities associated with Sal (*Shorea robusta*) regeneration in Dehra Dun valley. *Indian Forester***86(7)**: 417-23.
- Khan ML, Rai JPN and Tripathi RS. 1987. Population structure of some tree species in disturbed and protected sub-tropical forests of NE India. *Acta Oecologica***8**: 247-255.
- Khare PK, Yadav VK and Mishra GP. 1987. Collection, germination and storage of *Shorea robusta* seeds. In: Proceedings of the IUFRO international symposium on forest seed problems in Africa. Dept. of Forest Genetics. Swedish Agriculture University, S-90183, Umea, Sweden: 154-158pp.

- Kimble JM, Lal R and Follett RR. 2002. Agricultural practices and policy options for carbon sequestration: what we know and where we need to go. *In: Kimbel JM, Lal R and Follett RR (eds.). Agricultural practices and policies for carbon sequestration in soil.* New York, Lewis Publishers. 512pp.
- Kongkham B, Khanduri VP, Rawat D, Singh B, Riyal M and Ahmad T. 2021. Community structure, regeneration status, carbon sequestration potential and soil properties in Shivalik Sal forests of Uttarakhand, India. *Advances in Bioresearch***12(4)**: 206-215.
- Koop AL and Horvitz CC. 2005. Projection matrix analysis of the demography of an invasive, nonnative shrub (*Ardisia Elliptica*). *Ecology* **86**: 2661-2672.
- Koop AL. 2003. Population dynamics and invasion rate of an invasive, tropical understory shrub, *Ardisia elliptica*. Dissertation. University of Miami, Coral Gables, Florida, USA. 133pp.
- Koop AL. 2004. Differential seed mortality among habitats limits the distribution of the invasive non-native shrub *Ardisia elliptica*. *Plant Ecology***172**: 237-249.
- Krishnamurthy YL, Prakasha HM, Nanda A, Krishnappa M, Dattaraja HS and Suresh HS. 2010. Vegetation structure and floristic composition of a tropical dry deciduous forest in Bhadra Wildlife Sanctuary, Karnataka, India. *Tropical Ecology***51**: 235.
- Kumar M, Bhatt VP and Rajwar GS. 2006. Plant and soil diversities in a sub tropical forest of the Garhwal Himalaya. *Ghana Journal of Forestry***19**: 1-19.
- Kumar R and Saikia P. 2018. Floristic analysis and dominance pattern of sal (*Shorea robusta*) forests in Ranchi, Jharkhand and eastern India. *Journal of Forestry Research***10**:1-13.
- Kumar R and Saikia P. 2020. Forest resources of Jharkhand, Eastern India: socio-economic and bio-ecological perspectives. *Socio-economic and Eco-biological Dimensions in Resource use and Conservation: Strategies for Sustainability*. 61-101.
- Kumar R and Saikia P. 2021. Population structure and regeneration status of *Shorea robusta* and associated trees in Sal forests of Ranchi, Eastern India. *Tropical Ecology* **62**: 34-51.
- Kumar R, Kumar A and Saikia P. 2022. Forest composition regulates above-ground biomass in Sal forests of Ranchi, Eastern India. *Environmental-Sustainability***5(3)**: 2523-8922.
- Kumara A and Kumarb I. 2022. Physicochemical Characteristics of the Soil on the Growth of Sal Forest in Jharkhand. *International Journal of Innovative Science and Research Technology***7(9)**: 1782-1786.
- Kumara A, Kumarb I and Alamec MT. 2021. Review on the Growth of Sal Forest in Jharkhand. *Annals of Experimental Biology***9(3)**: 1-6.
- Kunwar RM, Duwadee NPS, Shrestha K, Bhandari GS, Gupta VNP, Vetaas OR and Chaudhary RP. 2008. Plant diversity and soil characteristics of *Shorea robusta* and *Castanopsis hystrix* forests and slash and burn habitats of Arun Valley, Eastern Nepal. *Pleione***2**: 87-97.

- Lal JB, Bahuguna VK, Hilaluddin M and Hussain S. 1994. Ecological studies of sal forest in Bankura north forest division, West Bengal. *Van Vigyan***32**: 15-22.
- Lal R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science***304**: 1623-1627.
- Lewis SL, Sonke B, Sunderland T, Begne S K, Lopez-Gonzalez G and Vander HGMF. 2013. Above-ground biomass and structure of 260 African tropical forests. *Philosophical Transactions of the Royal Society B: Biological Sciences***368**: 20120295. doi:10.1098/rstb.2012.0295
- Lorenz K and Lal R. 2009. Carbon sequestration in forest ecosystems. Springer Science and Business Media.
- Lorenz K and Lal KR. 2010. Carbon Sequestration in Forest Ecosystems. *Springer***34**: 132-141.
- Lorenzo B, Vittoria B, Diego M and Andrea C. 2010. Assessment of land use changes through an indicator-based approach: A case study from the Lamone river basin in Northern Italy. *Ecological Indicators***10**: 4-14.
- Luna and Kozlowski TT. 1979. Tree growth and environmental stresses. University of Washington Press.
- Magurran AE. 1988. Ecological diversity and its measurement. Princeton, New Jersey: Princeton university press.
- Majumdar K, Choudhary BK and Datta BK. 2016. Aboveground woody biomass, carbon stocks potential in selected tropical forest patches of Tripura, Northeast India. *Open Journal of Ecology***6(10)**: 598.
- Malhi Y, Aragao LEO, Metcalfe DB, Paiva R, Quesada CA, Almeida S, Anderson L, Brando P, Chambers JQ, Da Costa AC and Hutyrá LR. 2009. Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology***15**:1255-1274.
- Mamun A, Hossain MA, Hossain MK and Alam S. 2015. Quantifying diversity and composition of tree species in secondary hill forests of Chunati forest, Chittagong, Bangladesh. *Indian Forester***141**: 566-572.
- Mandal G and Joshi SP. 2014. Analysis of vegetation dynamics and phytodiversity from three dry deciduous forests of Doon Valley, Western Himalaya, India. *Journal of Asia-Pacific Biodiversity***7**: 292-304.
- Mandal G and Joshi SP. 2014. Biomass accumulation and carbon sequestration potential of *Shorea robusta* and *Lantana camara* from the dry deciduous forests of Doon valley, western Himalaya, India. *International Journal of Environmental Biology* **4(2)**: 157-169.
- Marasini S. 2003. Vegetation analysis of Churiya forest in Rupandehi, Nepal. M.Sc. Dissertation Submitted to Central Department of Botany, Tribhuvan University, Kathmandu, Nepal. 168pp.

