TREE DIVERSITY, CARBON STOCK AND REGENERATION PATTERN IN *SHOREA ROBUSTA* GAERTN. FORESTS ALONG THE ALTITUDINAL GRADIENT IN EASTERN NEPAL

A THESIS SUBMITTED FOR THE PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE MASTER'S DEGREE IN BOTANY

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DECLARATION

I, "Sujan Chaudhary", hereby declare that the work enclosed here is entirely my own, except where states otherwise by reference or acknowledgement, and has not been published or submitted elsewhere, in whole or in part, for the requirement for any other degree or professional qualification. Any literature, data or works done by others and cited within this thesis has been given due acknowledgement and listed in the reference section.

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RECOMMENDATION

This is to recommend that the proposed research work entitled "**Tree Diversity, Carbon Stock and Regeneration Pattern in *Shorea robusta* Gaertn. Forests Along the Altitudinal Gradient in Eastern Nepal**" is be carried out by Mr. Sujan Chaudhary "TU Reg. no. 5-2-8-86-2014" under my supervision for the partial fulfillment of Master's Degree in Botany. The entire work is based on original scientific investigation. I therefore, recommend this thesis to be accepted for Master's of Science in Botany from Tribhuvan University, Nepal.

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ABBREVIATIONS AND ACRONYMS

AGC	Aboveground carbon
BA	Basal area
BGC	Belowground carbon
C	Carbon
CF	Community forest
CMF	Collaborative managed forest
C-stock	Carbon stock
D	Density
DBH	Diameter at breast height
DS	Disturbed sites
F	Frequency
GIS	Geographical information system
GPS	Global positioning system
HSF	Hill Sal forest
IVI	Important value index
K	Potassium
kg ha^{-1}	Kilogram per hectare
ln	Natural logarithm
m^2 ha^{-1}	Meter square per hectare
Mg ha^{-1}	Megagram per hectare

MS	Microsoft
N	Nitrogen
OM	Organic matter
P	Phosphorous
pl ha^{-1}	Plants per hectare
RB	Relative basal area
RD	Relative density
REDD	Reducing emissions from deforestation and forest degradation
RF	Relative frequency
SE	South east
SW	South west
t ha^{-1}	Tons per hectare
TSF	Tarai Sal forest
US	Undisturbed sites
Yrs	Years

TABLE OF CONTENT

Contents **Page number**

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The forest with good regeneration can store a sufficient amount of carbon. The *Shorea robusta* Gaertn. (Sal) forests of Nepal are facing the problem of poor regeneration. The present study aimed to find out the tree diversity, carbon stock and regeneration status of *Shorea robusta* forests along an altitudinal gradient in eastern Nepal. The study was conducted in three community forests of Sunsari and Dhankuta District. The forests were Ramdhuni Kalijhora community forest (82-170 m a.s.l.), Patrangbari community forest (440-695 m a.s.l.) and Khanidada Malbase community forest (650-990 m a.s.l.) which were regarded as lower, middle and upper altitudinal range forest respectively in the present study. The stratified random sampling method was used for the sampling. Altogether, 90 circular plots (30 in each forest) were laid for trees and saplings each and 180 plots were (60 in each forest) laid for seedlings. Physico-chemical parameters (Nitrogen, potassium, phosphorus, organic matter, moisture, pH and bulk density) were analyzed from all 90 plots. The present investigation has recorded 43 tree species under 25 families and 35 genera. The Dominance-Diversity curve (DD curve) showed the highest IVI of *Shorea robusta* in all three altitudinal ranges. The value of Shannon Diversity index was higher in high altitudinal range (1.078) followed by low (0.966) and middle altitudinal range (0.833). Species richness increased with increasing altitudes (from 82 m to 990 m a.s.l). The tree carbon stock ranged from 134 – 372 t ha^{-1} .Similarly soil carbon stock was higher in high altitudinal range (60.03 t ha^{-1}) and lower in middle altitudinal range (27.69 t ha^{-1}). The seedling of *Shorea robusta* was higher in low altitudinal range and lower in high altitudinal range. Contrast results were obtained for sapling i.e. lower in low and middle altitudinal ranges and higher in high altitudinal range. The regeneration of *Shorea robusta* was affected by various edaphic factors and anthropogenic activities. The regeneration status of seedlings and trees in the forests was healthy but poor in terms of saplings. Organic matter, nitrogen and sand percentage were positively correlated to altitudinal range. However, potassium, pH, silt and clay content showed a negative correlation with altitudinal ranges. Bulk density and moisture content were negatively correlated. Therefore, the establishment of seedlings to saplings in the study areas was very crucial for the sustainability of forests.

Keywords: Tree diversity, distribution, sapling, seedling, soil parameters

Chapter 1

1. Introduction

1.1. Background

Nepal is very rich in biodiversity due to its variation in altitude, climate and physical geography. Nepal comprises of 35 different forest types, out of which Sal (*Shorea robusta* Gaertn., Dipterocarpaceae) forest is one of them (Stainton, 1972). According to Stainton (1972), Sal forest in Nepal is classified as lower tropical Sal forest and hill Sal forest which are situated in the Tarai and Siwaliks respectively. Although species composition in the two Sal forest types varies, Sal is found as a dominant species in both forest types (Paudel *et al*., 2012). Sal is a deciduous and valuable tree in the context of Nepal regarding its wood and timber quality. Sal forests cover 16% of the total forest area in Nepal (Lamichhane and Poudyal, 2019).

Sal tree grows in a variety of soil types, although not on soil that are sandy and gravely and are next to rivers or wet regions (Jackson, 1994). It prefers slightly acidic condition (5.1 - 6.8) (Gangopadhyay *et al.*, 1990) and may grow on alluvial to lateritic soils (Tewari, 1995). Sal trees may reach a height of 40 meters (Gautam and Devoe, 2006).

Shorea robusta forest is quite well off in floral diversity and encompasses different types of trees, herbs, shrubs, ferns and lianas (Gautam and Devoe, 2006). The different types of forests vary in the carbon stored by them. Sal forest can contribute in higher amount of biomass and carbon if good management practice can be introduced (Banik *et al.*, 2018).

1.1.1. Carbon stock

Forest can be considered as a both source and sink of the carbon (Liu *et al*., 2019). Plants assimilate a large amount of CO_2 from the atmosphere naturally through the process of photosynthesis and store it as aboveground biomass, belowground biomass and in soil (Adam, 2001; Aryal *et al.*, 2017; Aryal *et al.*, 2018). This process is known as carbon sequestration (Watson *et al*., 2000). Therefore, sequestering of carbon by green plants is a very good method to reduce the concentration of CO_2 and mitigate the impacts of climate change (Jina *et al*., 2008). The potential of the forest to store carbon depends upon various factors such as forest stand, age of the forest, density of trees, types of trees and biomass decomposition (Dixon *et al.*, 1994). Moreover, the Kyoto Protocol has supported the contribution of forests to mitigating the impact of climate change by reducing the emissions from deforestation and forest degradation (REDD) in developing countries (Angelsen, 2008).

Soil is also an important pool to store a huge amount of atmospheric carbon (Bajracharya *et al.*, 1998). Soils store twice as much organic carbon as vegetation and two-thirds as much as the atmosphere (Smith, 2004). Therefore, soil pool also contributes to mitigate the impact of climate change. Forest plants and soils make up a significant terrestrial carbon reservoir with the ability to absorb and store carbon dioxide (CO_2). At the present time, carbon stored by soil and vegetation is getting attention by different organizations, researchers, institutes, stakeholders, policy makers and globally to mitigate the hazardous impact of climate change (Khan *et al.*, 2021). Understanding the regeneration status of species and forest community is very crucial to determining and choosing the species with high value of carbon stock (Gairhe, 2015).

1.1.2. Regeneration

Regeneration is the phenomenon of reproducing new plants through their juvenile, where the numbers of seedlings, saplings and trees are enumerated or quantified in the particular area (Koirala, 2004). The role of regeneration is very crucial to sustain the community in the forest ecology. A healthy forest consists of a sufficient number of seedlings, saplings and trees for the vitality, better productivity and sustainability of the forest (Chauhan e*t al*., 2008a; Awasthi *et al*., 2015). Regeneration status is one of the important parameters of forest ecology which describes the future composition of a community and is highly dependent upon factors like grazing, disturbance, climate, soil (edaphic), seed, biotic condition (Mishra *et al*., 2021). The majority of these characteristics, however, stay more or less uniform throughout a narrow area in a forest (Tyagi *et al*., 2011).

Shorea robusta is listed among those legally protected trees which are illegal to cut, transport and export from Nepal. The regeneration status of *Shorea robusta* is running through very poor condition (Sapkota *et al.* 2009a; Sapkota *et al.*, 2009b). Several types of factors like logging, disturbance, gap formation, management activities and herbivory are responsible for the poor regeneration of *S. robusta* in Nepal (Khumbongmayum *et al.*, 2006). Sal forest in Southeast Asia is regarded as the most disturbed forest due to their high timber and fodder value (Sapkota *et al.*, 2009a; Sapkota *et al.*, 2009b). This anthropogenic disturbance contributes in failure of establishment of seedlings. According to International Union for Conservation of Nature (IUCN) (2015), *Shorea robusta* is still listed in "least concern" category.

1.1.3. Edaphic and altitudinal factor

Shorea robusta forest productivity appears to be influenced by mineral nutrition (Gautam and Devoe, 2006). Soil moisture, especially at the seedling stage (Gautam *et al*,. 2014), nitrogen availability and other soil nutrition, aeration, and soil erosion have all been identified as the key edaphic elements affecting Sal forests' natural regeneration (Mishra *et al*., 2021). On Sal seedlings, deficiencies in nitrogen, phosphorus, potassium, calcium, and magnesium cause noticeable symptoms (e.g., smaller leaves, thin tap roots, early defoliation, and sluggish shoot growth) on both the shoot and root (Bhatta, 2016). Slope aspect and elevation, for example, are also well recognized to alter microclimatic conditions, which have direct and indirect effects on forest biomass and regeneration (Fotis *et al*., 2017).

One of the most prominent gradational patterns of plants is altitudinal zonation (Oshawa, 1977). Geographical and climatic circumstances alter dramatically as altitude changes (Bandopadhyay, 2016). The elevation factor has an impact on vegetation composition and distribution patterns, which in turn has an impact on biomass and carbon storage (Murphy *et al.*, 2015). In tropical ecosystems, the availability of soil nutrients may vary with altitude. The concentrations of soil organic carbon, nitrogen, accessible phosphorus, and exchangeable cations increased with altitude in general (Unger *et al*., 2010). Temperature, precipitation, air pressure, solar radiation, and wind velocity are only a few examples of environmental elements that alter systematically with elevation. As a result, altitudinal gradients are effective natural experiments for evaluating forest ecological and evolutionary responses to environmental changes.

1.2. Rationale of the study

In the present condition, the forests of Nepal are at high risk due to the rapid growth of the population, haphazard collection of forest products, deforestation, illegal trading of forest products, unsustainable harvesting, overgrazing and other anthropogenic activity (Bajpati *et al*., 2018). Especially, forests of Tarai are getting more threatened due to the migration of people from hills to Tarai for settlement and are responsible for the destruction of forest areas for their daily livelihood (Acharya and Shrestha, 2011). Therefore, government of Nepal has been handing over most of the national forests to the community, changing it to community forest, which has stored a huge amount of carbon. Moreover, *S. robusta* forest in central Nepal is running through very poor regeneration and also changes in species composition, which has become a big issue to solve (Sapkota *et al*., 2009a). Until now in eastern Nepal very little research has been done regarding carbon stock and regeneration pattern of *S. robusta*. Therefore, understanding carbon stock and regeneration status in eastern Sal forest is crucial for the sustainability and vitality of the forest. The finding of the present study will also help the community or local people to implement forest management strategies. Moreover, the relation between different soil parameters and the regeneration pattern of *S. robusta* will help determine the status of regeneration and apply further strategies for improvement.

1.3. Research questions

- What is the status of tree diversity and IVI in forests along three altitudinal ranges?
- What is the distribution pattern of trees with respect to physico-chemical factor of the soil, altitude and disturbance in the forests along the altitudinal ranges?
- What is the estimated tree and soil carbon stock in the forests along the altitudinal ranges?
- What is the regeneration pattern of *Shorea robusta* in the forests along the altitudinal ranges?
- How do the selected soil parameters vary in the *Shorea robusta* forests along the altitudinal ranges?

1.4. Objectives

1.4.1. General objectives

- The general objective of the present study is to estimate the tree diversity, carbon stock of *Shorea robusta* forests and its regeneration pattern along the altitudinal gradient in eastern Nepal.

1.4.2. Specific objectives

- To determine tree diversity indices and Important Value Index (IVI) in the forests along three altitudinal ranges
- To determine trees distribution with respect to physico-chemical factor of the soil, altitude and disturbance in the forests along the altitudinal ranges.
- To estimate the tree and soil carbon stock in the forests along the altitudinal ranges.
- To study the regeneration pattern of *Shorea robusta* in the forests along the altitudinal ranges.
- To determine the soil parameters physico-chemical factors of the soil along the altitudinal ranges.

1.5. Delimitations

- Herbs and shrubs diversity were not studied.
- The carbon stock of shrubs, herbs, seedlings, saplings and litters were not estimated.
- Regeneration of other tree species except *Shorea robusta* was not studied.
- Forests were studied only from two districts of eastern Nepal.

Chapter 2

2. Literature review

2.1. Carbon sequestration by the forests of Nepal

Forests store 60% of the world's terrestrial carbon (C) in their vegetation and soil, which play an important role in reducing global climate change and accounts for over 80% of all above-ground terrestrial carbon and almost 40% of all below-ground terrestrial carbon (Dixon *et al.,* 1994; Bhatta and Devkota, 2020). Many researchers (Mandal *et al.*, 2013; Mbaabu *et al.*, 2014; Gairhe, 2015; Dhakal *et al.*, 2017; Bhatta and Devkota, 2020) have reported different amounts of carbon sequestered by collaborative and community forests in lower tropical and hill Sal forests of Nepal. The influence of vegetation types on carbon stock was studied in two CFs of Palpa, Nepal (Shrestha, 2009). It was reported that forest types have a significant role in overall carbon sequestration. *Shorea robusta* and *Schima-Castanopsis* forests had total biomass carbon of 101.66 t ha^{-1} and 44.43 t ha^{-1}, respectively (Shrestha, 2009). In *Schima-Castanopsis* and Sal forests, soil carbon sequestration was observed to be 130.76 and 126.07 t ha^{-1}, respectively. According to Shrestha (2009), the total carbon sequestration in Sal forest is 1.29 times that of *Schima-Castanopsis* forest.

The highest carbon stock was observed in Gadhanta-Bardibash CFM (274.66 t ha^{-1}) and the lowest in Banke-Maraha CFM (197.10 t ha^{-1}) (Mandal *et al*., 2013). The significant quantity of trees and poles in Gadhanta-Bardibash CFM compared to other CFMs was the key reason for the highest estimated carbon stock (Mandal *et al*., 2013). They have also described that C-stock had a positive and very weak relation with species richness and negative with Simpson's evenness of collaborative forests.

More than 90% of Nepal's national forest of hills have been handed over to communities for conservation and to improve local people's livelihoods by utilizing forest resources (Gairhe, 2015). Community forest contributes significantly to carbon sequestration efforts such as REDD and REDD+ projects. The tree carbon stock of two community forests in Tanahun District, central Nepal was found where Fulbari CF had a lower value of tree carbon stock (71.11 t ha^{-1}) than the carbon stock (109.82 t ha^{-1}) of regenerating Taldanda CF (Gairhe, 2015). Among all recorded tree species, *Shorea robusta* has contributed the highest carbon stock in both CFs (44.7% in Taldanda CF and 64.8% in Fulbari CF).

The assessment of C-stock in community managed hill Sal forest and government managed hill *Shorea robusta* forest was conducted in Karyakhola watershed of Chitwan District, which recorded 244 and 140 Mg ha^{-1} carbon respectively (Mbaabu *et al*., 2014). They reported a substantial difference in C-stock between the two forest management regimes, which they ascribed to species composition, tree density, canopy density, and basal area variation, and that forest management methods influenced forest C-stock.

Deforestation is becoming a widespread occurrence in developing countries, which has been a great threat (FAO, 2012; Thapa-Magar and Shrestha, 2015). As a result, community-based forest management may be a viable option for lowering deforestation and forest degradation rates, as well as minimizing the consequences of climate change. The study in nine CFs of Dhading District showed that Sal was dominant species for carbon stocking in all the forests (Thapa-Magar and Shrestha, 2015). They have estimated the carbon stock ranging between 70 and 183 Mg C ha^{-1} with a mean value of 120 Mg C ha^{-1}.

Biomass and production are important parameters for understanding the functioning of a forest ecosystem. Studies on biomass help to assess the effect of disturbances on productivity, C dynamics, nutrient cycling and stability of forest stands (Gautam and Mandal, 2016). Therefore, the effect of disturbance on biomass, production and carbon dynamics was studied in the moist tropical forest of eastern Nepal (Gautam and Mandal, 2016). They divided the forest into disturbed (DS) and undisturbed sites (US). The total standing biomass and C-stock was found to be higher (960.4 Mg ha^{-1} and 452.06 Mg ha^{-1} respectively) in the US in comparison to DS (449.1 Mg ha^{-1} and 211.33 Mg ha^{-1} respectively).

The assessment of carbon stock in urban forests is necessary to determine the carbon sequestration rate and plays a crucial role in the urban environment, as well as in biodiversity conservation (Dhakal *et al*., 2017). The aboveground tree carbon and belowground tree carbon were found to be 214.99 t ha^{-1} and 42.99 t ha^{-1} respectively in Gokarna Protected forest, Kathmandu (Dhakal *et al*., 2017).

Bhattarai and Mandal (2018) studied the variation in carbon stock in litterfall, fine root and soil in Sal forest of Jhapa (Tarai Sal Forest; TSF) and Ilam districts (Hill Sal forest; HSF), eastern Nepal. The altitude of TSF ranged between 62 and 129 m asl and that of HSF ranged between 500 and 800 m asl. Carbon stock in litter fall was higher (3.94 Mg ha^{-1}) in TSF than HSF (3.26 Mg ha^{-1}) and in fine root (0-5 mm size) in 0-30 cm soil depth it was higher (2.76 Mg ha^{-1}) in HSF than TSF (2.19 Mg ha^{-1}).

The community forests accumulated carbon stocks ranging from 148.5 to 202.3 Mg ha^{-1} (mean: 175.5 Mg ha^{-1}) in four community managed Sal forests of Dadeldhura district, western Nepal (Bhatta and Devkota, 2020). These four community forests (CFs) have been managed by the community for 10 to 21 years. This study showed that the canopy cover, ground vegetation cover, tree DBH and height were higher in the 10-year management category of (CFs), but tree density was higher in the 20-year management category.

2.2. Carbon stock by the age of community forest

Forest biomass and carbon stock grow as forest age, tree density, and area increase (Sedjo, 2001; Luyssaert *et al*., 2008). The amount of carbon stored in a forest changes regularly, with the development, death and decay of the plants (Kaul *et al*., 2010). Carbon sequestration happens considerably faster in young and regenerating forests than in older and matured forests, yet carbon stock is higher in older and matured forests (Luyssaert *et al*., 2008).