- Margalef DR. 1958. Information theory in ecology. *International Journal of General Systems***3**: 36-71.
- Marques MCM, Roper JJ and Salvalaggio APB. 2004. Phenological patterns among plant life forms in a subtropical forest in southern Brazil. *Plant Ecology***173**: 203-213.
- Masera OR, Garza-Caligaris JF, Kanninen M, Karjalainen T, Liski J, Nabuurs GJ, Pussinen A, De Jong BH and Mohren GMJ. 2003. Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO₂ FIX Vol. 2 Approach. *Ecological modeling***164(2&3)**:177-199.
- Matayaya G, Wuta M and Nyamadzawo G. 2017. Effects of different disturbance regimes on grass and herbaceous plant diversity and biomass in Zimbabwean dambo systems. *International Journal of Biodiversity Science***13(1)**:181-190.
- Mehraj A, Sheikh M and Kumar M. 2010. Nutrient Status and Economic Analysis of Soils in Oak and Pine Forests in Garhwal Himalaya. *Journal of American Science***6**: 117-122.
- Merwin HD and Peech M. 1951. Exchangeability of soil potassium in the sand, silt, and clay fractions as influenced by the nature of the complementary exchangeable cation. *Soil Science Society of America Journal***15**: 125-128.
- Mishra A, Sharma CM, Sharma SD and Baduni NP. 2000. Effect of aspect on the structure of vegetation community of moist Bhabar and Tarai *Shorea robusta* forest in Central Himalaya. *Indian Forester***126(6)**: 634-642.
- Mishra AK, Bajpai O, Sahu N, Kumar A, Behera SK, Mishra RM and Chaudhary LB. 2013. Study of Plant Regeneration Potential in Tropical Moist Deciduous Forest in Northern India. *International Journal of Environment***2**: 153-163.
- Mishra D, Mishra TK and Banerjee SK. 1997. Comparative phytosociological and soil physiochemical aspects between managed and unmanaged lateritic land. *Annals of Forestry***5(1)**: 16-25.
- Mishra M, Santos CAG, Do Nascimento TVM, Dash MK, DaSilva RM, Kar D and Acharyya T. 2022. Mining impacts on forest cover change in a tropical forest using remote sensing and spatial information from 2001-2019: A case study of Odisha (India). *Journal of Environmental Management***302**: 114067.
- Nag A and Gupta H. 2014. Population structure and natural regeneration of Sal (*Shorea robusta* Gaertn. F.) in dry deciduous forests of West Bengal. *International Journal of Scientific Research in Environmental Sciences***2**: 421-428.
- Negi PS, Vashisth A and Gusain YS. 2019. Physico-Chemical Properties of Sal (*Shorea robusta*) Forests in Foothills of Garhwal Himalaya. *Journal of Tree Sciences***37(2)**: 62-67.
- Nelson DW and Sommers LE. 1996. Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 3 Chemical methods***5**: 961-1010.
- Nonini L and Fiala M. 2019. Estimation of carbon storage of forest biomass for voluntary carbon markets: preliminary results. *Journal of Forestry Research***32**: 329-338.

- Odum EP. 1969. The strategy of ecosystem development. *Science***164**: 262-270.
- Odum EP. 1971. Fundamentals of Ecology WB Saunders and Co., Philadelphia. 574pp.
- Olsen SR. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate (No. 939). US Department of Agriculture.
- Padmakumar B, Sreekanth NP, Shanthiprabha V, Paul J, Sreedharan K, Augustine T, Jayasooryan KK, Rameshan M, Mohan M, Ramasamy EV and Thomas AP. 2018. Tree biomass and carbon density estimation in the tropical dry forest of Southern Western Ghats, India. *Forest Biogeosciences and Forestry***11**(4): 534.
- Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S, Rautiainen A, Sitch S and Hayes D. 2011. A large and persistent carbon sink in the world's forests. *Science***333**: 988-993.
- Pande PK and Patra AK. 2010. Biomass and productivity in sal and miscellaneous forests of Satpura plateau (Madhya Pradesh) India. *Advances in Bioscience and Biotechnology***1**: 30-38.
- Pandey DC. 1956. Preliminary investigation in respect of artificial regeneration of Sal by transplants and stumps in Uttar Pradesh, Book Proceedings of the Ninth Silvicultural Conference, Dehradun, 7th and 10th to 19th December, 26-32pp.
- Pandey RK, Maranville JW and Chetima MM. 2000. Deficit irrigation and nitrogen effects on maize in a Sahelian environment: II. Shoot growth, nitrogen uptake and water extraction. *Agricultural water management* **46**(1): 15-27.
- Pandey SK and Shukla RP. 2003. Plant diversity in managed sal (*Shorea robusta* Gaertn. f) forests of Gorakhpur, India: species composition, regeneration and conservation. *Biodiversity and Conservation* **12**: 2295-2319.
- Pandey SK. 2000. Population status and regeneration strategy of some perennial legumes in plantation forests of North-Eastern Uttar Pradesh, Ph.D. thesis, DDU Gorakhpur University, Gorakhpur, India. 192pp.
- Pandita S, Kumar V and Dutt HC. 2019. Environmental variables vis-a-vis distribution of herbaceous tracheophytes on northern sub-slopes in Western Himalayan ecotone. *Ecological Processes***8**: 1-9.
- Paudel P, Kalakheti R and Maraseni T. 2020. Carbon Status and Regression Model for Tree Carbon by Crown Cover for Sal Forest of Nepal. doi:<https://doi.org/10.21203/rs.3.rs-127258/v1>
- Paudel S and Sah JP. 2003. Physiochemical characteristics of soil in tropical sal (*Shorea robusta* Gaertn. f) forests in eastern Nepal. *Himalayan Journal of Sciences* **1**: 107-110.
- Peech M. 1965. Hydrogen-ion activity. *Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties***9**: 914-926.
- Phillips EA. 1959. Methods of vegetation study. Henry Holt and Co. Inc. New York.

- Phillips O and Gentry AH. 1993. The Useful Plants of Tamboapata, Peru: I. Statistical hypothesis testing with a new quantitative technique. *Economic Botany***47**: 15-32.
- Pielou EC. 1966. The measurement of diversity in different types of biological collections. *Journal of Theoretical Biology***13**: 131-144. doi:10.1016/0022-5193(66)90013-0
- Poudel P and Devkota A. 2021. Regeneration Status of Sal (*Shorea robusta* Gaertn. f) in community managed forests, Tanahun district Nepal. *Journal of Institute of Science and Technology***26**: 23-30.
- Poudel P and Devkota A. 2022. Vegetation structure and species diversity in community managed Sal (*Shorea robusta*) forest of Tanahun district, Nepal. *International Journal of Ecology and Environmental Sciences***48(2)**: 165-175.
- Pradhan B and Rahaman CH. 2015. Phytosociological study of plant species in three tropical dry deciduous forests of Birbhum District, West Bengal, India. *Journal of Biodiversity and Environmental Sciences***7**: 22-31.
- Prakasham U, Meshram PB, Khatri PK, Singh S and Singh J. 2016. Influence of canopy gap on regeneration of Sal (*Shorea robusta*) in borer affected area of Dindori Forest Division, Madhya Pradesh. *Indian Journal of Tropical Biodiversity***24(1)**: 1-7.
- Pressler M. 1865. Das Gesetz der Stambildung Leipzig. 153pp.
- Puri S, Singh S and Khara A. 1992. Effect of windbreak on the yield of cotton crop in semiarid regions of Haryana. *Agroforestry systems***18**: 183-195.
- Purohit AN, Sharma MM and Thapliyal RC. 1982. Effect of storage temperatures on the viability of Sal (*Shorea robusta*) and Talura (*Shorea talura*) seed. *Forest Science***28**: 526-530.
- Rabha D. 2014. Aboveground biomass and carbon stocks of an undisturbed regenerating sal (*Shorea robusta* Gaertn. f.) forest of Goalpara district, Assam, Northeast India. *International Journal of Environment***3**: 147-155.
- Raj A and Jhariya MK. 2021. Carbon storage flux and mitigation potential of tropical Sal mixed deciduous forest ecosystem in Chhattisgarh, India. *Journal of Environmental Management***293**: 112-120.
- Raj A and Jhariya MK. 2021. Site quality and vegetation biomass in the tropical Sal mixed deciduous forest of Central India. *Landscape and Ecological Engineering* **17**: 1-13.
- Ramachandran A, Radhapriya P, Jayakumar S, Dhanya P and Geetha R. 2016. Critical analysis of forest degradation in the Southern Eastern Ghats of India: comparison of satellite imagery and soil quality index. *PLoS One***11(1)**: e0147541.
- Ranawat MPS and Vyas LN. 1975. Litter production in deciduous forests of Koriyat, Udaipur (South Rajasthan), India. *Biologia***30**: 41-47.
- Rao P, Barik SK, Pandey HN and Tripathi RS. 1990. Community composition and tree population structure in a sub-tropical broad-leaved forest along a disturbance gradient. *Vegetation***88**: 151-162.