According to Baral *et al.* (2009), 75-year-old Sal stands have greater C-stock than 18, 25, and 28-year-old *Alnus nepalensis*, tropical riverine, and *Pinus roxburghii* forests in Nepal. The Carbon stock of a 24-year-old pine plantation forest (189.7 $Mgha^{-1}$) was higher than that of a 16-year-old broad-leaved natural forest in Gorkha's Ludhikhola sub-watershed (Pandey *et al.*, 2012).

The C-stock was found to be increasing in 17-73 year old Japanese red pine (*Pinus densiflora*) forests in Central Korea (Li *et al.,* 2013a). Community forest which has been managed for > 20 years stored the highest carbon and CF managed < 10 years stored the lowest amount of carbon (Thapa-Magar and Shrestha, 2015). The forests managed by CFUGs for a longer period have the higher carbon stock or those which have been managed for a shorter period (Thapa-Magar and Shrestha, 2015). One of the researches established a baseline for C-stock and regeneration status in community-managed forests in Far Western Nepal. Bhatta (2016) estimated carbon stock in community forests of Dadeldhura where he categorized CFs into two groups according to management duration (≤ 11 yrs and ≥ 20 yrs). The average carbon stock of living biomass of the studied forests was 175 Mg ha^{-1} (148-202 Mg ha^{-1}) where the forest managed for ≥ 20 yrs (199 Mg ha^{-1}) higher than the forests managed for ≤ 11 yrs (151 Mg ha^{-1}).

2.3. Regeneration status of *Shorea robusta* forests

The existence of distinct age groups of seedlings, saplings, and trees determines the forest's regenerative and productive nature (Chauhan *et al*., 2008a). The most relevant criteria for successful regeneration are a larger number and proper establishment of seedlings (Napit, 2015). Sal regeneration is abundant wherever openings are created and preserved, although natural regeneration is more difficult to protect than planted regeneration (Shrestha, 1992). The regeneration of Sal is complex and baffling problem (Bisht, 1989). The number of seedlings > 5000 and saplings > 2000 per hectare is regarded as a very suitable number for the replacement of old Sal trees by new ones (Pandey *et al.*, 2012).

Acharya and Shrestha (2011) have worked regarding the regeneration status of Sal in Parroha CF Rupandehi facing south east (SE) and south west (SW) slope. The regeneration potential of *Shorea robusta* was found to be higher than *Terminalia alata* on both slopes. The number of seedlings and saplings of *Shorea robusta* on the SE slope were 15208 and 1228 pl ha^{-1} respectively and 24792 and 744 pl ha^{-1} on the SW slope respectively.

Basyal *et al.* (2011) have studied regeneration of Sal in the tropical forest of Palpa District, central Nepal and recorded 26 tree species where the total density of saplings was 3437.5 pl ha^{-1}. Out of which, Sal had the highest density of saplings with 2250 pl ha^{-1}. Paudyal (2013) has recorded 6,126 seedlings of Sal per hectare which was considered as satisfactory in Pragatisil CF in Kaski District.

Scientific forest management is becoming increasingly important for managing Nepal's existing natural forests through silvicultural intervention (Awasthi *et al*., 2015). One of the studies was carried out in Lumbini collaborative forest, where the study area was classified into managed (Block I and II) and unmanaged sites (Block III) (Awasthi *et al.*, 2015). Higher seedling and sapling densities were reported in the managed regions (Block I and Block II), possibly as a result of regeneration felling, compared to the unmanaged area (Block III), which had no regeneration felling (Awasthi *et al*., 2015). Napit (2015) had studied Species Diversity, Forest Community Structure and Regeneration in Banke National Park, western Nepal. He has divided the study area into 17 equal grids. Fifty eight species of tree saplings and 40 species of tree seedlings were recorded. Among them, *Shorea robusta* had the highest density of seedlings (27153.4 pl ha^{-1}) and saplings (200.49 pl ha^{-1}).

2.4. Factor affecting regeneration of *Shorea robusta*

The several factors like altitude, temperature, disturbances, light intensity and edaphic factors influence species composition, regeneration state, and diversity in the Sal forest (Shankar, 2001). A poor soil aeration and inadequate moisture are the main causes of inefficient Sal regeneration (Boyce and Bakshi, 1959). Crown cover is also one of the ecological measures of the forest ecosystem because of its association with natural regeneration and species richness (Baral and Ghimire, 2020).

A strong positive correlation was observed between regeneration of Sal and soil moisture (Seth and Bhatnagar, 1960). The relationship between Sal and soil moisture was positive ($r = 0.127$ and $P < 0.01$) in seedlings, positive but not significant in saplings, and negative ($r = – 0.102$ and $P > 0.05$) in mature plants (Gautam *et al.,* 2007). Chauhan *et al.* (2008b) carried out a multiple regression between seedling density of Sal and six soil parameters (soil moisture, soil organic carbon, pH, nitrogen, phosphorous and potassium) and reported the value of coefficient of determination (R^2) as 0.042 and 0.222 in natural and planted forest, respectively. Sapkota *et al.* (2009) elucidated that how advanced regeneration and spatial patterns of tree species are related to the level of disturbance. They came to the conclusion that moderate disturbance intensity not only provides high stand density, but also promotes advanced regeneration of Sal and influences their dispersion patterns (Sapkota *et al*., 2009a). Moreover, the seedling regeneration of Sal differed significantly between the gap and intact vegetation environments (Sapkota, 2009a). The seedling density was higher in the gaps than in the intact vegetation. Moreover, Chauhan *et al.* (2010) observed the significant impact of soil parameters on seedling and tree density in the planted and natural Sal forest of India.

The study was performed to observe how variations in soil moisture and light intensity affected natural regeneration of the *Shorea robusta* species in different micro-environments caused by varrying forest densities (Tyagi *et al*., 2011). Natural regeneration was strongest under C1 (up to-0.30) canopy, followed by C2 (0.30–0.50), and C3 (0.50–0.70) canopies, according to the study's findings. The R^2 value between incremental plot regeneration score and yearly average light intensity was 0.688, indicating that plot regeneration is heavily influenced by light intensity (Tyagi *et al*., 2011).

The influence of tree canopy opening in the regeneration layer of Sal (*Shorea robusta*) forest was examined in four strata of forest (0–25, 25–50, 50–75, and 75–100 percent crown cover vegetation) in the Buddha-Shanti Collaborative Forest Management of Nawalparasi District, Nepal (Baral and Ghimire, 2020). The seedling density of Sal was found higher in the 0–25 and 25–50 percentage crown cover (22,167 pl ha^{-1} and 13,667 pl ha^{-1}) respectively than 50–75 and 75–100 percentage crown cover area (11,667 pl ha^{-1} and 11,000 pl ha^{-1}) respectively. In the same way, the density of saplings was also higher in the open canopy in comparison to the closed canopy (Baral and Ghimire, 2020).

Different soil conditions influenced regeneration of *Shorea robusta*. Nitrogen, pH, and canopy cover had detrimental effects on seedling development ($P < 0.05$). Soil organic carbon, potassium, phosphorus, ground vegetation cover, and litter cover had no effect on seedling, sapling, and tree development ($P > 0.05$) (Poudel and Devkota, 2021).

2.5. Soil parameters

Soil is a mixture of, organic matter, water, mineral nutrients, air and living organisms. Nepal's vegetation zones clearly reflect edaphic variations (Bhatta, 1981). Moreover, Soil is the greatest source of organic carbon on the planet and act as a huge carbon pool (Mikhailova and Post, 2006). Soil contains 1.5-3 times more organic carbon than plants (Wang *et al*., 2004) and nearly twice as much carbon as the atmosphere (Lal, 2004). The variations in topography, temperature, weathering processes, plant cover, and microbiological activity, affect the physico-chemical characteristics of forest throughout time and place (Paudel and Sah, 2003). The various soil factors like nitrogen, phosphorus, potassium, bulk density, moisture and soil pH all impact the growth of *Shorea robusta* (Bhatnagar, 1965).

The physiochemical properties of two Sal forests (Pure Sal forest and mixed Sal forest) were analyzed from eastern Nepal (Paudel and Sah, 2003). Soil texture was found to be sandy loamy in both the study sites. The pH was lower in pure Sal forest compared to mixed Sal forest. The organic matter content, nitrogen and humus content were higher in pure Sal forest in comparison to mixed Sal forest. However, available phosphorous was higher in mixed Sal forest. According to Pearson correlation, organic matter was positively related to nitrogen content, phosphorous content humus content and negatively correlated to potassium and pH (Paudel and Sah, 2003).

Bhattarai and Mandal (2012) studied the status of soil microbial biomass and physico-chemical parameters of soil in both disturbed and undisturbed tropical Sal forest stands over the summer. Disturbed forest had a higher pH compared to undisturbed forest. Undisturbed forest stands had a higher WHC, nitrogen and organic carbon than disturbed forest stands. Moreover, the soil organic carbon has a positive relation with total nitrogen (Bhattarai and Mandal, 2012).

In the Guto Gida District of Oromia Region, Western Ethiopia, researchers looked at the impacts of land use on soil physicochemical parameters characterizing soil fertility under three different land use patterns (natural forest, grazing, and cultivated land) (Chimdi *et al*., 2012). The land use types had a variation in organic matter, total nitrogen, available phosphorous, pH and exchangeable bases. Organic matter content was found in natural forest land compared to grazing and cultivated land. According to the Pearson correlation, pH was positively related to total phosphorous and negatively related to bulk density and available water holding capacity (Chimdi *et al*., 2012).

In the Sunsari district of eastern Nepal, the physico-chemical characteristics of soils from tropical moist forest (Charkoshe jungle) were studied at three depths: top (0-15 cm), medium (15-30 cm), and deep (30-45 cm) (Gautam and Mandal, 2013). Water holding capacity, moisture, total nitrogen, organic carbon and organic matter were higher in upper layer (0-15 cm) in compared to the two deeper layers. However, pH and bulk density were in increasing order with the depth (Gautam and Mandal, 2013).

Bhattarai and Mandal (2016) carried out the study in Tarai Sal forest (TSF) and Hill Sal forest (HSF) in eastern Nepal to see how altitude affects the soil properties. HSF had a higher organic carbon, total nitrogen, soil organic matter, total phosphorous, and potassium than TSF (Bhattarai and Mandal, 2016). According to Pearson’s correlation, soil organic carbon was positively related to water holding capacity (r = 0.355), total nitrogen (r = 0.640) and available phosphorous (r = 0.493).

Rawat *et al.* (2021) assessed altitudinal variation in soil physio-chemical properties in a six temperate forest at different altitudes. The study found that altitude had a positive association with water holding capacity (r = 0.994), soil organic carbon (r = 0.967), organic matter (r = 0.966), nitrogen (r = 0.993), phosphorus (r = 0.982), and potassium content (r = 0.994), but a negative correlation with soil pH (r = -0.983) (Rawat *et al*., 2021).

2.6. Community forest in Nepal

Forests of Nepal encompass 5.96 million hectares, or 40.36 percent of the country's total land area (DFRS, 2014). There are 19,361 community forest user groups in Nepal (DoF, 2017). Tarai (low land) physiographic region of Nepal occupies 13.7% of the total land area of the country. Out of total area of forest 6.90% lies in Tarai (DFRS, 2014). In the Nepalese lands, where agriculture, livestock raising, and forests are all intertwined, community woods play an important part in people's everyday life. The Government of Nepal (GoN) has made it a policy to include local populations in forest management, based on the 1976 National Forestry Plan, in order to combat deforestation and the worsening status of forests throughout the nation (Karky *et al*., 2007). However, it was introduced in 1978. Community forest user groups (CFUGs) have handled around 25% of all national forests, or around 1.1 million hectares of Nepal's forests, by 2004 (Karky *et al*., 2007).

In Nepal, community forestry is regarded as one of the most effective natural resource management practices for recovering degraded land and ecosystems, maintaining biodiversity, boosting forest product supply, producing rural income, and developing human resources (Acharya, 2004). Community forest management not only reverses deforestation and forest degradation rates (Nagendra *et al.* 2007), but also has a beneficial influence on the forest in terms of carbon stock and sequestration (Pandey *et al.*, 2014; Solomon *et al.*, 2017). Although the extent to which CFs contribute to biodiversity conservation is debatable (Shrestha *et al*., 2010), these forests play an essential role in participatory natural resource management and conservation techniques (Thapa-Magar and Shrestha, 2015). As a result, community-based forest management may be a viable option for lowering deforestation and forest degradation rates, as well as minimizing the consequences of climate change.

Researchers have studied the regeneration status of Sal forest in the central and western regions of Nepal. However, they have left a huge gap to study the regeneration status of Sal forest in eastern Nepal, which is still uncovered. As the climatic pattern differs highly in the eastern, western and central regions of Nepal, this study will fulfill the required gap to study the regeneration pattern of Sal forest in eastern Nepal along the altitudinal gradient. Hence, comparison between the regeneration patterns of Sal forests between all three regions can be made. This will help to identify the stability and sustainability of Sal forests of eastern Nepal. Moreover, the study of regeneration and estimation of carbon stock has been studied by various researchers. However, study of regeneration of *S. robusta* and estimation of carbon stock by *S. robusta* forest along an altitudinal gradient is yet to be explored.

Until now, very little research has been done regarding carbon stock and no study has been conducted in the realm of regeneration pattern of *S. robusta* from Eastern Nepal. Therefore the present study regarding carbon stock, regeneration status of *S. robusta* and its species diversity will be helpful in selecting high priority species for the storage of carbon and planning for future level carbon storage. Moreover, it could also be beneficial for habitat restoration of degraded Sal forest.

Chapter 3

3. Materials and methods

3.1. Study area

The present study was conducted in three community forests of Sunsari and Dhankuta districts (Figure 3.1). Ramdhuni Kalijhoda community forest (RKCF) and Patrangbari community forest (PCF) were situated in Sunsari District whereas Khanidada Malbase community forest (KMCF) is situated in Dhankuta District, eastern Nepal (Figure 3.1).

RKCF has an area of 131.18 ha and lies at 26°41' north and 87°08' east. It lies at the altitudinal range between 82 m to 170 m above the sea level (asl) and regarded as lower altitude forest and also termed an Tarai sal forest (TSF). PCF lies at an altitudinal range of 440 m to 695 m asl and regarded as middle altitude forest. It has an area of 186.82 ha. PCF lies at 26°48' north and 87°19' east. KMCF covers an area of 147.55 hectare and lies at 26°51' north and 87°19' east. It is situated at an altitudinal range between 650 m and 990 m asl regarded as higher altitude forest and also termed as Hill Sal forest (HSF). The RKCF, PCF and KMCF were handed over as community forest to the local people in 2002, 1996 and 1992 AD respectively.

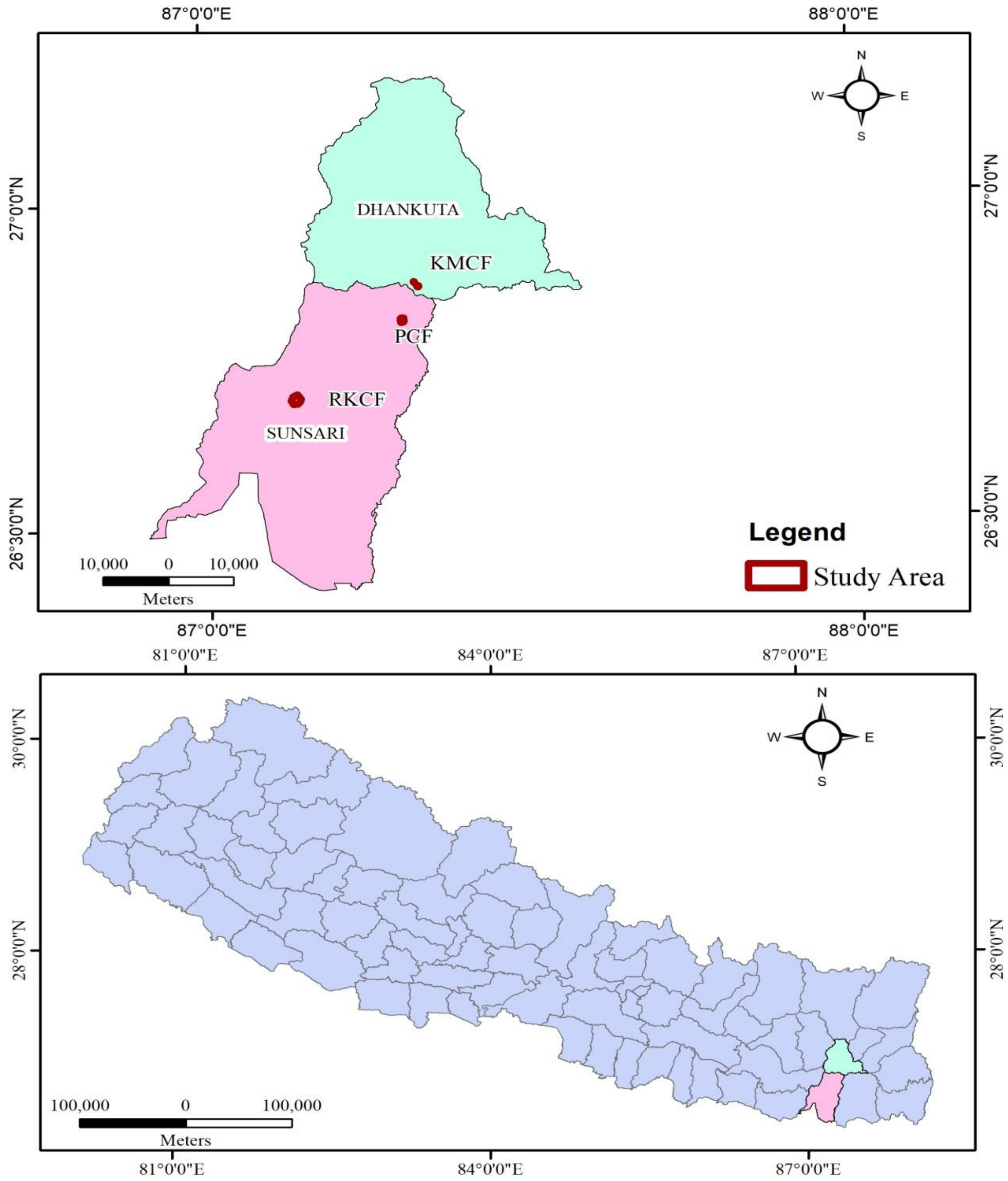

Figure 3.1 Map of the study area showing RKCF and PCF in pink portion (Sunsari) and KMCF in green portion (Dhankuta).

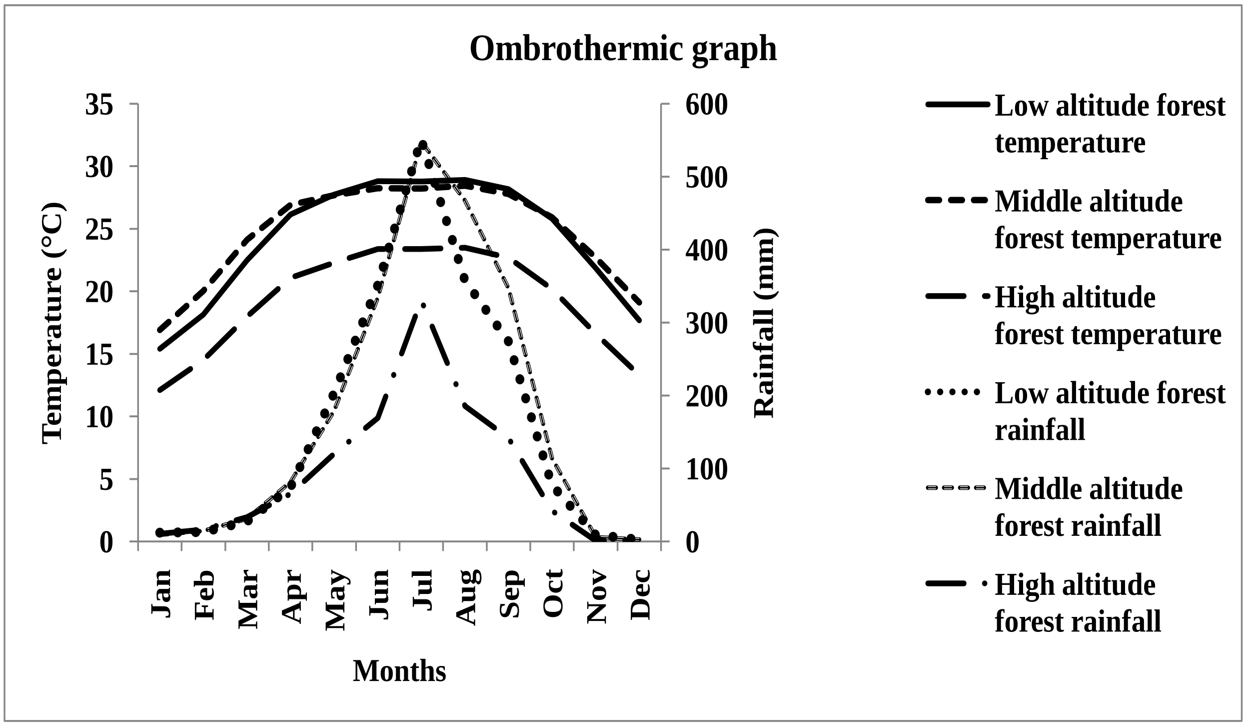

Figure 3.2 Twenty years (2000-2020) monthly average data of average temperature and rainfall recorded at Tarahara, Dharan and Dhankuta station for RKCF (low altitude), PCF (middle altitude) and KMCF (high altitude) respectively (Source: Department of Hydrology and Meteorology, Kathmandu).

3.2. Climate

The average annual rainfall of Tarahara is 1953.49 mm. It has an average maximum and minimum temperature of 29.9°C and 18.4°C respectively. However, the average annual temperature is 24.1°C (average data of 20 years) (Figure 3.2). The climate is very warm in summer and mild cold in winter. The rainfall in summer is very high and very scanty in winter.

Dharan has mild and warm temperature. Summer season receives very huge rainfall and winter receives very scanty rainfall. It has an annual average temperature of 24.6°C. Moreover, it receives 2134.2 mm of rainfall annually in average (Figure 3.2).

The average annual temperature of Dhankuta is 19.2°C. The data regarding temperature for Dhankuta was not available in Department of Hydrology and Meteorology. Therefore, we took the data from climatedata.org. The average annual rainfall of Dhankuta is 1118 mm (average data of 20 years) (Figure 3.2). The climate of Dhankuta is warm and temperate. The area receives a very high rainfall in summer and very less in winter.

3.3. Vegetation

The forest vegetation was dominated by *S. robusta* in low altitudinal forest with associated tree species like *Terminalia alata* B.Heyne ex Roth, *Syzygium cumini* (L.) Skeels, *Terminalia anogeissiana* Gere and Boatwr., and *Falconeria insignis* Royle (DFO, 2019/20). However, in middle altitude, the tree vegetation was covered by *S. robusta* associated with *Schima wallichi* (DC.) Korth., *Semecarpus anacardium* L.fil., *S. cumini* and *Cassia fistula* L. Similarly, in upper altitude was also a *S. robusta* forest associated with other species like *S. wallichi, T. anogeissiana, Adina cordifolia* (Roxb.) Brandis. *Casearia graveolens* Dalzell and *Castanopsis indica* (Roxb. ex Lindl.) A.DC (DFO, 2018/19).

3.4. Selection of the community forests

The community forests were visited in October and November, 2021 for preliminary studies. In total, seven community forests were visited in Sunsari and Dhankuta districts. However, three community forests were selected on the basis following criterias;

- The forest vegetation must have included *Shorea robusta* as a part of it.
- The study area must be a community forest.
- Three forests should be approximately at the altitudinal range of below 300 m, 300-600 m and above 600 m elevation.

3.5. Experimental design

3.5.1. Sampling methods

The stratified random sampling method was used for the sampling in the study areas. All the study areas were differentiated into different blocks or strata on the basis of species composition, different age blocks and geographical locations by the forest authorities (Gairhe, 2015). The random sampling was then used in the different stratas. However, each random plot had the minimal distance of 50 m. The circular plots were used for the sampling purpose to avoid the angle error which might occur in rectangular or square plot in the hill forest. The map of each community forest was taken as the guide for the study. Altogether, 90 plots were studied for trees and saplings each with 30 plots in each altitudinal ranges. However, 180 plots were studied for seedlings with 60 plots in each forest.

3.5.2. Sampling techniques inside the plot

The nested plot method was carried out for the selection of the area of plot to be laid for trees. In total, five nested plots were laid in low altitudinal range from 6 m radius to 10 m radius (Figure 3.3). The average number of tree species of five plots was listed in Figure 3.3. There is no consensus, but as a rule of thumb, the sample plot should have roughly 15-20 trees on average (Asrat and Tesfaya, 2013). Therefore, the radius with 7 m was used for the study of trees. However, to study the regeneration, seedlings and saplings were quantified in circular plots with 1m and 3m radius respectively (Devkota *et al.,* 2021). The circular plots for trees and saplings were measured with the same center point while for the seedlings two circular plots were laid randomly inside the circle with 7 m radius.

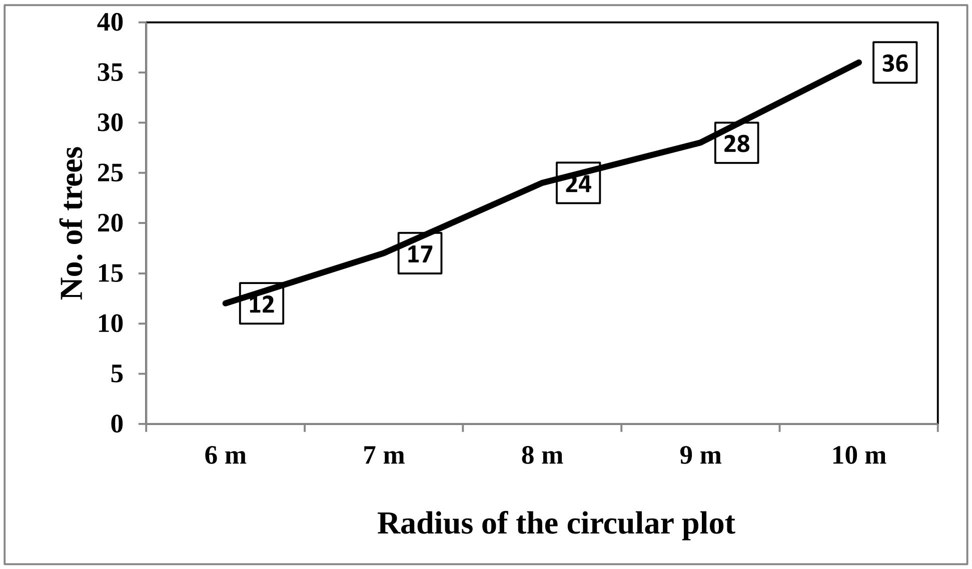

Figure 3.3 Nested plot method for the selection of the area of plot to be laid for trees where A, B, C, D and E represents the circular plot with 6 m, 7 m, 8 m, 9 m and 10 m respectively.

Diameter at breast height (DBH = 1.37 m) was calculated for every tree located in the plot with DBH tape. The basal part of the tree whose 50% or > 50% area occurs on the boundary was included in the plot (Bhatta, 2016). Plant species were sampled in three stata: trees (> 5 cm DBH), saplings (1–5 cm DBH and > 1 m height) and seedlings (< 1 m height) (Timilsina *et al*., 2007). Plants having DBH less than 5 cm were excluded for the estimation carbon stock (Chave *et al.,* 2005). Geographical co-ordinates and altitude of the study area were measured with the help of GPS tracker device. Compass (IOS device) was used to find the aspect of the hill forests. A clinometer was used to estimate an angle between the top of the tree and head of a person carrying clinometer, which was finally used to calculate the height of the tree with the help of trigonometry tangent formula.

$$\tan \theta = \frac{p}{b}$$

Where, p is the height of the tree excluding height of a person carrying clinometer, b is the distance between the tree and the person carrying clinometer.

Hence, actual height of tree = p + height of the person carrying clinometer

Litter depth was measured in every plot with the help of a 20 cm cylindrical stick which had a ruler mark in it. Steel core was used to measure the bulk density inside the plots. Disturbance level was also measured in every plot and scored as 0 (undisturbed), 1 (less disturbed), 2 (moderately disturbed) and 3 (highly disturbed). The score was given at the same time in the plot on the basis of parameters like tree density, dung and hoof marks of livestock's, presence of grazing, regeneration, crown cover, cut trees, sign mark of axe or other sharp instruments, ground vegetation, presence of industrial wastes (e.g. cover of noodles, bottles etc) and falling of branches and twigs. All these parameters were analyzed and score were provided regarding disturbance level of forest.

3.5.3. Data collection

The data collection was done with the help of local people and the authorities of the community forests in each forest. The annual progress reports of community forests were obtained from the Sub-division offices of RKCF, PCF and KMCF. The preliminary study was conducted from September 12 to 18, 2021 where the nested plot was also laid. The primary data collection was carried out from October to November, 2021.

3.6. Quantitative analysis

3.6.1. Community attributes

The ecological parameters like density (pl ha^{-1}), frequency (%), basal area (m^{2} ha^{-1}), coverage (%) as well as their relative values and importance value index (IVI) were calculated following Zobel *et al.* (1987).

The degree of dispersion of individual species in a community is referred to as frequency. It is the percentage of sample units in a given region where a species occur. It was calculated by the following formula:

$$\text{Frequency (\%)} = \frac{\text{Number of plots in which the species occured}}{\text{Total number of plots}} \times 100$$

Relative frequency is defined as the degree of dispersion of particular species in a given region in proportion to the total number of species present, and it was computed using the following formula:

$$\text{Relative frequency (RF) (\%)} = \frac{\text{Frequency of individual species}}{\text{Sum of frequencies of all species}} \times 100$$

The number of individual per unit area is known as density. It shows the species' numerical strength in the community. The following equation was used to compute density:

$$\text{Density (pl ha}^{-1}\text{)} = \frac{\text{Total number of studied plants in all the plots}}{\text{Number of plots studied} \times \text{Area of each plot (m2)}} \times 10000$$

The study of a species' numerical strength in proportion to the total number of individuals in all species is known as relative density, and it is computed as follows:

$$\text{Relative density (RD) (\%)} = \frac{\text{Density of individual species}}{\text{Sum of densities of all species}} \times 100$$

The total of the BA of all individuals of a species was used to calculate the basal area of a species in each sample plot. The following equation was used to convert BA to a percentage:

Basal area (m^2/ m^2) = πr^2

Where r refers to the radius of a tree measured at breast height. Therefore, r = $\frac{\mathrm{DBH}}{2}$

Basal area ($m^2\ ha^{-1}$) = $\frac{\pi r 2}{\text{Area of quadrat}} \times 10000$

The relative basal area is calculated by multiplying the basal area of particular tree species by the total basal area of all tree species.

Relative basal area (RB) (%) = $\frac{\text{Basal area of individual species}}{\text{Sum of basal areas of all species}} \times 100$

To determine the overall relevance of each species in the community structure, the important value index (IVI) is utilized. IVI was calculated by using the following formula.

IVI = RF + RD + RB

3.6.2. Species diversity

The tree species diversity was calculated using the method of Shannon–Wiener's index (Shannon and Weaver, 1949). The diversity includes both richness and evenness of trees in the community. However, evenness of tree species was calculated using the Shannon Equitability index (E_H). The Shannon's diversity index was calculated using following formula;

H = $\sum \mathrm{pi.\,lnpi}$

Where H = Shannon's diversity index

pi = species proportion (total number of species divide by total number of all the species)

ln = natural logarithm

The higher value of H represents higher diversity.

The Shannon equitability index (E_H) = $\frac{H}{\ln(S)}$

Where S = Total number of unique species

The value of E_H ranges from 0-1, where 1 refers to the complete evenness.

3.6.3. Biomass and carbon stock estimation

3.6.3.1. Above ground biomass

Aboveground biomass (AGB) included biomass of bole, branches and leaves. Volume of the bole was calculated by using the formula; $\pi r^2 h/2$ following the literature of Tamrakar (2000). Biomass of bole was then calculated by multiplying the specific wood density with volume of bole proposed by Tamrakar (2000) which was also followed by Aryal *et al.* (2017) and Godar (2021). Biomass of branches and leaves for each species were calculated by multiplying the default fraction (listed in MPFSN, 1988; Tamrakar, 2000) with the biomass of bole. The lists of specific wood density were used from Reyes *et al.* (1992), Jackson *et al.* (1994), Carsan *et al.* (2012) and Karki *et al.* (2016) (Annex 1). Finally, the biomass of bole, branches and leaves were added to represent total aboveground biomass. The carbon stock was calculated by multiplying default carbon fraction of 0.47 with the biomass (Eggleston *et al.*, 2006).

3.6.3.2. Below ground biomass

The Below Ground biomass includes all biomass of underground parts. The below ground biomass was calculated by multiplying the default factor of 0.15 with the biomass of bole (MacDicken, 1997)

3.7. Herbarium preparation and Plant identification

Available samples for the preparation of herbarium specimen were collected with the help of local people and forest authorities. The herbarium specimens of all the plants were prepared according to Lawrence (1951). Most of the identification of plants with the local name was done in the field by the help of members of particular CFs and local people of that area. However, unidentified plants were taken to the central campus of technology (Dharan) and Post Graduate Campus (Biratnagar) for the further identification by the experts. After the identification of plants, confirmation of latest and accepted scientific names and families were done with the help of websites; www.gbif.org and www.efloras.org (Annotated checklist of flowering plants of Nepal). Herbarium specimens were deposited in Ascol herbarium, Kathmandu, Nepal.

3.8. Soil sample collection

Soil samples at the depth of 0-30 cm were taken from all 90 plots of all altitudinal ranges. Soil samples were collected from each plot. Soil samples were collected from four quadrats in a single plot, which were again mixed readily to form a single sample of 750 g. The collected soil samples were dried and used to determine moisture, bulk density, soil texture, pH, nitrogen content (N), phosphorous content (P), potassium content (K) and organic matter content (OM).The sample taken for bulk density was measured instantly in the field to calculate moisture content.

3.9. Soil analysis

Soil texture was analyzed by hydrometric method. Soil organic matter was determined by the titration method proposed by Walkley and Black (1934). Soil organic matter (%) was converted to soil organic carbon by dividing the soil OM by the default fraction of 1.724 (Anderson and Ingram, 1993). Moreover, to estimate soil carbon stock, the soil organic carbon (%) was converted to soil organic carbon (t ha^{-1}) by using the literature of Chhabra *et al.* (2003).

Total nitrogen content was determined by the micro-Kjeldal method (Jackson, 1958). Total phosphorus content was quanitifed by the modified Olsen and bicarbonate method (Olsen and Sommers, 1982). Total potassium content was estimated using flame photometer method (Jackson, 1958). Soil pH was determined with a 1:2.5 soil-water suspension using digital pH meter (Cottenie, 1980). Soil bulk density was determined using core sampling methods (Brady and Weil, 2013) with the following formula:

$$\text{Soil bulk density (g cm}^{-3}\text{)} = \frac{\text{Oven dry weight of soil (g)}}{\text{Volume of the soil (cm3)}}$$

The moisture content was calculated according to Piper (1966) using the following formula:

$$\text{Moisture (\%)} = \frac{\text{Moisture content (g)}}{\text{Dry mass of soil (g)}} \times 100$$

The given soil analyses were performed in Soil and Fertilizer Testing Laboratory, Jhumka, Province 1. However, bulk density and moisture content were measured in Central Campus of Technology, Tribhuvan University, Dharan.

3.10. Statistical data analysis

The ArcGIS version 8.2 was used to prepare the location map of the study area. All the descriptive analysis was performed with MS Excel 2007. Normality of the data was tested by Shapiro-Wilk test for correlation and One-way ANOVA. Detrended correspondence analysis (DCA) was performed to quantify the axis length and eigen values for species distribution analysis. VEGAN package was used in R studio for DCA. According to eigen values and axis length, Canonical Correspondence Analysis (CCA) was performed to observe the species distribution in relation to selected variables. Multiple correlation was performed between the soil parameters and some selected parameters of the forests. Kruskal-Wallis test was performed to observe the significant difference of tree carbon stock among the altitudinal range. Pairwise wilcoxon test was performed to calculate pairwise comparison of variables between altitudes. One-way ANOVA was performed to evaluate the significant difference between the soil carbon stock among the altitudinal ranges. Spearman correlation test was performed to evaluate the relationship of seedlings, saplings and carbon stock with the selected factors. Moreover, linear regression analysis was performed to evaluate the best fitted line in order to observe relationship of seedlings, saplings and carbon stock with the selected factors for each. All the statistical analysis was performed in R software with version 4.0.3. However, one-way ANOVA and Duncan multiple range test were done in SPSS 2017 to test the significant difference of tree species richness among the three different altitudinal ranges.

Chapter 4

4. Results

4.1. Tree diversity and distribution

4.1.1. Diversity indices

The study areas recorded 43 tree species under 35 genera and 25 families (Table 4.1). Low and middle altitudinal range forests had 17 tree species in each. However, high altitudinal range forest had the highest tree species richness (n = 29) (Figure 4.1). One-way ANOVA showed that there was high significant difference ($P = 0.004$) in tree species richness among the altitudinal ranges. *F. insignis*, *S. robusta*, *S. cumini* and *T. alata* were found in all three altitudinal ranges (Table 4.1).