- Rao PB and Singh SP. 1985. Population dynamics of a foot-hill sal (*Shorea robusta* Gaertn. f.) forest in Kumaun Himalaya. *Acta Oecologica***6**: 147-152.
- Rawat GS and Bhainsora NS. 1999. Woody vegetation of Shivaliks and outer Himalaya in north western India. *Tropical Ecology***40(1)**: 119-128.
- Rogers P. 2002. Using Forest Health Monitoring to assess aspen forest cover change in the southern Rockies ecoregion. *Forest Ecology Management***155**: 223-236.
- Sahu SC, Dhal NK and Mohanty RC. 2012. Tree species diversity, distribution and population structure in a tropical dry deciduous forest of Malyagiri hill ranges, Eastern Ghats, India. *Tropical Ecology***53**: 163-168.
- Saikia P and Khan ML. 2012. Seedling survival and growth of *Aquilaria malaccensis* Lam. in different microclimatic conditions of northeast India. *Journal of Forestry Research***23**: 569-574.
- Saikia P and Khan ML. 2013. Population structure and regeneration status of *Aquilaria malaccensis* Lam. in home gardens of Upper Assam, northeast India. *Tropical Ecology***54**:1-13.
- Salunkhe O, Khare PK, Sahu TR and Singh S. 2016. Estimation of tree biomass reserves in tropical deciduous forests of Central India by non-destructive approach. *Tropical Ecology***57(2)**: 153-161.
- Sapkota I. 2009. Species diversity, regeneration and early growth of Sal forests in Nepal. 91pp.
- Sapkota IP, Tigabu M and Oden P. 2009. Species diversity and regeneration of old growth seasonally dry *Shorea robusta* forests following gap formation. *Journal of Forestry Research***20**: 7-14.
- Sapkota IP, Tigabu M and Oden PC. 2009. Spatial distribution, advanced regeneration and stand structure of Nepalese Sal (*Shorea robusta*) forests subject to disturbances of different intensities. *Forest Ecology and Management***257**: 1966-1975.
- Sapkota RP, Stahl PD, Hengaju K and Rijal K. 2018. Changes in the ecological parameters of mixed forests of sal (*Shorea robusta* Gaertn. f) are a function of distance from the human settlements. *International Journal of Ecology***112**: 1-29. doi:10.1155/2018/1394814
- Sarkar M and Devi A. 2014. Assessment of diversity, population structure and regeneration status of tree species in Hollongapar Gibbon Wildlife Sanctuary, Assam, Northeast India. *Tropical plant research***1**: 26-36.
- Saxena AK and Singh JS. 1984. Tree population structure of certain Himalayan forest associations and implications concerning their future composition. *Vegetation***58(2)**: 61-69.
- Seth SK and Bhatnagar HP. 1960. Inter-relation between mineral constituents of foliage, soil properties, site quality and regeneration status in some *Shorea robusta* forests. *Indian Forester***86**: 590-601.

- Shahid M and Joshi SP. 2015. Biomass and carbon stock assessment in moist deciduous forests of Doon valley, western Himalaya, India. *Taiwania***60(2)**: 71-76.
- Shahid M, Nayak AK, Shukla AK, Tripathi R, Kumar A, Mohanty S, Bhattacharyya P, Raja R and Panda BB. 2013. Long-term effects of fertilizer and manure applications on soil quality and yields in a sub-humid tropical rice-rice system. *Soil Use and Management***29(3)**: 322-332.
- Shankar U. 2001. A case of High tree diversity in a Sal (*Shorea robusta*) dominated lowland forests of Eastern Himalayas: floristic composition, regeneration and conservation. *Current Science***81**: 776-786.
- Shannon CE and Weaver W. 1963. The mathematical theory of communication. Urbana, USA: University Illinois Press, 117pp.
- Sharma CM, Gairola S, Baduni NP, Ghildiyal SK and Suyal S. 2011. Variation in carbon stocks on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya, India. *Journal of Bioscience***36(4)**: 701-708.
- Sharma GP and Raghubanshi AS. 2007. Effect of *Lantana camara* L. cover on local depletion of tree population in the Vindhyan tropical dry deciduous forest of India. *Applied Ecology and Environmental Research***5(1)**: 109-121.
- Sharma P, Mahajan A, Lata K, Bharti H and Randhawa SS. 2020. Himachal Pradesh- A Review. *State Council for Science, Technology and Environment***1**: 4-10.
- Sheikh MA and Kumar M. 2010. Nutrient status and economic analysis of soils in oak and pine forests in Garhwal Himalaya. *Journal of American Science***6(2)**: 117-122.
- Simpson EH. 1949. Measurement of diversity. *Nature* 163: 688. doi:10.1038/163688a0
- Singh KP and Singh RP. 1981. Seasonal variation in biomass and energy of small roots in tropical dry deciduous forest, Varanasi, India. *Oikos***37(1)**: 88-92.
- Singh NP, Vashisth A and Gusain YS. 2019. Physico-chemical properties of Sal (*Shorea robusta*) forests in foothills of Garhwal Himalaya. *Journal of Tree Sciences***37**: 62-67.
- Singh R and Joshi MC. 1979. Floristic composition and life forms of sand dune herbaceous vegetation near Pilani, Rajasthan. *Indian journal of Ecology***6**: 9-19.
- Singh R. 1976. Structure and net community production of the herbaceous vegetation in the sand dune regions around Pilani, Rajasthan. Ph.D. Thesis, BITS, Pilani, Rajasthan. 450pp.
- Sinha S, Badola HK, Chhetri B, Gaira KS, Lepcha J and Dhyani PP. 2018. Effect of altitude and climate in shaping the forest compositions of Singalila National Park in Khangchendzonga Landscape, Eastern Himalaya, India. *Journal of Asia-Pacific Biodiversity***11**: 267-275.
- Slik JF, Paoli G, McGuire K, Amaral I, Barroso J, Bastian M, Blanc L, Bongers F, Boundja P, Clark C, Collins M. 2013. Large trees drive forest aboveground biomass variation in moist lowland forests across the tropics. *Global ecology and Biogeography***22(12)**: 1261-1271.

- Smith DM. 1954. Maximum moisture content method for determining specific gravity of small wood samples. *U.S. For. Prod. Lab. Rep.* 8pp.
- Subbiah BV and Asija GL. 1956. A rapid method for the estimation of nitrogen in soil. *Current Science***26**: 259-260.
- Subedi T. 2018. Volume models for Sal (*Shorea robusta* Gaertn.) in far-western Terai of Nepal. *Banko Janakari***27(2)**: 3-11.
- Tewari DN. 1995. A monograph on Sal (*Shorea robusta*). International Book Distributors, Dehradun. 277pp.
- Tewari JC. 1982. Vegetational analysis along altitudinal gradients around Nainital. Ph.D. Thesis, Kumaon University, Nainital, India. 165pp.
- Tiwari GPK, Tadele K, Aramde F and Tiwari SC. 2010. Community structure and regeneration potential of *Shorea robusta* forest in subtropical submontane zone of Garhwal Himalaya, India. *Nature and Science***8**: 70-74.
- Tripathi RS and Khan ML. 2007. Regeneration dynamics of natural forests. *Proceedings of the Indian National Science Academy***73**:167–195.
- Troup RS. 1921. The silviculture of Indian trees. Vol. I. Oxford University Press, London, 336pp.
- Troup RS. 1986. The Silviculture of Indian Trees. International Book Distributors, Dehradun, India. 413pp.
- Tyagi JV, Kumar R, Srivastava SL and Singh RD. 2011. Effect of micro-environmental factors on natural regeneration of Sal (*Shorea robusta*). *Journal of Forestry Research* **22**: 543-550.
- Usuga JCL, Toro JAR, Alzate MVR and Tapias ÁDJL. 2010. Estimation of biomass and carbon stocks in plants, soil and forest floor in different tropical forests. *Forest Ecology and Management***260**:1906-1913.
- Vetaas OR. 2000. The effect of environmental factors on the regeneration of *Quercus semecarpifolia* in central Himalaya, Nepal. *Plant ecology***146**:137-144.
- Vitousek PM, Dantonio CM, Loope LL, Rejmanek M, Westbrooks R. 1997. Introduced species: a significant component of human-caused global change. *New Zealand Journal of Ecology* **21**: 1-16.
- Walkley A and Black JA. 1934. Estimation of soil organic carbon by chromic acid filtration method. *Soil Science***37**: 38-39.
- Weidelt HJ. 1988. On the diversity of tree species in tropical Rain Forest Ecosystems. *Plant Research and Development***28**: 110-125.
- Welden CW, Hewett SW, Hubbell SP and Foster RB. 1991. Sapling survival, growth and recruitment: relationship to canopy height in a Neotropical forest. *Ecology***72**: 35-50.

- Whittaker RH. 1977. Evolution of species diversity in land communities. *Evolutionary biology***10**:1-67.
- Zamprogno GC, Tognella MMP, Quaresma VDS, Costa MBD, Pascoalini SS and Couto GFD. 2016. The structural heterogeneity of an urbanised mangrove forest area in southeastern Brazil: Influence of environmental factors and anthropogenic stressors. *Brazilian Journal of Oceanography***64**: 157-172.
- Zhao J, Kang F, Wang L, Yu X, Zhao W, Song X, Zhang Y, Chen F, Sun Y, He T and Han H. 2014. Patterns of biomass and carbon distribution across a chronosequence of Chinese pine (*Pinus tabulaeformis*) forests. *PLoS ONE***9**(4): e94966.

APPENDIX-I

Wood density, biomass expansion factor and Root: Shoot ratio of different forest tree species (FSI, 1996)

Sr. No.	Scientific Name	Wood density	Biomass expansion factor	Root:Shoot ratio
1	<i>Acacia catachu</i>	0.875	2.52	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
2	<i>Bauhinia variegata</i>	0.67	1.40	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
3	<i>Calicapra japonica</i>	0.57	1.40	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
4	<i>Cassia fistula</i>	0.746	1.50	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
5	<i>Cordia dichotoma</i>	0.43	1.50	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
6	<i>Eucalyptus globulus</i>	0.619	1.50	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
7	<i>Ficus palmata</i>	0.57	1.40	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
8	<i>Mallotus philippenensis</i>	0.64	1.50	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
9	<i>Shorea robusta</i>	0.726	1.74	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
10	<i>Syzyguim cuminii</i>	0.647	1.40	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)
11	<i>Terminalia tomentosa</i>	0.622	1.50	BEF=EXP(-1.05+0.884*LN(AGB)+0.284)

APPENDIX-II

ANALYSIS OF VARIANCE FOR STAND CHARACTERISTICS, BIOMASS AND CARBON

ANOVA 1: Tree density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	896.429	298.81	1.272
Treatment	6	17,542.86	2,923.81	12.446
Error	18	4,228.57	234.921	
Total	27	22,667.86		

ANOVA 2: Tree basal area

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.055	0.018	1.216
Treatment	6	1.607	0.268	17.788
Error	18	0.271	0.015	
Total	27	1.933		

ANOVA 3: Shrub density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	4.524	1.508	1.342
Treatment	6	2,733.10	455.517	405.235
Error	18	20.233	1.124	
Total	27	2,757.86		

ANOVA 4: Shrub basal area

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	548.585	182.862	1.72
Treatment	6	38,686.71	6,447.79	60.635
Error	18	1,914.08	106.338	
Total	27	41,149.38		

ANOVA 5: Herb density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	74.935	24.978	0.76
Treatment	6	16,508.81	2,751.47	83.708
Error	18	591.656	32.87	
Total	27	17,175.40		

ANOVA 6: Herb basal area

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	10,073.20	3,357.73	3.498
Treatment	6	36,564.40	6,094.07	6.349
Error	18	17,278.33	959.907	
Total	27	63,915.93		

ANOVA 7: Tree diameter

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	29.125	9.708	2.315
Treatment	6	441.737	73.623	17.556
Error	18	75.484	4.194	
Total	27	546.346		

ANOVA 8: Tree height

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	10.972	3.657	3.264
Treatment	6	52.167	8.695	7.761
Error	18	20.166	1.12	
Total	27	83.305		

ANOVA 9: Tree volume

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	2,292.51	764.169	0.792
Treatment	6	116,407.02	19,401.17	20.1
Error	18	17,374.21	965.234	
Total	27	136,073.74		

ANOVA 10: Stem biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	1,191.20	397.067	0.779
Treatment	6	60,864.29	10,144.05	19.908
Error	18	9,171.74	509.541	
Total	27	71,227.23		