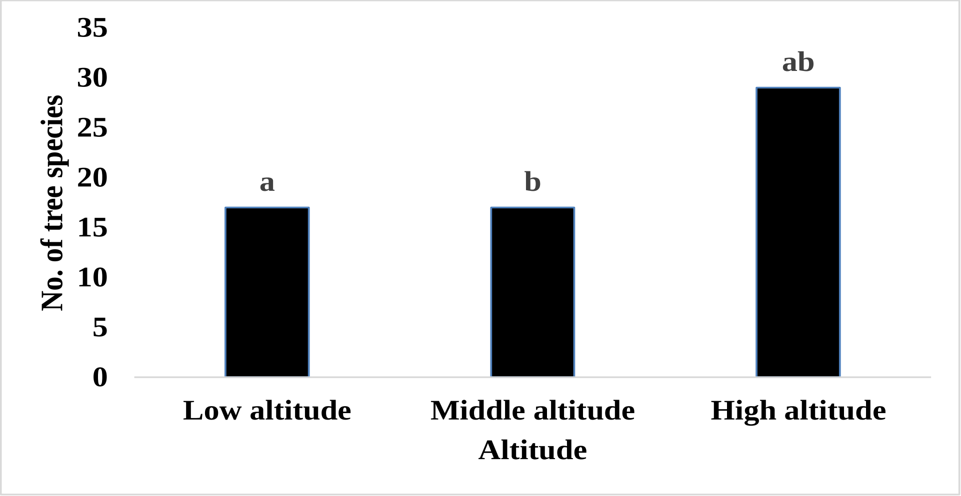

Figure 4.1 Tree species richness in the study areas along the altitudinal ranges. Shared superscript indicated significant difference ($P < 0.01$) of tree species richness among the altitudinal ranges tested by Duncan multiple range tests (n=30).

Table 4.1 List of the tree species with their respective families and presence or absence in three altitudinal ranges.

S.N.	Tree species	Families	RKCF	PCF	KMCF
1	*Adina cordifolia* (Roxb.) Brandis	Rubiaceae	1	0	1

2	*Albizia lebbeck* (L.) Benth.	Fabaceae	0	1	1
3	*Albizia lucidior* (Steud.) I.C.Nielson ex H.Hara	Fabaceae	1	0	0
4	*Albizia odoratissima* (L.f.) Benth.	Fabaceae	0	1	0
5	*Albizia* sp.	Fabaceae	0	1	1
6	*Alnus nepalensis* D.Don	Betulaceae	0	0	1
7	*Bombax ceiba* L.	Malvaceae	0	0	1
8	*Casearia graveolens* Dalzell	Salicaceae	0	1	1
9	*Cassia fistula* L.	Fabaceae	0	1	1
10	*Castanopsis indica* (Roxb. ex Lindl.) A.DC.	Fagaceae	0	0	1
11	*Dalbergia sissoo* Roxb. ex DC.	Fabaceae	0	0	1
12	*Dillenia pentagyna* Roxb.	Dilleniaceae	1	0	0
13	*Elaeocarpus angustifolius* Blume	Elaeocarpaceae	0	0	1
14	*Falconeria insignis* Royle	Euphorbiaceae	1	1	1
15	*Ficus benghalensis* L.	Moraceae	0	1	0
16	*Ficus semicordata* Buch.-Ham. ex J.E.Sm.	Moraceae	0	0	1
17	*Heynea trijuga* Roxb.	Meliaceae	0	1	0
18	*Lagerstroemia parviflora* Roxb.	Lythraceae	1	0	1
19	*Lannea coromandelica* (Houtt.) Merr.	Anacardiaceae	1	0	0
20	*Litsea monopetala* (Roxb. ex Baker) Pers.	Lauraceae	0	0	1
21	*Lyonia ovalifolia* (Wall.) Drude	Ericaceae	0	0	1
22	*Machilus odoratissima* (Nees) Kosterm.	Lauraceae	0	1	0
23	*Madhuca longifolia* (J.Koenig ex L.) J.F.Macbr.	Sapotaceae	0	0	1
24	*Mallotus philippensis* (Lam.) Mull.Arg	Euphorbiaceae	1	0	1
25	*Mangifera indica* L.	Anacardiaceae	1	0	0
26	*Neolamarckia cadamba* (Roxb.) Bosser	Rubiaceae	0	1	1
27	*Phyllanthus emblica* L.	Phyllanthaceae	1	0	0
28	*Pyrus pyrifolia (Burm.fil.)* Nakai	Rosaceae	0	0	1
29	*Rhus chinensis* Mill.	Anacardiaceae	0	0	1
30	*Schima wallichi* (DC.) Korth.	Theaceae	0	1	1
31	*Schleichera oleosa* (Lour.) Oken	Sapindaceae	1	0	0
32	*Semecarpus anacardium* L.fil.	Anacardiaceae	0	1	1

33	*Senegalia catechu* (L.f.) P.J.H.Hurter and Mabb.	Fabaceae	0	0	1
34	*Shorea robusta* Gaertn.	Dipterocarpaceae	1	1	1
35	*Syzygium cumini* (L.) Skeels	Myrtaceae	1	1	1
36	*Syzygium nervosum* DC.	Myrtaceae	1	0	0
37	*Tectona grandis* L.f.	Lamiaceae	0	1	0
38	*Terminalia alata* B.Heyne ex Roth	Combretaceae	1	1	1
39	*Terminalia anogeissiana* Gere and Boatwr.	Combretaceae	1	0	1
40	*Terminalia bellirica* (Gaertn.) Roxb.	Combretaceae	1	1	0
41	*Terminalia chebula* Retz.	Combretaceae	1	0	0
42	*Toona ciliata* M.Roem.	Meliaceae	0	0	1
43	*Zanthoxullym* sp.	Rutaceae	0	1	0

0 = Absent, 1 = Present

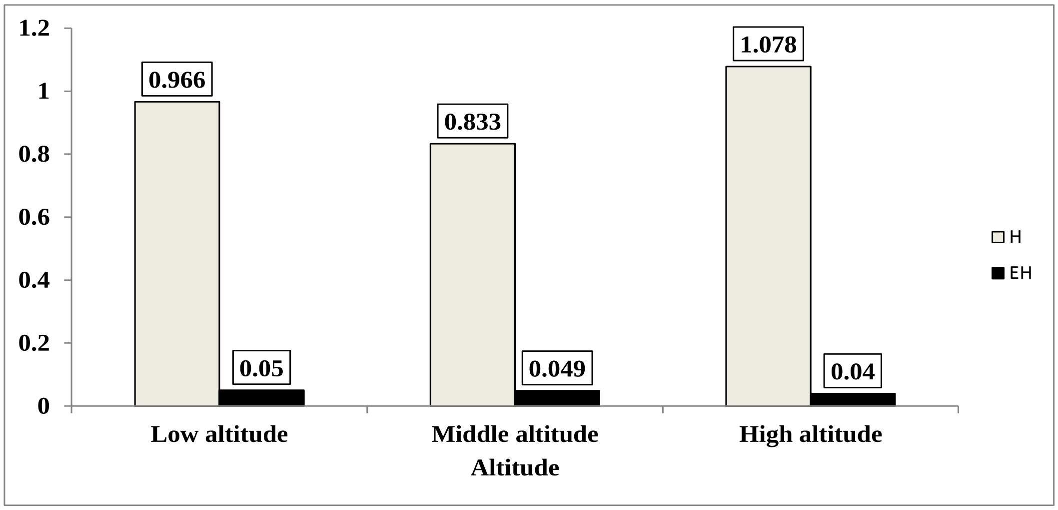

Figure 4.2 Shannon Diversity index (H) and Equitability index (EH) of the tree species in three different altitudinal ranges.

The value of Shannon Diversity index (H) was higher (1.078) in high altitudinal range followed by low (0.966) and middle altitude (0.833) (Figure 5). However, the Shannon Equitability index (E_H) was higher in the lower altitudinal range (0.05) followed by middle (0.049) and higher range (0.04) (Figure 4.2).

4.1.2. Tree distribution

The eigen value and axis length of first axis DCA was 0.458 and 4.107 respectively (Table 4.2). The eigen values and axis lengths decreased with the axis number from 1st to 4th. The given parameters of DCA suggested Canonical Correspondence Analysis (CCA) for the analysis of tree distribution with respect to environmental gradients.

Table 4.2 Summary of Detrended correspondence analysis (DCA).

	DCA1	**DCA2**	**DCA3**	**DCA4**
Eigen values	0.458	0.287	0.232	0.135
Decorana value	0.466	0.281	0.192	0.119
Axis lengths	4.107	2.631	2.020	1.168

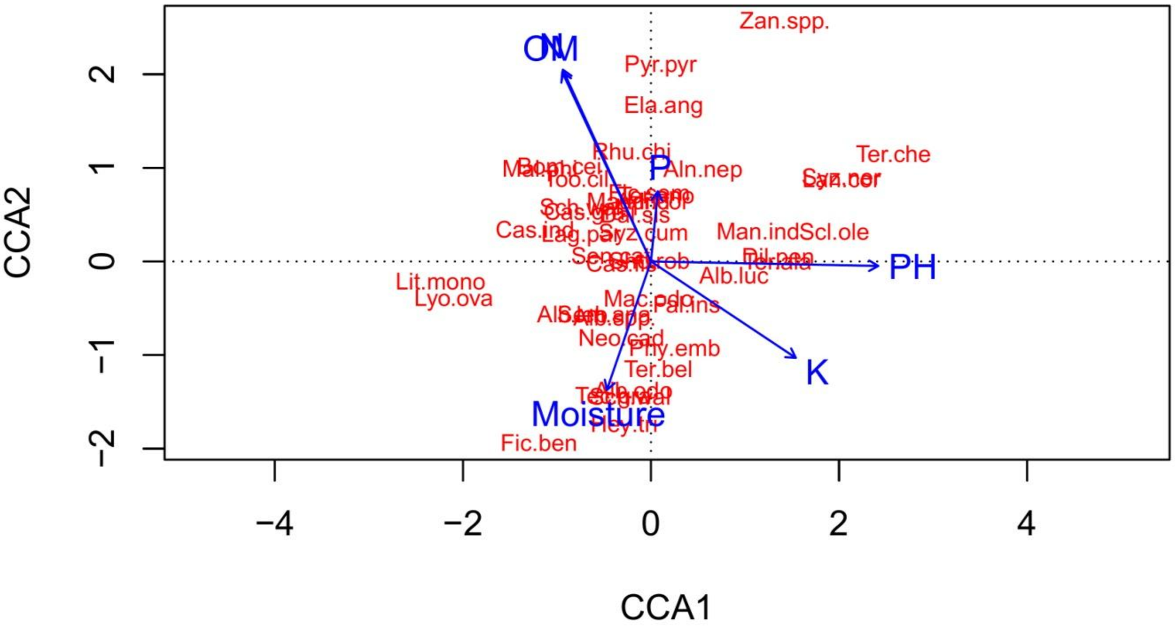

Figure 4.3 Tree species distribution with respect to soil factors (P, K, pH, OM, Moisture) collectively among three altitudinal ranges (n = 90).

Distribution of tree species with respect to selected variables was analyzed from CCA. Tree species were distributed with respect to the selected parameters in the present study. *A. nepalnensis, F. semicordata* and *A. cordifolia* were suited to higher phosphorous content. Moreover, *T. alata* and *D. pentagyna* were distributed towards higher pH value and *S. catechu* and *C. fistula* towards lower pH value. Higher moisture content favored the condition to *F. benghalensis, H. trijuga, S. wallichi, T. grandis* and *A. odoratissima* (Figure 4.3).

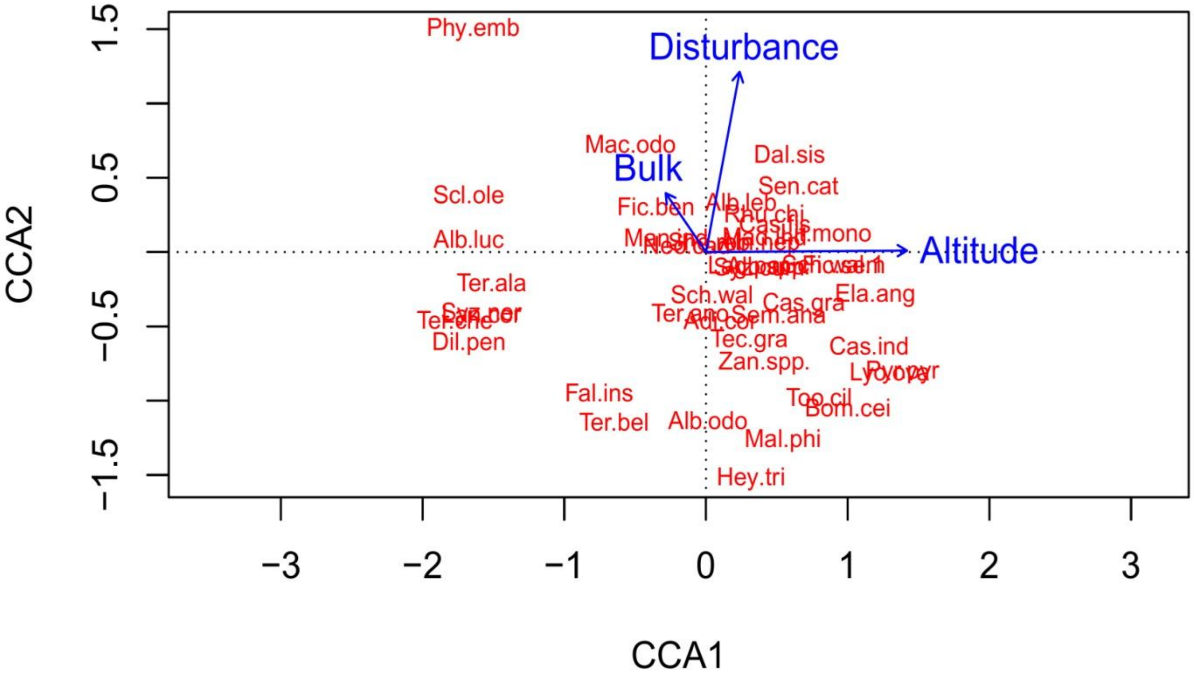

Figure 4.4 Tree species distribution with respect to disturbance, bulk density and altitudes collectively in study areas among three altitudinal ranges (n = 90).

Moreover, the abundance of *M. odoratissima* and *F. benghalensis* was positively correlated to bulk density. *L. monopetala*, *S. wallichi*, *A. nepalensis* and *F. semicordata* were favored by higher altitude. However, *T. bellirica, T. chebula, S. oleosa*, *S. nervosum* and *T. alata* were negatively correlated to altitudes (Figure 4.4).

4.2. Community attributes

The Dominance-Diversity curve (DD curve) showed the highest IVI of *S. robusta* in all altitudinal ranges (Annex 2-4). According to DD curve *S. robusta* was highly dominated in all three altitudinal ranges. In low altitudinal range, IVI of *S. robusta* (178.28) was followed by *T. alata* (64.08) and *T. anogeissiana* (12.74) (Figure 4.5). Moreover, in middle (191.25) (Figure 4.6) and upper altitude (178.29) (Figure 4.7), IVI of *S. robusta* was highest.

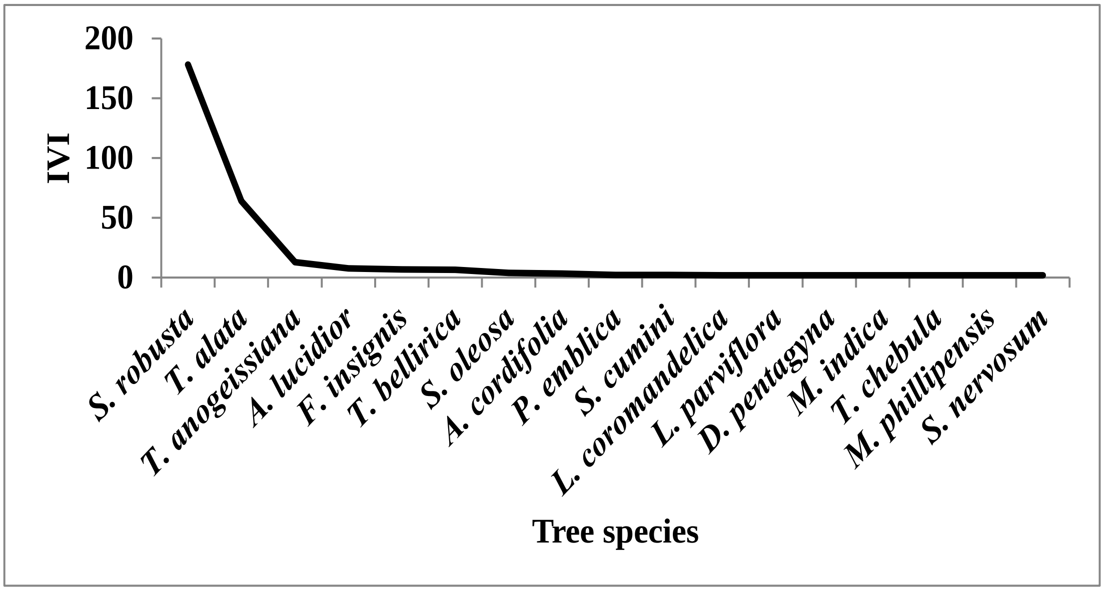

Figure 4.5 Dominance-Diversity (DD) curve of trees in low altitudinal range**.**

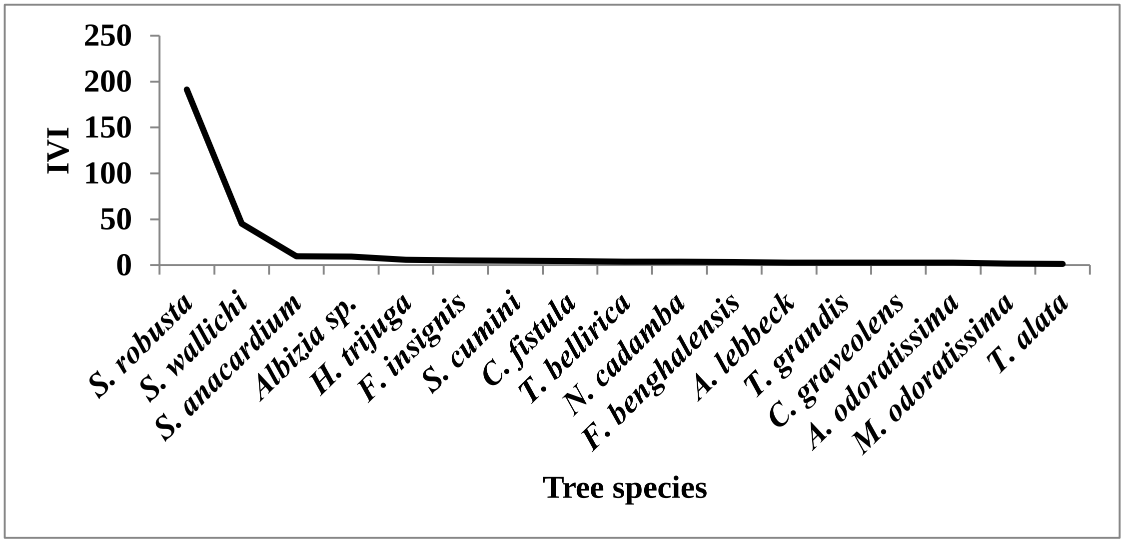

Figure 4.6 Dominance Diversity (DD) curve of trees in middle altitudinal range.