ANOVA 11: Above ground biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	821.863	273.954	0.791
Treatment	6	41,344.67	6,890.78	19.908
Error	18	6,230.23	346.124	
Total	27	48,396.77		

ANOVA 12: Below ground biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	177.512	59.171	1.105
Treatment	6	6,593.68	1,098.95	20.524
Error	18	963.781	53.543	
Total	27	7,734.97		

ANOVA 13: Total biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	3,643.85	1,214.62	0.792
Treatment	6	183,246.39	30,541.06	19.91
Error	18	27,611.77	1,533.99	
Total	27	214,502.00		

ANOVA 14: Total carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	2,028.41	676.135	1.044
Treatment	6	81,304.16	13,550.69	20.914
Error	18	11,662.87	647.937	
Total	27	94,995.43		

ANOVA 15: Shrub above ground biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.01	0.00	4.18
Treatment	6	0.758	0.126	26.356
Error	18	0.086	0.005	
Total	27	0.854		

ANOVA 16: Shrub below ground biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.031	0.00	4.56
Treatment	6	0.287	0.048	10.687
Error	18	0.081	0.004	
Total	27	0.399		

ANOVA 17: Shrub total biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.018	0.00	4.13
Treatment	6	1.974	0.329	29.02
Error	18	0.204	0.011	
Total	27	2.196		

ANOVA 18: Herb above ground biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.413	0.00	1.35
Treatment	6	9.653	1.609	13.156
Error	18	2.201	0.122	
Total	27	12.267		

ANOVA 19: Herb below ground biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.413	0.00	1.38
Treatment	6	9.653	1.609	13.156
Error	18	2.201	0.122	
Total	27	12.267		

ANOVA 20: Herb total biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	3.72	0.00	1.34
Treatment	6	74.403	12.401	14.447
Error	18	15.45	0.858	
Total	27	93.574		

ANOVA 21: Shrub carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.004	0.001	0.485
Treatment	6	0.447	0.075	29.11
Error	18	0.046	0.003	
Total	27	0.497		

ANOVA 22: Herb carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.842	0.281	1.444
Treatment	6	16.811	2.802	14.406
Error	18	3.501	0.194	
Total	27	21.155		

ANOVA 23: Leaf litter

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.022	0.007	0.16
Treatment	6	8.306	1.384	30.227
Error	18	0.824	0.046	
Total	27	9.153		

ANOVA 24: Dead twigs and branches

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.014	0.005	0.467
Treatment	6	1.188	0.198	19.747
Error	18	0.181	0.01	
Total	27	1.383		

ANOVA 25: Dead trees

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.014	0.005	0.429
Treatment	6	0.287	0.048	4.468
Error	18	0.193	0.011	
Total	27	0.493		

ANOVA 26: Total detritus biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.023	0.008	0.572
Treatment	6	3.78	0.63	47.906
Error	18	0.237	0.013	
Total	27	4.039		

ANOVA 27: Vegetation carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.022	0.007	0.16
Treatment	6	8.306	1.384	30.227
Error	18	0.824	0.046	
Total	27	9.153		

ANOVA 28: Humus carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.044	0.015	0.506
Treatment	6	17.859	2.977	102.322
Error	18	0.524	0.029	
Total	27	18.427		

ANOVA 29: Soil carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	234.651	78.217	0.653
Treatment	6	2,599.35	433.226	3.615
Error	18	2,156.90	119.828	
Total	27	4,990.91		

ANOVA 30: Carbon density (Soil+Humus)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	253.868	84.623	16.901
Treatment	6	4,294.15	715.691	142.943
Error	18	90.123	5.01	
Total	27	4,638.14		

ANOVA 31: Detritus carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.018	0.006	2.288
Treatment	6	4.148	0.691	259.066
Error	18	0.048	0.003	
Total	27	4.215		

ANOVA 32: Total ecosystem carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	6,060.74	2,020.25	1.758
Treatment	6	82,765.95	13,794.33	12.004
Error	18	20,684.61	1,149.15	
Total	27	109,511.29		

ANOVA 33: Humus depth

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.015	0.005	1.404
Treatment	6	8.011	1.335	365.21
Error	18	0.066	0.004	
Total	27	8.092		

APPENDIX-III

ANALYSIS OF VARIANCE FOR PHYSICO-CHEMICAL PROPERTIES OF SOIL

ANOVA 1: pH

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.498		
Compartment (C)	6	27.229	4.538	5.817
Soil depth (D)	1	4.045	4.045	5.185
C×D	6	5.242	0.874	1.12
Error	39	30.427	0.78	
Total	55	67.441		

ANOVA 2: Electrical conductivity

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.002		
Compartment (C)	6	0.024	0.004	12.741
Soil depth (D)	1	0	0.00	1.466
C×D	6	0.019	0.003	10.095
Error	39	0.012	0.00	
Total	55	0.057		

ANOVA 3: Soil Bulk density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.965		
Compartment (C)	6	3.059	0.51	1.991
Soil depth (D)	1	0.5	0.5	1.952
C×D	6	1.403	0.234	0.913
Error	39	9.986	0.256	
Total	55	15.912		

ANOVA 4: Available Phosphorus

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	16.371		
Compartment (C)	6	3,583.98	597.33	10.384
Soil depth (D)	1	383.29	383.29	6.663
C×D	6	749.086	124.848	2.17
Error	39	2,243.43	57.524	
Total	55	6,976.16		

ANOVA 5: Available Potassium

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	6,881.63		
Compartment (C)	6	324,171.50	54,028.58	43.172
Soil depth (D)	1	16,480.34	16,480.34	13.169
C×D	6	13,605.16	2,267.53	1.812
Error	39	48,807.49	1,251.47	
Total	55	409,946.12		