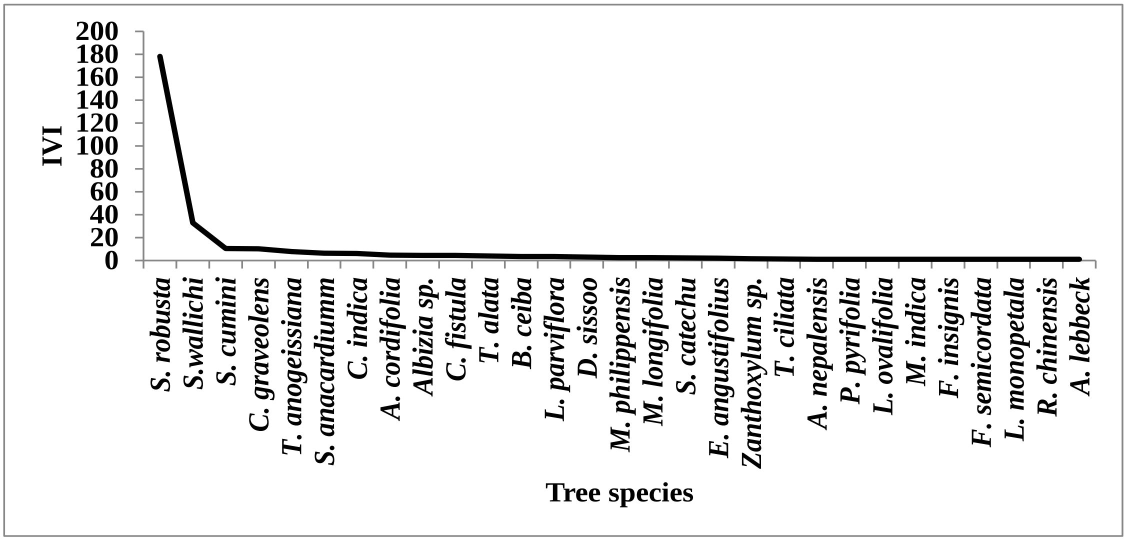

Figure 4.7 Dominance Diversity (DD) curve of trees in high altitudinal range.

Upper altitudinal range had the highest tree density (1865.3 pl ha^{-1}) followed by middle (1134.9 pl ha$^{-1)}$ and low altitudinal range (831.9 pl ha^{-1}). Among the trees, *S. robusta* had the highest density in all three forests where high altitude forest had the highest (1490.53 pl ha^{-1}) density of Sal followed by middle (937.8 pl ha^{-1}) and low altitude (593.6 pl ha^{-1}).

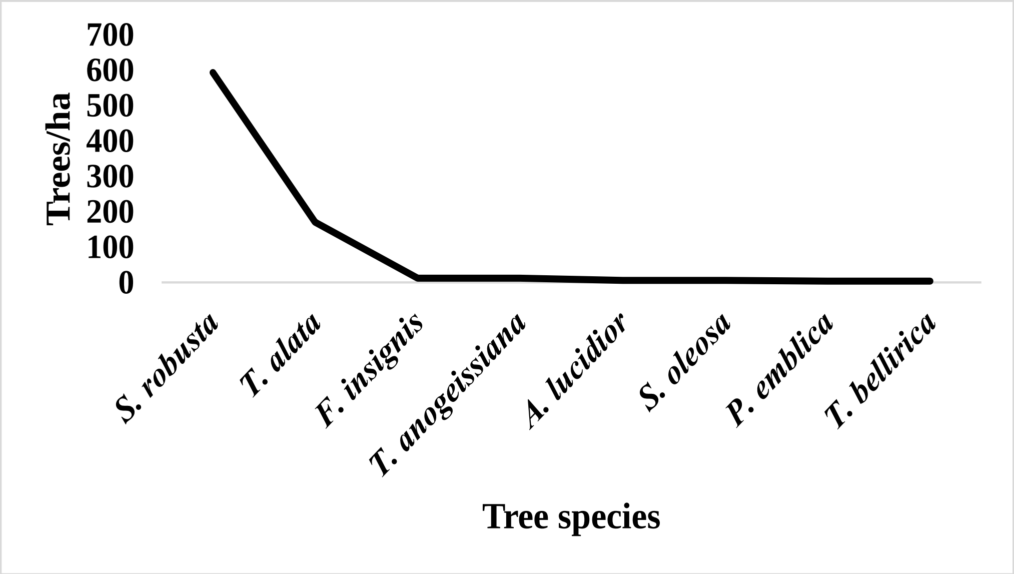

Figure 4.8 Tree species with higher density in lower altitudinal range.

T. alata (171.15 pl ha^{-1}) and *T. anogeissiana* (12.99 pl ha^{-1}) had the second and third highest density in low altitude forest respectively (Figure 4.8). Moreover, *S. wallichi* and *Albizia* sp. followed the density of trees in middle altitudinal range (Figure 4.9). However, *S. wallich1i* (121.31 pl ha^{-1}) and *C. graveolens* (34.66 pl ha^{-1}) followed the density of trees in high altitude (Figure 4.10).

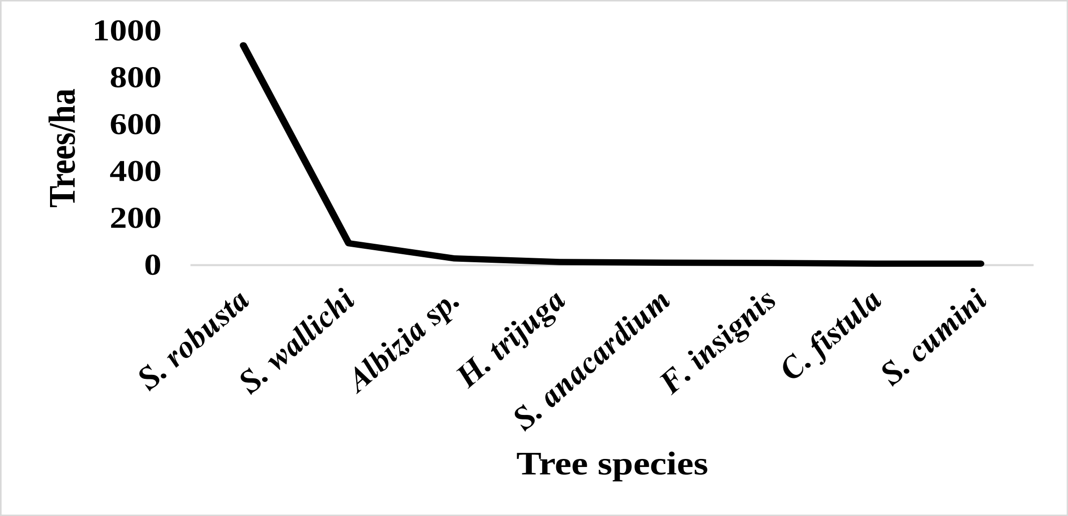

Figure 4.9 Tree species with higher density in middle altitudinal range.

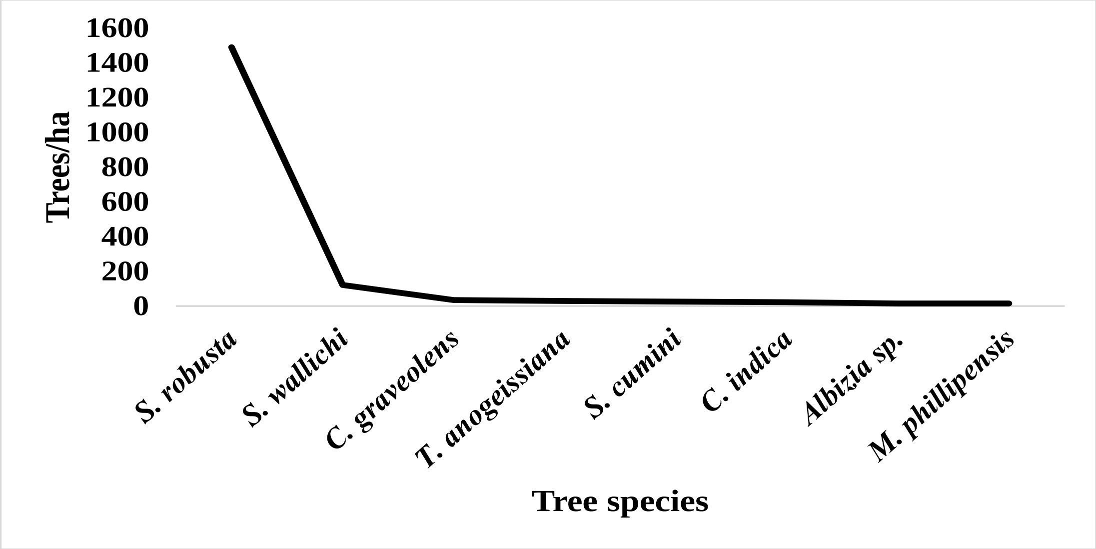

Figure 4.10 Tree species with higher density in higher altitudinal range.

4.3. Size-class distribution

DBH classes were categorized into 10 groups in the present study. The density of trees in lower altitude were higher (476.6 tree ha^{-1}) in the DBH category of 10-20 cm followed by 20-30 cm (155.9 tree ha^{-1}), 5-10 cm (60.6 tree ha^{-1}) and 30-40 cm (54.1 tree ha^{-1}) (Figure 4.11). Nevertheless, two trees per hectare were recorded with the DBH ranging 90-100 cm. In middle altitudinal range, the higher number was presented in the DBH category of 20-30 cm (420.2 tree ha^{-1}) followed by 10-20 cm (372.6 tree ha^{-1}), 5-10 cm (223.1 tree ha^{-1}), 30-40 cm (77.9 tree ha^{-1}) and 40-50 cm (8.6 tree ha^{-1}). However, 17.1 trees per hectare were recorded in the DBH category of 50-80 cm. No trees were recorded with the DBH more than 80 cm (Figure 4.11). Moreover, high altitude forest also showed the similar pattern like low and middle where higher number of species was observed within the DBH class below 30 cm compared to the higher DBH classes (more than 30 cm).

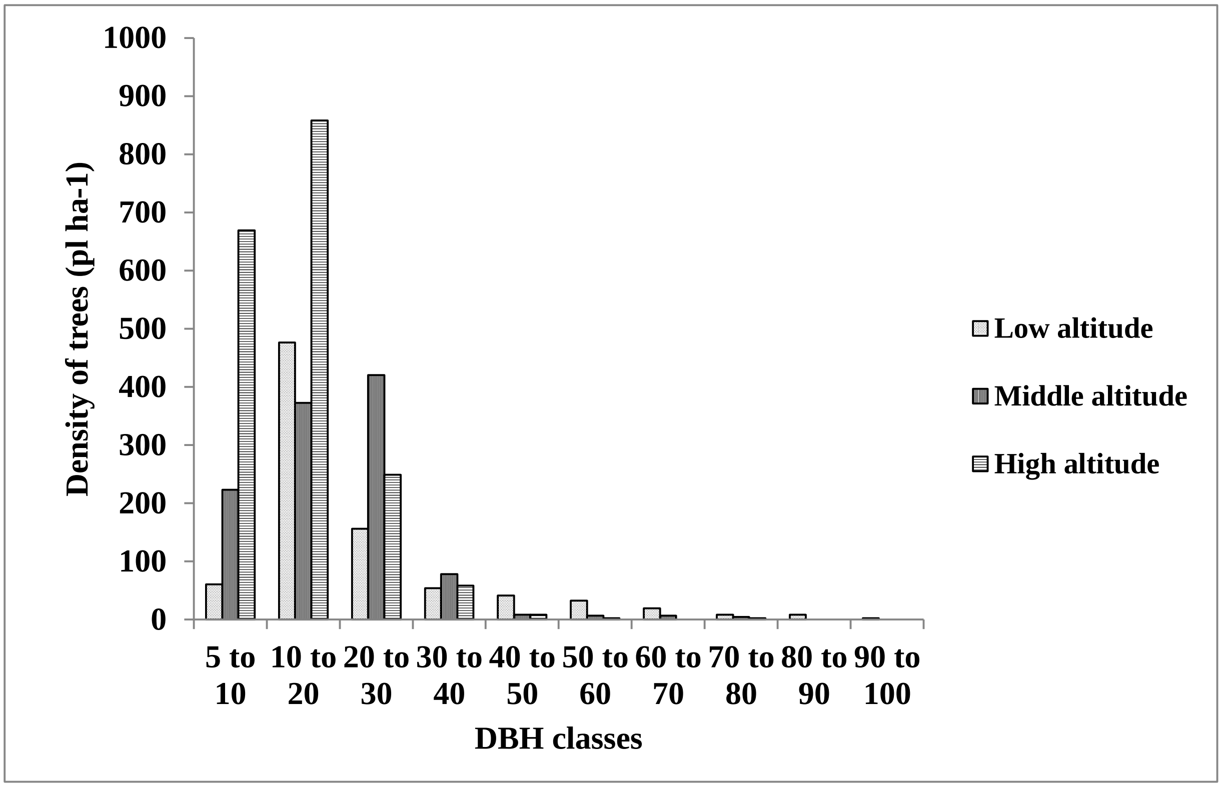

Figure 4.11 Size-class distribution of the trees with the density of trees species in each DBH class category in all altitudinal ranges.

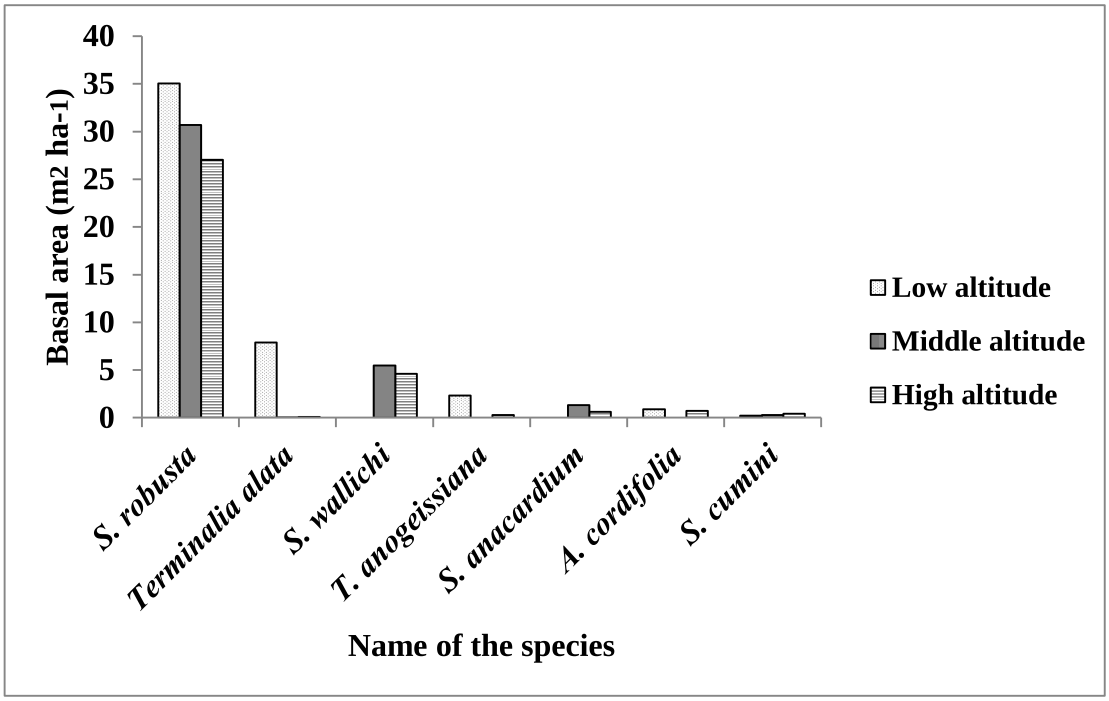

Figure 4.12 Basal area of highest seven species in all altitudinal ranges**.**

Low, middle and high altitudinal range forests had a total basal area of 51.41 m^2ha^{-1}, 40.79 m^2 ha^{-1} and 35.9 m^2 ha^{-1} respectively (Figure 4.12). *S. robusta* had the highest basal area in all three sites compared to other species. *S. robusta* occupied 35.06 m^2 ha^{-1}, 30.68 m^2 ha^{-1} and 27.04 m^2 ha^{-1} which were 68.19%, 75.21% and 75.32% of total basal area in low, middle and high altitudinal range respectively.

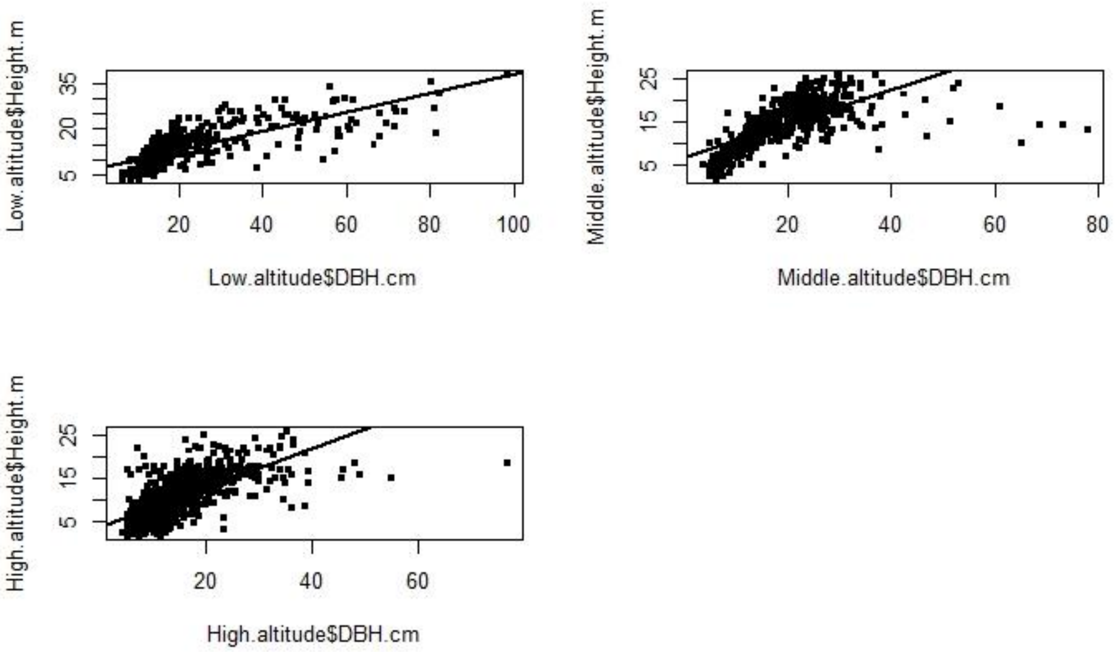

Figure 4.13 A simple linear regression between DBH (cm) and Height (m) in each altitudinal range (n = 30)

According to the simple linear regression and Spearman correlation, height and DBH of the trees in the study areas were positively related with each other (Table 4.3, Figure 4.13). The rho-value for DBH and height in low, middle and high altitude forest was 0.819, 0.793 and 0.769 respectively with high significant difference (*P* < 0.001). Moreover, the line in simple linear regression also fitted its best with highly significant difference (*P* < 0.001) in all three altitudinal ranges for DBH and height (Figure 4.13, Table 4.3).

Table 4.3 Spearman correlation coefficient (rho-value) and goodness of fit value (R^2) of DBH and height of trees among three altitudinal ranges.

	R^2 value	Rho-value
Low altitude	0.576***	0.819***
Middle altitude	0.466***	0.793***
High altitude	0.494***	0.769***

*** = significant level < 0.001

4.4. Tree and soil carbon stock

The mean of total tree carbon stock was highest (372.08 t ha^{-1}) in lower altitudinal range followed by middle (192.27 t ha^{-1}) and high altitudinal range (134.18 t ha^{-1}) (Figure 4.14).