ANOVA 6: Available Nitrogen

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	48,339.03		
Compartment (C)	6	158,410.06	26,401.68	7.196
Soil depth (D)	1	17,141.18	17,141.18	4.672
C×D	6	27,064.40	4,510.73	1.229
Error	39	143,096.00	3,669.13	
Total	55	394,050.67		

ANOVA 7: Soil Organic carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.173		
Compartment (C)	6	10.435	1.739	8.732
Soil depth (D)	1	0.58	0.58	2.913
C×D	6	1.01	0.168	0.846
Error	39	7.767	0.199	
Total	55	19.966		

ANOVA 8: Soil Labile carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.872		
Compartment (C)	6	0.408	0.068	3.383
Soil depth (D)	1	0.094	0.094	4.658
C×D	6	0.15	0.025	1.243
Error	39	0.784	0.02	
Total	55	2.308		

ANOVA 9: Soil Non-labile carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.872		
Compartment (C)	6	0.546	0.091	4.523
Soil depth (D)	1	0.104	0.104	5.159
C×D	6	0.18	0.03	1.496
Error	39	0.784	0.02	
Total	55	2.486		

ANOVA 10: Available Iron

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	575.764		
Compartment (C)	6	8,051.82	1,341.97	7.218
Soil depth (D)	1	1,534.36	1,534.36	8.253
C×D	6	2,213.53	368.921	1.984
Error	39	7,250.58	185.912	
Total	55	19,626.06		

ANOVA 11: Available Sulfur

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	9.629		
Compartment (C)	6	196.188	32.698	7.441
Soil depth (D)	1	21.379	21.379	4.865
C×D	6	13.975	2.329	0.53
Error	39	171.377	4.394	
Total	55	412.548		

ANOVA 12: Available Zinc

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.592		
Compartment (C)	6	23.283	3.881	4.876
Soil depth (D)	1	3.754	3.754	4.717
C×D	6	9.17	1.528	1.921
Error	39	31.036	0.796	
Total	55	67.835		

ANOVA 13: Available Boron

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.866		
Compartment (C)	6	0.447	0.075	3.787
Soil depth (D)	1	0.099	0.099	5.051
C×D	6	0.184	0.031	1.553
Error	39	0.768	0.02	
Total	55	2.364		

ANOVA 14: Available Copper

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	3	0.092		
Compartment (C)	6	7.289	1.215	6.173
Soil depth (D)	1	0.865	0.865	4.396
C×D	6	1.698	0.283	1.438
Error	39	7.675	0.197	
Total	55	17.619		

APPENDIX-IV

ANOVA TABLES

Linear and non-linear allometric equations for estimation of Volume in *Shorea robusta* trees based on diameter over bark, height and density variables.

ANOVA 1: DBH

Equation	R Square	F	df	Sum of squares
Linear	0.943	933.674	1	115.117
Quadratic	0.985	1842.507	2	120.227
Power	0.978	2458.086	1	61.286
Exponential	0.910	563.167	1	61.286

ANOVA 2: Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.669	113.391	1	81.682
Quadratic	0.851	157.477	2	103.881
Power	0.909	558.066	1	61.235
Growth	0.935	806.431	1	63.005

ANOVA 3: Density

Equation	R Square	F	df	Sum of squares
Linear	0.889	448.347	1	108.473
Quadratic	0.973	998.017	2	118.749
Power	0.919	637.128	1	61.936
Growth	0.930	745.041	1	62.669

Linear and non-linear allometric equations for estimation of total biomass in *Shorea robusta* trees based on diameter over bark, height and density variables.

ANOVA 4: DBH

Equation	R Square	F	df	Sum of squares
Linear	0.861	345.699	1	2835.353
Logarithmic	0.915	605.443	1	3015.716
Quadratic	0.919	313.529	2	3028.978
Power	0.875	393.291	1	7.461

ANOVA 5: Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.988	4517.663	1	3254.313
Quadratic	0.994	4967.006	2	3276.513
Power	0.995	10506.268	1	8.478
Growth	0.988	4466.248	1	8.417

ANOVA 6: Density

Equation	R Square	F	df	Sum of squares
Linear	0.878	404.243	1	2893.776
Logarithmic	0.830	272.462	1	2732.942
Quadratic	0.901	249.912	2	2968.053
Power	0.865	358.977	1	7.373

Linear and non-linear allometric equations for estimation of carbon in *Shorea robusta* trees based on diameter over bark, height and density variables.

ANOVA 7: DBH

Equation	R Square	F	df	Sum of squares
Linear	0.861	345.632	1	639.712
Logarithmic	0.915	605.445	1	680.425
Quadratic	0.919	313.498	2	683.411
Power	0.875	393.238	1	7.461

ANOVA 8: Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.988	4520.354	1	734.263
Quadratic	0.994	4957.497	2	739.259
Power	0.995	10518.734	1	8.479
Exponential	0.988	4458.303	1	8.418

ANOVA 9: Density

Equation	R Square	F	df	Sum of squares
Linear	0.878	404.096	1	652.883
Logarithmic	0.830	272.468	1	616.626
Quadratic	0.901	249.844	2	669.652
Power	0.865	358.882	1	7.373

Linear and non-linear allometric equations for estimation of Volume in *Shorea robusta* trees based on diameter under bark, height and density variables.