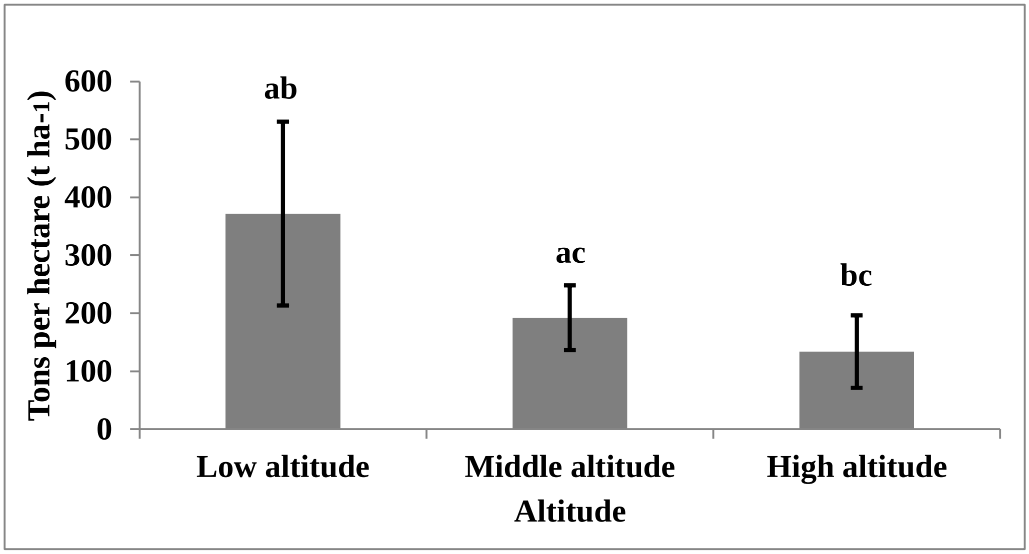

Figure 4.14 The mean total tree carbon stock in all three altitudinal ranges. Error bar has been showed as standard deviation (n=30). Shared superscript indicated significant difference ($P < 0.01$) of tree species richness among the altitudinal ranges tested by Pairwise-Wilcoxon test.

According to Kruskal-Wallis test, there was a significant difference ($P < 0.001$) between the estimated mean total tree carbon stock of all altitudes. Moreover, the significant difference was seen among all altitudes regarding tree carbon stock (Table 4.4).

Table 4.4 Pairwise Wilcoxon test to observe the significant difference in mean total tree carbon stock between each altitudes.

	High altitude	Middle altitude
Middle altitude	< 0.001	-
Low altitude	< 0.001	< 0.001

Table 4.5 The percentage of mean total tree carbon stock per hectare (t ha^{-1}) by each tree species in low altitudinal range.

Tree species	Tree carbon stock (%) species
Adina cordifolia	1.385401
Albizia lucidior	1.923845
Dillenia pentagyna	0.079748
Falconeria insignis	1.117634
Lagerstroemia parviflora	0.189183
Lannea coromandelica	0.093136
Mallotus philippensis	0.096047
Mangifera indica	0.0553
Phyllanthus emblica	0.160078
Schleichera oleosa	0.433665
Shorea robusta	71.66249
Syzygium cumini	0.212467
Syzygium nervosum	0.032016
Terminalia alata	16.45018
Terminalia anogeissiana	3.568281
Terminalia bellirica	1.519284
Terminalia chebula	1.021273

Table 4.6 The percentage of mean total tree carbon stock per hectare (t ha^{-1}) by each tree species in middle altitudinal range.

Tree species	Tree carbon stock (%) tree species
Albizia sp.	0.06252
Albizia lebbeck	0.147569
Albizia odoratissima	0.004506
Cassia fistula	0.632519
Casearia graveolens	0.006196
Falconeria insignis	0.012955

Ficus benghalensis	0.788537
Heynea trijuga	0.015771
Machilus odoratissima	0.44496
Neolamarckia cadamba	1.252647
Schima wallichi	9.506375
Semecarpus anacardium	1.890799
Shorea robusta	82.91972
Syzygium cumini	0.480444
Tectona grandis	0.009575
Terminalia alata	0.016897
Terminalia bellirica	1.808002

Table 4.7 The percentage of mean total tree carbon stock per hectare (t ha^{-1}) by each tree species in high altitudinal range.

Tree species	**Tree carbon stock (%)tree species**
Adina cordifolia	1.665028
Albizia sp.	0.353506
Albizia lebbeck	0.001614
Alnus nepalensis	0.016142
Bombax ceiba	0.497168
Cassia fistula	0.359155
Casearia graveolens	0.118642
Castanopsis indica	0.504432
Dalbergia sissoo	0.048425
Elaeocarpus angustifolius	0.057303
Falconeria insignis	0.00565
Ficus semicordata	0.000807
Lagerstroemia parviflora	0.224371
Litsea monopetala	0.004843

Lyonia ovalifolia	0.008071
Madhuca longifolia	0.790949
Mallotus philippensis	0.048425
Mangifera indica	0.003228
Pyrus communis	0.040355
Rhus chinensis	0.002421
Schima wallichi	8.642327
Semecarpus anacardium	1.475362
Senegalia catechu	0.185631
Shorea robusta	82.13036
Syzygium cumini	1.216286
Terminalia alata	0.706204
Terminalia anogeissiana	0.327679
Toona ciliate	0.035512
Zanthoxylum sp.	0.53268

S. robusta had the highest proportion of mean total tree carbon stock in all altitudinal ranges, where it resulted 71.6%, 82.91% and 82.13% in lower, middle and higher altitude forests respectively (Table 4.5-4.7, Annex 5-7). Moreover, *T. alata* (16.45%), *S. wallichi* (9.5%) and *S. wallichi* (8.64%) had the second highest proportion of mean total tree carbon stock in lower, middle and higher altitude forests respectively.

Table 4.8 Soil carbon stock (t ha^{-1}) in three altitudinal ranges tested by One-way ANOVA.

Sites	**Soil carbon stock (t ha^{-1})**	**P value**
Low altitude	33.05 ± 12.27	< 0.001
Middle altitude	27.69 ± 13.21	
High altitude	60.03 ± 16.54	

Moreover, the soil carbon stock was higher in higher altitudinal range forest (60.03 t ha^{-1}) and lower in middle altitudinal range forest (27.69 t ha^{-1}) (Table 4.8). There was the high significant difference ($P < 0.001$) between the soil carbon stock and the altitudinal ranges tested by one-way ANOVA. Soil carbon stock was positively correlated to the altitudinal ranges (rho-value = 0.456, $P < 0.001$).

4.4.1. Factor affecting carbon stock

Altogether nine variables were studied whether they affect the quantity of carbon stock. According to the Spearman correlation (Table 4.9) and a simple linear regression (Table 4.10), potassium and pH were positively correlated to the tree carbon stocks. However, organic matter, nitrogen content and altitude had a negative relation with tree carbon stock.

Table 4.9 Spearman correlation representing the relationship between the selected variables and carbon stock (t. ha^{-1}).

Variables	**Tree carbon stock (rho-value)**
Organic matter	-0.283^{**}
Nitrogen	-0.284^{**}
Phosphorus	0.081
Potassium	0.415^{***}
pH	0.369^{***}
Altitude	-0.711^{***}
Moisture	0.062
Basal area	0.779^{***}
Density	-0.293^{**}

*, **, *and* *** *represent significance at* $P \leq 0.05$, $P \leq 0.01$ *and* $P \leq 0.001$ *respectively.*

Table 4.10 A simple linear regression between tree carbon stock and the selected variables listed with R square value and p-value.

	Tree carbon stock	
	R square	p-value
Organic matter	0.050	0.018
Nitrogen	0.051	0.018
Phosphorus	-0.002	0.391
Potassium	0.071	0.006

pH	0.190	0.000
Altitude	0.479	0.000
Moisture	0.003	0.251
Basal area	0.638	0.000
Density	0.061	0.010

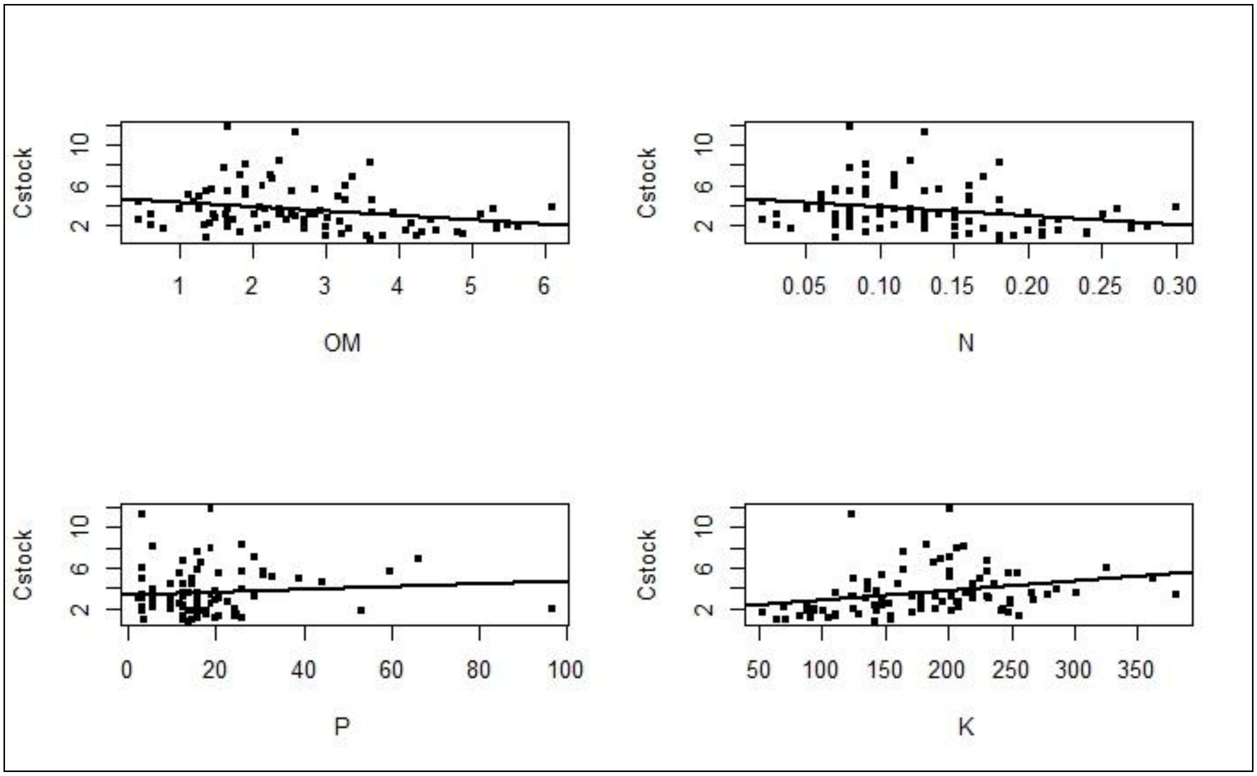

Figure 4.15 A linear regression between the tree carbon stock t. plot^{-1} and organic matter (OM) in %, Nitrogen (N) in %, Phosphorus (P) in kg ha^{-1} and Potassium (K) in kg ha^{-1} collectively in all altitudinal ranges (n = 90).

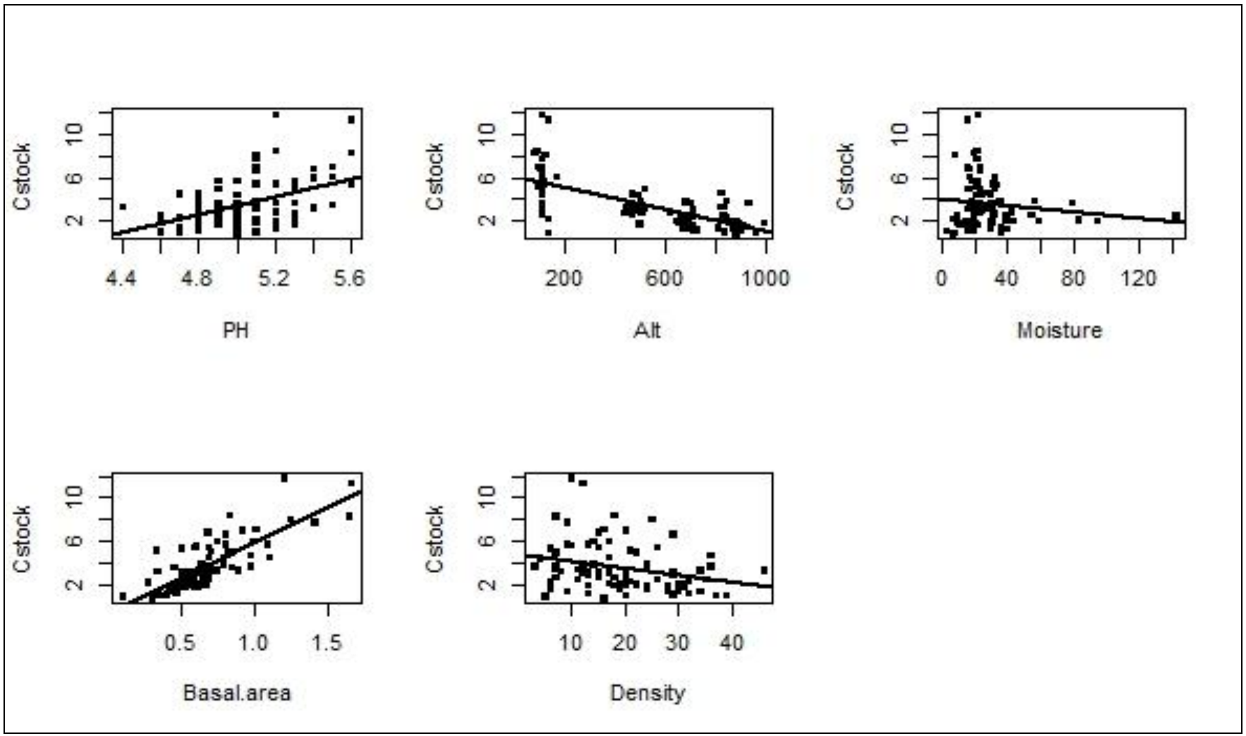

Figure 4.16 A linear regression between tree carbon stock t. plot^{-1} and pH, altitude (Alt) in m, moisture in %, basal area in m^{2} plot^{-1} and density in number of species plot^{-1} collectively in all altitudinal ranges (n = 90).

Moreover, a simple linear regression also supports the positive relationship of potassium and pH to the tree carbon stocks (Figure 4.15 and 4.16). However, negative relationship between organic matter, nitrogen content and altitude with tree carbon stock was also supported by a simple linear regression (Figure 4.15 and 4.16).

4.5. Regeneration status of *S. robusta*

The density of seedlings, saplings and trees were estimated to study the regeneration pattern of *S. robusa* in the study areas. The density of the seedlings was higher in low altitudinal range (76485.8 pl ha^{-1}) followed by middle (21549.8 pl ha^{-1}) and high altitudinal range (15445.8 pl ha^{-1}) (Figure 4.17). However, the density of saplings was highest in high altitudinal range (2122.8 pl ha^{-1}) and lowest in middle altitudinal range (129.7 pl ha^{-1}). Moreover, high altitudinal range had the highest density of trees (1490.5 pl ha^{-1}) followed by middle (937.8 pl ha^{-1}) and low altitudinal range forest (593.6 pl ha^{-1}) (Figure 4.17).

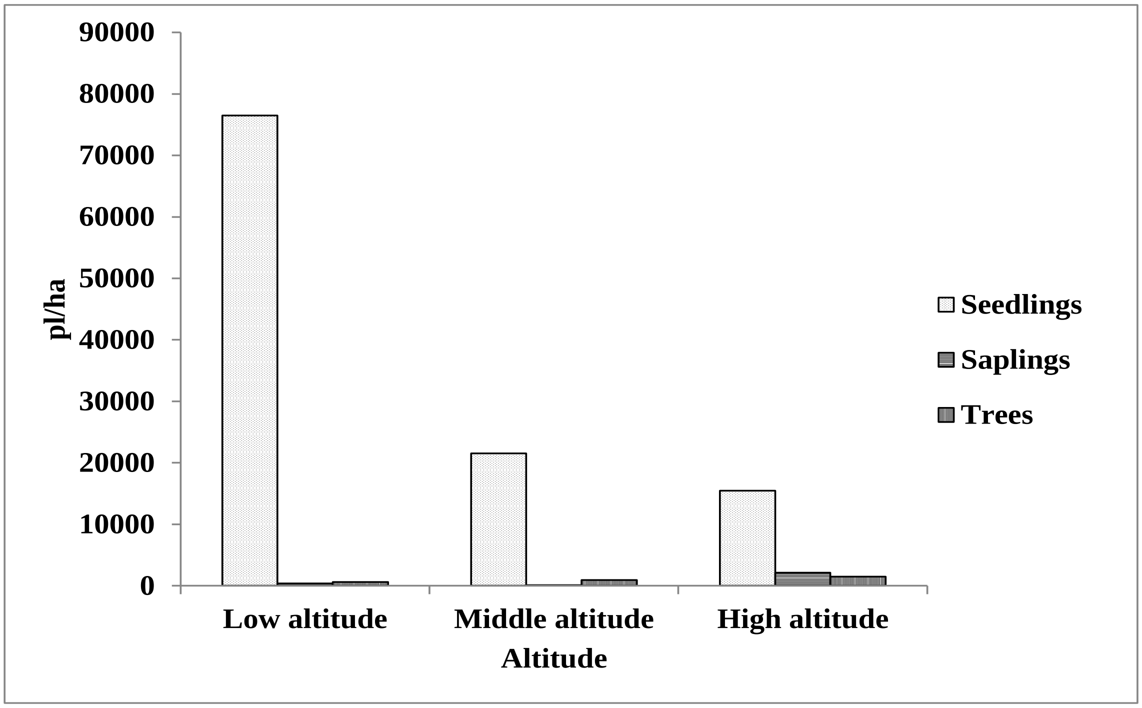

Figure 4.17 Regeneration status of *S. robusta* in three altitudinal ranges

Table 4.11 The density of seedlings, saplings and trees in the study areas are given as plants per hectare with the significant difference (p-value) of variables in three altitudinal ranges. Shared similar superscripts represent the significant differences between the shared groups.

	Low altitude	**Middle altitude**	**High altitude**	**p-value**
Seedlings (pl ha^{-1})	76485.8^{ab}	21549.8^{a}	15445.8^{b}	< 0.001
Saplings (pl ha^{-1})	365.6^{a}	129.7^{b}	2122.8^{ab}	< 0.001
Trees (pl ha^{-1})	593.6^{ab}	937.8^{ac}	1490.5^{bc}	< 0.001

Statistically, the density of saplings, seedlings and trees were significantly different in three altitudinal ranges. According to the Pairwise-Wilcoxon test, the number of seedlings in low altitude significantly differed with middle and high altitudinal ranges (Table 4.11). Moreover, the number of saplings in high altitude significantly differed with low and middle altitudinal ranges. However, the density of trees has a significant difference in each altitudinal ranges (Table 4.11).

4.5.1. Factors affecting regeneration of *S. robusta*

Among the selected variables, nine variables each had the effect on the density of seedlings and saplings of *S. robusta*. According to the Spearman correlation pH (ρ = 0.393), disturbance (ρ = 0.274), silt content (ρ = 0.408) and clay content (ρ = 0.284) were positively correlated with the density of seedlings. However, organic matter (ρ = -0.264), Nitrogen (ρ = -0.273), crown coverage (ρ = -0.356), altitude (ρ = -0.460) and sand (ρ = -0.415) were negatively correlated with the density of seedlings (Table 4.12).

Table 4.12 Spearman correlation of density of seedlings and saplings with the selected factors which are represented by rho-value.

Variables	**Seedlings (rho-value)**	**Saplings (rho-value)**
Organic matter	-0.264^{**}	0.503^{***}
Nitrogen	$- 0.273^{**}$	0.498^{***}
Phosphorous	$- 0.030^{ns}$	0.243^{*}
Potassium	0.127^{ns}	-0.209^{*}
pH	0.393^{***}	-0.132^{ns}
Crown coverage	-0.356^{***}	-0.057^{ns}
Litter depth	0.016^{ns}	0.215^{*}
Disturbance	0.274^{**}	0.187^{ns}
Altitude	-0.460^{***}	0.495^{***}
Moisture	-0.070^{ns}	0.084^{ns}
Bulk density	0.091^{ns}	-0.188^{ns}
Sand	-0.415^{***}	0.509^{***}
Silt	0.408^{***}	-0.562^{***}
Clay	0.284^{**}	-0.385^{**}

*, **, ***, *and* ^{ns} *represent significance at* $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$and not significant *respectively.*

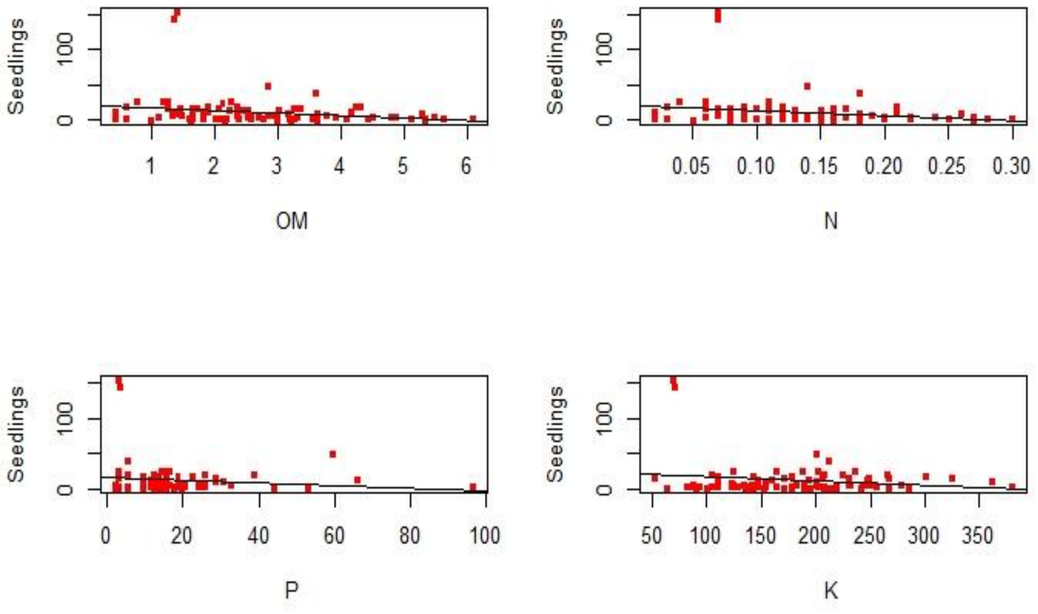

Figure 4.18 A linear regression between the number of seedlings (plants per plot) and edaphic factors like organic matter (OM) in %, Nitrogen (N) in %, Phosphorus (P) kg ha^{-1} and Potassium (K) in kg ha^{-1} collectively in all altitudinal ranges (n = 90).

A linear regression model also supports the evidence of relationship of the density of seedlings with organic matter ($P = 0.042$), nitrogen ($P = 0.041$), crown coverage ($P < 0.001$), altitude ($P < 0.001$), disturbance ($P = 0.022$), silt content ($P < 0.001$), sand content ($P < 0.001$) and clay content ($P = 0.013$) (Figure 4.18-4.21, Table 4.13).

Table 4.13 A simple linear regression among seedlings and saplings with the selected variables listed with R square value and P value.

	Seedlings		**Saplings**	
	R square	P value	R square	P value

Organic matter (%)	0.135	0.042	0.069	0.006
Nitrogen (%)	0.035	0.041	0.068	0.007
Phosphorus (kg ha^{-1})	0.000	0.303	-0.002	0.392
Potassium (kg ha^{-1})	0.019	0.098	0.039	0.032
pH	0.013	0.160	-0.007	0.580
Sand (%)	0.180	< 0.001	0.110	< 0.001
Silt (%)	0.203	0< 0.001	0.110	< 0.001
Clay (%)	0.057	0.013	0.036	0.039
Cover (%)	0.203	< 0.001	0.012	0.151
Altitude (m)	0.110	< 0.001	0.076	0.004
Moisture (%)	0.021	0.056	-0.009	0.679
Bulk density (g cm^{-3})	0.048	0.020	-0.010	0.803
Litter depth (cm)	0.018	0.153	-0.007	0.571
Disturbance	0.047	0.022	0.073	0.005

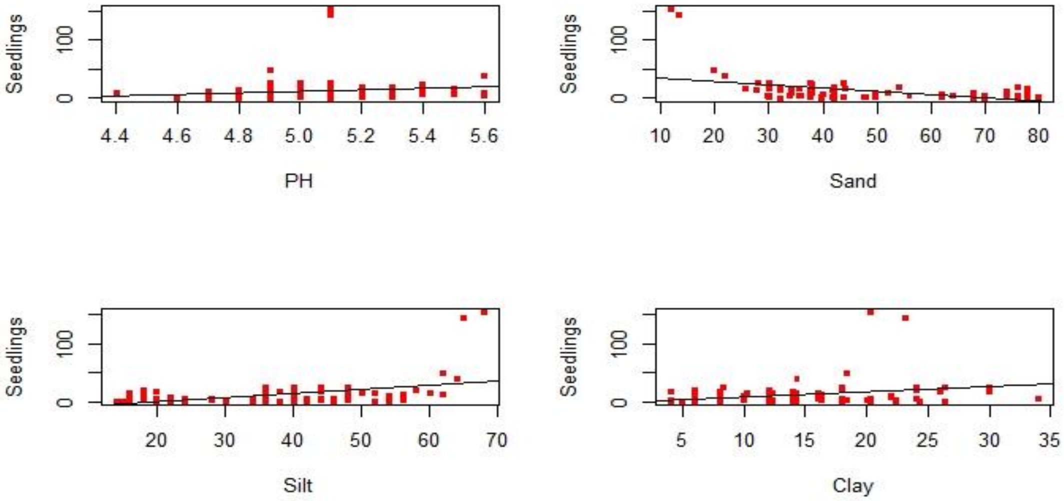

Figure 4.19 A linear regression between the number of seedlings (plants per plot) and edaphic factors like pH, sand (%), silt (%) and clay (%) collectively in all altitudinal ranges (n = 90).

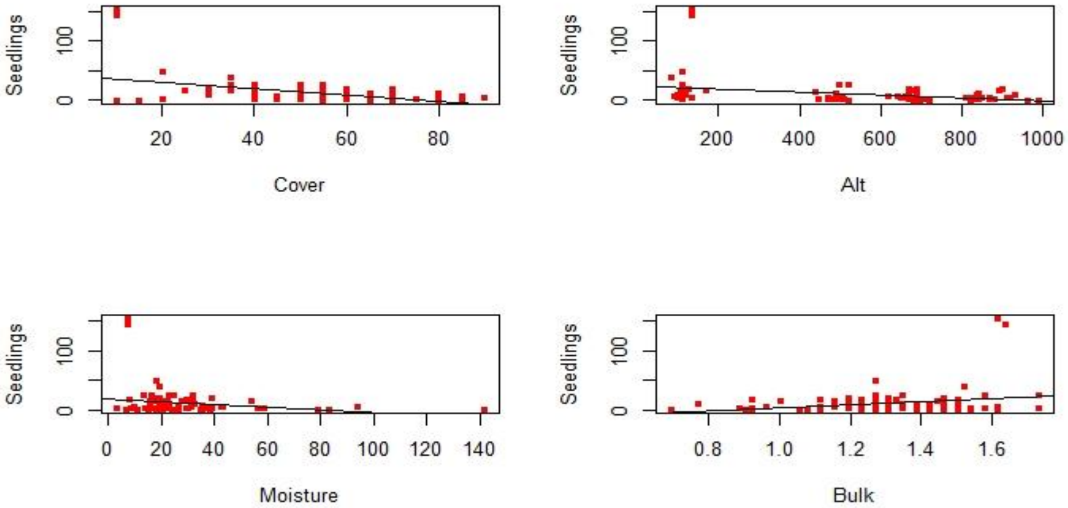

Figure 4.20 A linear regression between the number of seedlings and factors like coverage (cover) in %, altitudes (Alt) in m, moisture in % and bulk density (Bulk) in gm cm^{-3} collectively in all altitudinal ranges (n = 90).

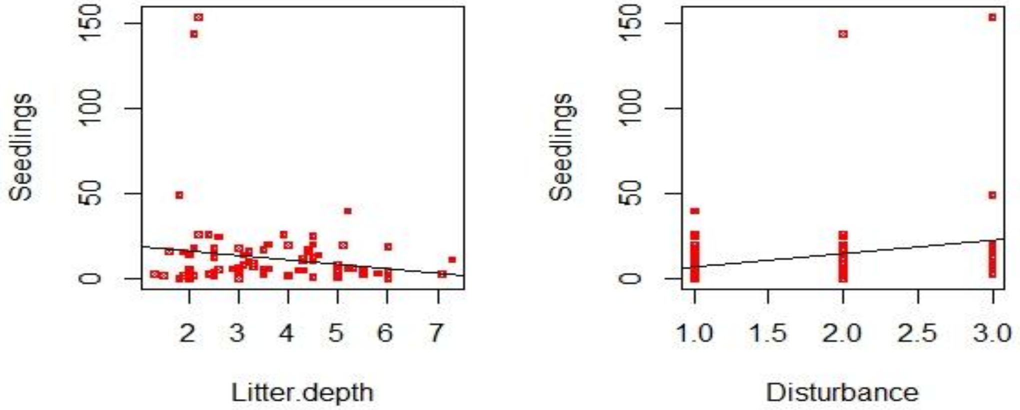

Figure 4.21 A linear regression between the number of seedlings (plants per plot) and litter depth in cm and disturbance collectively in all altitudinal ranges (n = 90).

The density of saplings was positively affected by organic matter (ρ = 0.503), nitrogen (ρ = 0.498), phosphorous (ρ = 0.243), litter depth (ρ = 0.215), altitude (ρ = 0.495) and sand (ρ = 0.509) (Figure 4.22-4.25, Table 4.12).

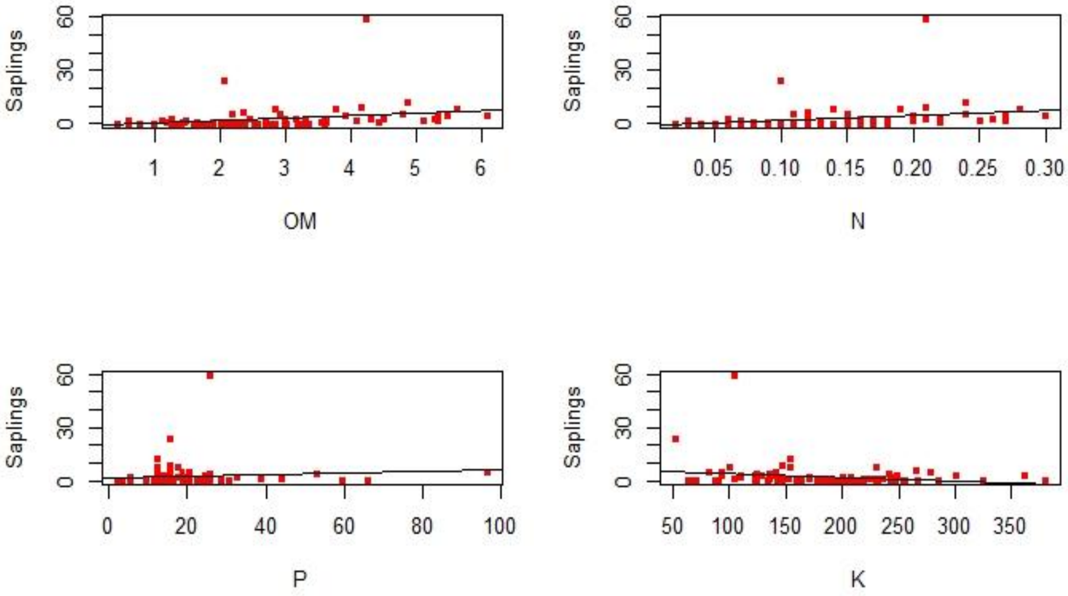

Figure 4.22 A linear regression between the number of saplings (plants per plot) and edaphic factors like organic matter (OM) in %, Nitrogen (N) in %, Phosphorus (P) kg ha^{-1} and Potassium (K) in kg ha^{-1} collectively in all altitudinal ranges (n = 90).

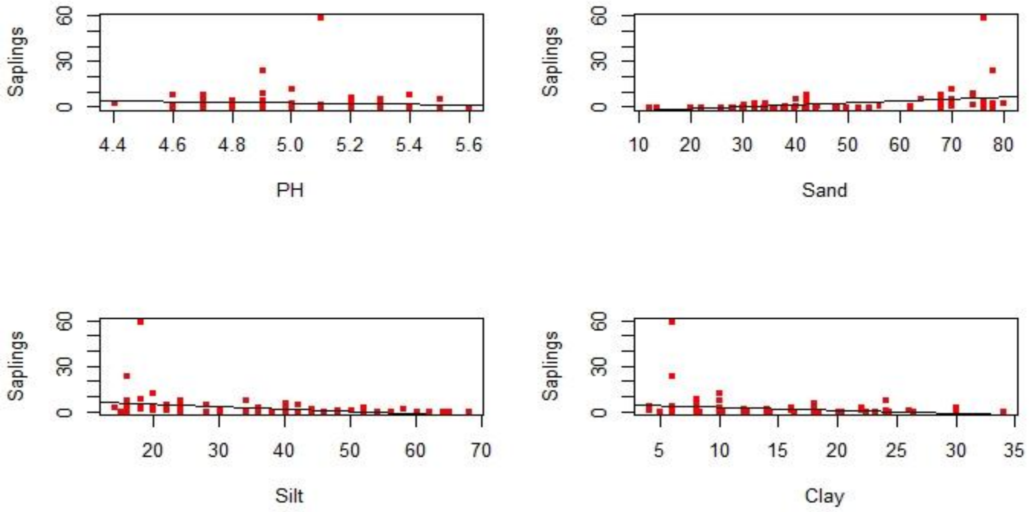

Figure 4.23 A linear regression between the number of saplings (plants per plot) and edaphic factors like pH, sand (%), silt (%) and clay (%) collectively in altitudinal ranges (n = 90).

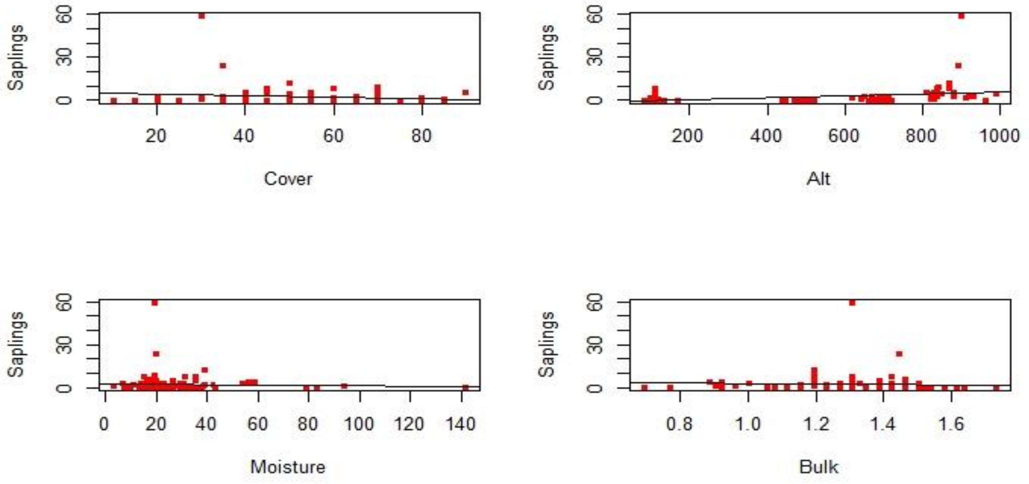

Figure 4.24 A linear regression between the number of saplings and factors like coverage (cover) in %, altitude (Alt) in m, moisture in % and bulk density (Bulk) in gm cm^{-3} collectively in all altitudinal ranges (n = 90).

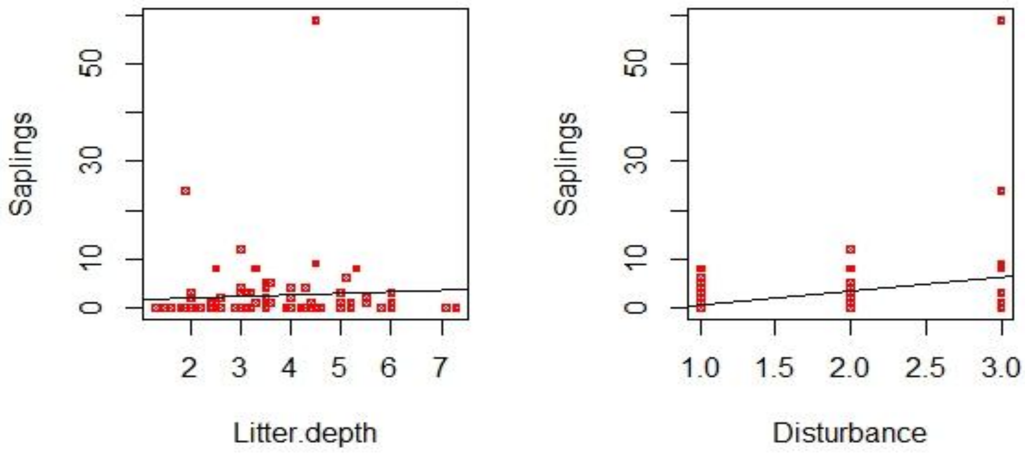

Figure 4.25 A linear regression between the number of saplings (plants per plot) and litter depth in cm and disturbance collectively in altitudinal ranges (n = 90).

However, Potassium (ρ = -0.209), silt content (ρ = -0.562) and clay content (ρ = -0.385) were negatively correlated to the density of saplings in the study**.** The relationship between the density of saplings and organic matter, nitrogen, potassium, altitude, disturbances, sand content, silt content and clay content was also supported by a linear regression model (Table 4.13, Figure 4.22-4.25).