ANOVA 10: DBH

Equation	R Square	F	df	Sum of squares
Linear	0.943	930.434	1	102.280
Quadratic	0.985	1862.610	2	106.858
Power	0.978	2473.323	1	65.806
Growth	0.910	566.791	1	61.245

ANOVA 11: Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.671	114.176	1	72.753
Quadratic	0.852	158.100	2	92.369
Power	0.908	554.795	1	61.126
Growth	0.934	796.938	1	62.878

ANOVA 12: Density

Equation	R Square	F	df	Sum of squares
Linear	0.890	454.054	1	96.531
Quadratic	0.973	995.272	2	105.521
Power	0.919	637.031	1	61.858
Growth	0.929	735.408	1	62.534

Linear and non-linear allometric equations for estimation of total biomass in *Shorea robusta* trees based on diameter under bark, height and density variables.

ANOVA 13: DBH

Equation	R Square	F	df	Sum of squares
Linear	0.682	120.162	1	215.939
Quadratic	0.871	186.284	2	275.852
Power	0.907	545.325	1	56.829
Growth	0.935	811.290	1	58.619

ANOVA 14: Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.682	120.162	1	215.939
Quadratic	0.871	186.284	2	275.852
Power	0.907	545.325	1	56.829
Growth	0.935	811.290	1	58.619

ANOVA 15: Density

Equation	R Square	F	df	Sum of squares
Linear	0.887	438.148	1	280.698
Quadratic	0.964	744.109	2	305.291
Power	0.915	603.397	1	57.343
Growth	0.929	728.085	1	58.190

Linear and non-linear allometric equations for estimation of carbon in *Shorea robusta* trees based on diameter under bark, height and density variables.

ANOVA 16: DBH

Equation	R Square	F	df	Sum of squares
Linear	0.938	850.390	1	67.039
Quadratic	0.977	1159.511	2	69.798
Power	0.977	2344.178	1	60.764
Exponential	0.912	577.622	1	56.716

ANOVA 17: Tree height

Equation	R Square	F	df	Sum of squares
Linear	0.682	119.894	1	48.704
Quadratic	0.871	186.424	2	62.268
Power	0.905	533.458	1	56.304
Exponential	0.935	801.334	1	58.151

ANOVA 18: Density

Equation	R Square	F	df	Sum of squares
Linear	0.887	437.662	1	63.348
Quadratic	0.965	747.944	2	68.919
Power	0.914	598.268	1	56.890
Exponential	0.930	742.938	1	57.854

Linear and non-linear allometric equations for estimation of Volume, total biomass and carbon in *Shorea robusta* trees based on diameter over bark and height, and density variables.

ANOVA 19: diameter over bark and height and density variables.

Variable	R Square	F	df	Sum of squares
Volume	0.943	540.879	2	116.118
Total biomass	0.985	15319.094	2	3288.749
Carbon	0.978	15321.014	2	742.028

Linear and non-linear allometric equations for estimation of Volume, total biomass and carbon in *Shorea robusta* trees based on diameter under bark and height and density variables.

ANOVA 20: diameter under bark and height and density variables.

Variable	R Square	F	df	Sum of squares
Volume	0.943	538.910	2	103.171
Total biomass	0.985	457.982	2	298.642
Carbon	0.978	457.930	2	67.405

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ABSTRACT

The present investigation entitled “**Inter compartmental variations in floristic composition, biomass productivity and physico-chemical characteristics of Sal forest in Himachal Pradesh**” was conducted in seven compartments viz., Rajban C₆, Rajban C₇, Gorakhpur C₇, Rajban C₁₀, Kukron C₁₄, Kukron C₁₅ and Lai C₂₈ in the Paonta Forest Range of the Paonta Forest Division in Himachal Pradesh to access floral diversity, stand structure, total biomass of trees, shrubs and herbs, carbon stock, stand characteristics, natural regeneration and soil physico-chemical properties. The flora of different compartments constituted 33 genera with 34 species belonging to 26 families. The Lai C₂₈ (9) had the maximum tree species, Kukron C₁₅ and Rajban C₁₀ has maximum shrub species and Rajban C₆ and Rajban C₇ had maximum herb species among all the compartments. The maximum tree density (323 number ha⁻¹) was recorded in Gorakhpur C₇ and minimum (250 number ha⁻¹) was found in Rajban C₇. Rajban C₁₀ had the highest shrub density (11,200.00 ha⁻¹) and basal area (81,326.94 cm² ha⁻¹). Kukron C₁₄ (185,800.00 number ha⁻¹) had maximum herb density and basal area (212,444.10 cm² ha⁻¹). *Shorea robusta* was the dominant species with IVI varied between 126.72 to 156.59 under different compartments. The similarity index of trees in different compartments ranged from 0.67 to 1.00. Rajban C₆ and Rajban C₇ had the maximum similarity index. Highest value of tree height, density and biomass was maximum in SQ-II (Kukron C₁₄) followed by SQ-III (Rajban C₁₀). The significant variation in total tree biomass (123.89 to 487.35 Mg C ha⁻¹), vegetation carbon density (89.89 to 234.26 Mg C ha⁻¹), detritus carbon density (2.36 to 3.40 Mg C ha⁻¹) and ecosystem carbon density (114.53 to 287.58 Mg C ha⁻¹) was recorded across the SQ. The maximum carbon stock was accumulated in Kukron C₁₄ (9314.10 Mg C ha⁻¹), whereas, minimum carbon stock was observed in Gorakhpur C₇ (4718 Mg C ha⁻¹). Kukron C₁₄ (42.39 %) showed fair regeneration of *Shorea robusta* followed by Rajban C₁₀ but poor in Rajban C₆ and Rajban C₆. Organic carbon (%), labile (%), non-labile carbon (%), available N, available P and available K were maximum in Kukron C₁₄ and minimum in Rajban C₇. The significantly positive correlation was reported between bulk density, soil organic carbon, available N, available P and available K and soil quality index. Hence, management involvement is required to comprehend site quality variation, which has a huge impact on vegetation structure and biomass pattern, which will aid in strengthening the sustainable forest management practices.

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