4.6. Edaphic and other selected factors

The significant difference was observed between the selected variables among three altitudinal ranges. Some physiochemical factors of soil were studied in the study areas such as organic matter, nitrogen, phosphorous, potassium, pH, bulk density, moisture, litter depth and soil texture (Annex 8-11). Moreover, crown cover and disturbance level in the forests were also studied (Table 4.14). The soil was loamy, silty loamy and sandy loamy in low, middle and high altitudinal range forest respectively. Low altitude forest was composed of 47.76% sand, 34.56% silt and 17.71% clay, whereas middle and high altitudinal ranges comprised of 41.03% and 73.26% sand, 42.93% and 19.96% silt and 16.03% and 6.63% clay respectively. The organic matter in the study areas ranged from 2.1% to 4.11%. The organic matter in low, middle and high altitudinal range was 2.10%, 1.79% and 4.11% respectively. Nitrogen content was highest in high altitudinal range (0.20%) and lowest in middle altitudinal range (0.08%). The result showed the similar potassium content in low (209 kg ha^{-1}) and middle altitudinal range (209 kg ha^{-1}). A higher phosphorous content was observed in high altitudinal range (21.43%) followed by low (20.93%) and middle altitudinal range (10.17%). The soil of all three forests was acidic in nature. The pH value was 5.27 in low, 4.98 in middle and 4.89 in high altitudinal range. The highest litter depth was observed in high altitudinal range (3.87 cm), followed by low (3.79 cm) and middle altitudinal range (2.95 cm). Disturbance level was found higher in high altitudinal range (1.9) and lower in middle altitudinal range (1.56). Moreover, the bulk density was 1.35 g cm^{-3} in low, 1.33 g cm^{-3} in middle and 1.26 in g cm^{-3} high altitudinal range. The moisture content was highest in middle (35.97%) and lowest in low altitudinal range forest (21.77%) (Table 4.14).

Table 4.1 Edaphic factors and other selected variables in the study areas, which are given as mean ± standard deviation. Kruskal-wallis test has been performed to observe the significant difference of the variables among the altitudinal ranges and the similar shared superscript in a row denotes the significant difference between the shared variables.

	Low altitude	**Middle altitude**	**High altitude**	**p-value**
Organic matter (%)	2.10 ± 0.70^{a}	1.79 ± 0.78^{b}	4.11 ± 1.05^{ab}	< 0.001
Nitrogen (%)	0.10 ± 0.03^{a}	0.08 ± 0.03^{b}	0.20 ± 0.05^{ab}	< 0.001
Phosphorous (kg ha^{-1})	20.93 ± 14.76^{a}	10.17 ± 6.34^{ab}	21.43 ± 16.76^{b}	< 0.001
Potassium (kg ha^{-1})	209.24 ± 63.28^{a}	209.17 ± 53.06^{b}	125.16 ± 43.16^{ab}	< 0.001
pH	5.27 ± 0.19^{ab}	4.98 ± 0.13^{a}	4.89 ± 0.22^{b}	< 0.001
Crown coverage (%)	51.50 ± 19.12	61.16 ± 16.22^{a}	48.5 ± 19.03^{a}	0.027
Litter depth (cm)	3.79 ± 1.44^{a}	2.95 ± 1.27^{ab}	3.87 ± 1.19^{b}	0.010
Disturbance	1.66 ± 0.71	1.56 ± 0.62	1.9 ± 0.71	0.167
Moisture (%)	21.77 ± 7.25	35.97 ± 24.48^{a}	22.76 ± 13.19^{a}	0.042
Bulk density (g cm^{-3})	1.35 ± 0.18	1.33 ± 0.23	1.26 ± 0.19	0.248
Sand (%)	47.76 ± 10.01^{a}	41.03 ± 7.55^{b}	73.26 ± 4.68^{ab}	< 0.001
Silt (%)	34.56 ± 10.11^{a}	42.93 ± 7.06^{b}	19.96 ± 3.86^{ab}	< 0.001
Clay (%)	17.71 ± 6.56^{a}	16.03 ± 5.55^{b}	6.63 ± 1.79^{ab}	< 0.001

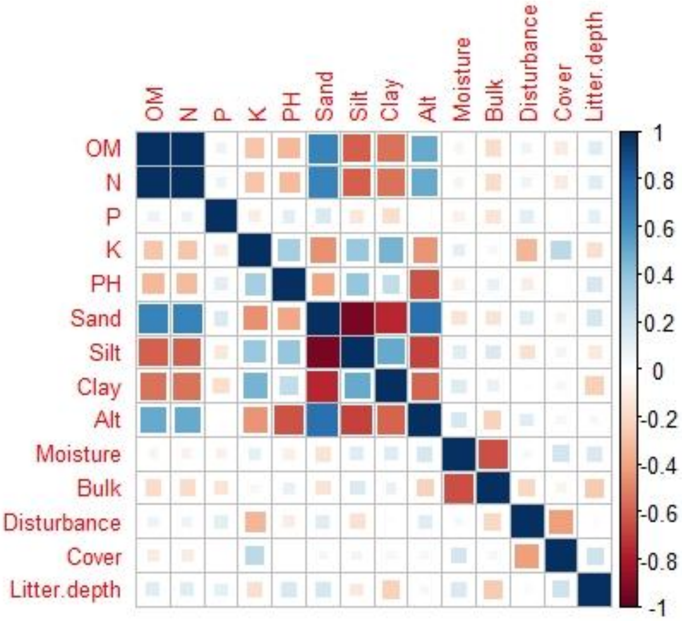

Figure 4.26 Correlation among different variables in the study areas collectively in all altitudinal ranges (n = 90).

The relationship between all selected variables was evaluated using multi correlation. Organic matter, nitrogen and sand content were positively correlated to altitude. Moreover, organic matter and nitrogen also had a positive relation. However, potassium, pH, silt and clay content had a negative correlation with an altitude. Bulk density and moisture content were negatively correlated with each other (Figure 4.26).

5. Discussion

5.1. Tree diversity and distribution

The value of Shannon Diversity index (H) was higher in high altitudinal range forest (1.078) followed by low (0.966) and middle altitudinal range (0.833). Tree diversity may be affected by management practices as plant species are affected by it (Awasthi *et al*., 2015). Management activities like thinning, pruning and cutting was effectively performed by low and middle altitudinal range which was least observed in high altitude forest. This might have played enormous role in the variation in tree diversity in the forests because thinning, pruning and cutting affect the species composition and abundance. Similar result was recorded by Awasthi *et al*. (2015) where they found low and high Shannon Weiner's Diversity Index in the managed and unmanaged block of community forests' respectively.

Species richness was observed greater in high altitudinal range forest followed by middle and low altitudinal range in *S. robusta* forest. In contrast to present study, Kumar and Ram (2005) had reported the decrease of species richness along an altitudinal gradient in Uttaranchal, Central Himalaya. It is believed that the variation in species richness is always governed by two or more environmental factors rather than a single factor (Pausas and Austin, 2001). Suitable physico-chemical environment for tree species and management strategies of forest users may be the reasons in the variation of tree species richness in the altitudinal ranges. This also might be due to the reason that the present study was carried out in small altitudinal range i.e., 82 m to 990 m. The species richness in Himalaya's increases from low altitude and reaches saturation at middle altitude and decline further (Baniya *et al*., 2010; Bhattarai *et al*., 2014). However, highest species richness in Nepal has been reported in 1500 to 2500 m (Grytnes and Vetaas 2002).

5.2. Community attributes

The IVI of *S. robusta* was highest in all three investigation sites. The plant species with high IVI value represents its' dominance in the forest, success to grow, higher ecological adaptation to the particular environment and a good potential of regeneration (Shameem and Kangroo, 2011). Moreover, according to the DD curve and IVI, all three sites were found to be dominanted by *S. robusta*. Age of the forest, disturbances, management practices of the community group, available resources and associate species are the main factors which affects the growth and development of Sal (Mandal and Joshi, 2014). *T. alata* had the second highest IVI in forest of low altitudinal range. Similar results were obtained by DFRS (2014) carried out the Tarai Forest Inventory and recorded highest IVI of *S. robusta* followed by *T. alata.*

In the present study highest tree density was recorded in high altitudinal range lowest in low and intermediate in middle altitudinal range. Higher value was recorded by previous authors (Basyal, 2005; Duwadee *et al*., 2006). The tree density ranging from 550-1100 pl ha^{-1} is normally found in the tropical forests (Saxena, 1979). However, the tree density of high altitudinal range forest was above this range and the tree density of middle altitude forest was in upper limit of this range. Nonetheless, the tree density of low altitudinal range forest followed the normal trend of tropical forest. Higher density of tree in high altitude forest was observed due to the presence of large number of young trees with the small girth (poles) and reflecting a good regeneration (Basyal *et al*., 2011). The variation in tree density may be due to the anthropogenic activities, natural calamities and soil properties (Naidu and Kumar, 2016).

5.3. Size-class distribution

The density of trees in low altitudinal range forest was higher (476.6 tree ha^{-1}) in the DBH category of 10-20 cm followed by 20-30 cm (155.9 tree ha^{-1}). However, two trees per hectare were recorded with the DBH ranging 90-100 cm. In middle altitude forest, the highest density was presented in the DBH category of 20-30 cm (420.2 tree ha^{-1}) followed by 10-20 cm (372.6 tree ha^{-1}). However, 17.1 tree ha^{-1} were recorded in the DBH category of 50-80cm. Moreover, high altitudinal range forest also showed the similar pattern like low and middle altitudinal range. The Density-Diameter curve did not show an inverse J shaped curve but rather showed an interrupted pattern of curve. This pattern was similar to Sharma *et al.* (2020) in *S. robusta* forest of Baglung, Nepal. The deviation of Density-Diameter curve from an inverse J shape shows the sign of disturbance (Timilsina *et al.*, 2007) as seen in the present study. The higher density of trees in all three forests between the DBH ranging 5-30 cm shows the regenerating forest. Moreover, some trees ranging the DBH between 70-100 cm in low altitudinal range showed the maturity of forest before some period of time. Therefore, some calamities, disturbance or anthropogenic activities might have occurred and regeneration of forest had started. The status of middle and high altitudinal range forests also reflected the regenerating forest after some anthropogenic or natural disturbance.

5.4. Carbon stock

5.4.1. Tree and soil carbon stock in *S. robusta* forests

The mean total tree carbon stock in the present investigation ranged from 134 – 372 t ha^{-1}. The tree carbon stock was highest in lower altitudinal range forest, followed by middle and high altitudinal range. The mean total tree carbon stock estimated in the present study of eastern Nepal was higher than the previous investigations done in the *S. robusta* forests of Nepal (Baral *et al.,* 2009; Neupane and Sharma, 2014; Thapa-Magar and Shrestha, 2015; Banik *et al.,* 2018; Bhatta and Devkota, 2020; Godar, 2021). Godar (2021) reported higher (280 t ha^{-1}) value of tree carbon stock from Butwal area (Altitude about 800 m) of central Nepal compared to high altitudinal range of the present study, Moreover, Pandey *et al.* (2014) have reported 345.1 t ha^{-1} which was also similar to the carbon estimated in the present study of low altitudinal range. However, Aryal *et al.* (2017) have recorded 704 t ha^{-1} in burned forest of *Pinus roxburghii* forest of Langtang National Park, central Nepal, which was very high compared to the present investigation. The average carbon stock in the present study was lower in comparison to the tropical deciduous forest, India (Behera *et al.* 2017). Low value of tree carbon stock might be due to disturbances such as illegal logging, cattle grazing, fire, leaf collection, human encroachment etc. However, the carbon stock in the present study was higher than that of previous studies (Baishya *et al.* 2009; Singh, 2010; Rabha, 2014; Shahid and Joshi, 2015) carried out in S. *robusta* forest in different area of India. Several factors like DBH measurement, size of the plot, biomass estimation, belowground carbon estimation, site comparison and total estimation of the total carbon stock in trees like branches, twigs and leaves affect the quantity of carbon stock in forest (Saner *et al*., 2012). This may result in the slightly variation in estimation of carbon stock even in the same forest with different methodology. Some of the reasons among them might be the reason for higher carbon stock in the present study. The carbon stock was highest in lower altitudinal range forest, followed by middle and high altitude. The potential of forests to sequester and store carbon is not limited to a sole factor (Bhatta and Devkota, 2020). Various factors such as density of trees, size of trees, the decomposition of biomass, age of forest, degree of disturbances and the type of forest affect the carbon stored in the forest (Dixon *et al*., 1994; Brown *et al*., 1989; Bhatta, 2016).

The present study recorded higher soil carbon stock in high altitudinal range forest which was in agreement with the study of Pandey and Bhusal (2016). Soil organic carbon is highly dependent upon bulk density, depth of soil layer and amount of carbon present in soil (Chhabra *et al.*, 2003). Soil depth was constant for every soil samples in the present investigation. Therefore, bulk density and organic carbon played crucial role to define the variation of carbon stock along the altitudinal gradient. Though, bulk density was less in high altitudinal range forest, it stored maximum carbon due to the presence of higher amount of organic carbon in the soil. The decomposition and turnover rate of organic matter in high altitude is very slow due to low temperature and water precipitation (Bhattarai and Mandal, 2016). This might be the reason of higher carbon stock in soil in higher altitudinal range forest.

5.4.2. Variation of tree carbon stock with different factors

The tree carbon stock was negatively correlated with an altitude at significant level at $P < 0.001$. The highest carbon stock in low altitudinal range forest may be due to the high temperature and rainfall compared to high altitude. Organic matter had a positive correlation with an altitude. Relatively low organic matter content in soil may indicate the higher uptake of those nutrients inside the plant body which might have also resulted in the higher biomass and carbon stock within it. This view was also supported by Bhattarai and Mandal (2016), where they indicate the higher amount of carbon in soil due to the lower net uptake and mineralization of carbon. The reverse mechanism might have occurred in the middle and high altitudinal ranges. The decomposition rate of organic matter in hill Sal forest is very low (Bhatarai and Mandal, 2016). The temperature and rainfall in high and middle altitude was less compared to low altitude. Therefore, the decomposition and turnover rate of organic matter in high and middle altitudinal range may be very less which could be another reason for higher carbon stock in low altitudinal range forest. Moreover, the present study showed a positive relation between, carbon stock and pH, which was supported by Pathak and Baniya (2017). According to the Spearman correlation, the carbon stock was positively related to potassium content. Phosphorous and moisture content in soil did not show any relationship with the carbon stock.

The carbon stock in the investigation was positively and negatively correlated to basal area and density of trees respectively. Higher density of trees result competition for nutrition and light which affects the growth and development of all size trees (Coomes and Allen, 2007). Therefore, the site with higher density may have resulted in poorly developed trees with low biomass and vice-versa. The potential to sequester carbon and store it as biomass increases with the age of forest (Bhatta, 2016) and the young aged forest store less carbon in compared to mature forest (Behera *et al*., 2017). The present investigation reported the higher carbon stock with the increase in basal area and decrease in density. However, some researchers have reported the prominent role of tree density on biomass (Mbaabu *et al*., 2014; Thapa-Magar and Shrestha, 2015; Dangal *et al.,* 2017).

S. robusta contributed the higher tree carbon stock in all three altitudinal ranges. The highest density, basal area and IVI of *S robusta* among all the trees in the study areas resulted in monodominancy of *S robusta* and resulted to higher carbon stock. The present result was supported by Bhatta (2016).

5.5. Regeneration of *Shorea robusta*

5.5.1. Regeneration status of *Shorea robusta*

A good number of seedling and sapling in the forest shows the sustainability and reflects a character of healthy forest. The number of seedlings > 5000 and saplings > 2000 per hectare is regarded as a very suitable number for the replacement of old *S. robusta* trees by new ones (Pandey *et al.*, 2012). The average number of seedlings (37827.1 pl ha^{-1}) in the present investigation was higher than previous studies (Giri *et al*; 1999; Shrestha, 2009; Acharya and Shrestha, 2011; Basyal *et al*., 2011; Poudyal, 2013; Napit, 2015; Bhatta, 2016; Malla and Acharya, 2018). However, the present study recorded less average number of seedlings in comparison to the previous studies (Kandel, 2007; Timilsina *et al*., 2007; Poudel and Devkota, 2021). However, the number of saplings reflect a very poor regeneration in low and middle altitude and satisfactory in higher altitude. The satisfactory number of saplings in high altitudinal range forest ensures the composition of future vegetation (Swaine and Hall, 1988). The higher density of trees with smaller girth also represents a good regeneration of high altitudinal range (Basyal *et al*., 2011). The average number of saplings (872.7 pl ha^{-1}) in the present investigation was higher than some investigations (Giri *et al*., 1999; Bhatta, 2006; Napit, 2015) and lower than the previous studies (Kandel, 2007; Timilsina *et al*., 2007; Basyal *et al*., 2011; Awasthi *et al*., 2015). A poor number of saplings in low and middle altitudinal range forest might be due to the higher intensity of grazing of livestock, looping, fodder and firewood collection and short distance from the settlement. A low density of saplings in low and middle altitude might be due to the failure of development of seedlings. All the seedlings might not have been able to tolerate the harsh environmental condition and compete with the herbaceous flora (Basyal *et al*., 2011). The regeneration pattern of Sal in Nepalese forests show different pattern (Bhatta, 2016). This may be due to some of the reasons among variation in altitude, precipitation, temperature, soil nutrients, disturbances, crown cover, forest type, topography, and management strategies (Gautam and Devoe, 2006). Higher altitudinal range forest showed the reverse J shaped curve regarding regeneration of Sal which is known to have stable population and a good regeneration pattern (Geldenhuys, 1993; Vetaas, 2000). However, low and middle altitudinal range forests showed L shaped curve, which reflected poor regeneration.

According to Pandey *et al.* (2012) and regeneration curve of forests, the regeneration status of high altitudinal range forest was in a better condition. However, the regeneration of low and middle altitudinal range forests cannot be considered at a good condition due to very low number of saplings. According to the density trees, it is sure that community had played an enormous role to protect the forests after it had been handovered to it. They have protected the trees of forest from cutting and also may be from illegal trade. However, they have failed to establish the seedlings to the phase saplings.

5.5.2. Variation of regeneration of *S. robusta* with different factors

Seed generation and seedling establishment is very necessary for a better regeneration. The number of seedlings was positively correlated with pH. A low pH condition favors the growth of seedlings and higher pH is considered to have a poor regeneration of Sal (Souheimo, 1995; Paudel and Sah, 2003). Therefore, the pH range (4.89-5.27) might have supported the growth of seedlings in the study areas. However, the number of saplings was insignificant and did not have any relation with pH. The soil with pH range of 4.5-5.5 is considered as a best condition for sapling growth (Paudel and Sah, 2003). Though the pH of the study areas ranged from 4.89 - 5.27, the numbers of sapling were poorly recorded in low and middle altitudinal range forests. Grazing of livestock, collection of fodder and short distance from settlement area may be the reason of poor number of saplings in these two study areas. However, the number of saplings in high altitudinal range forest was satisfactory (Pandey *et al*., 2012).

Nitrogen content and organic matter were negatively correlated to the number of seedlings. The proportion of N and OM in low and middle altitude was very low in comparison to high altitudinal range forest. This might have resulted in the higher number of seedlings in low altitudinal range forest. The present evidence was also in agreement with Bhatnagar (1965), where N and OM content were negatively correlated with the number of seedlings. The number of seedlings was negatively correlated to crown cover. *Shorea robusta* is considered as a light demanding species (Sapkota *et al*., 2009). Higher percentage of crown cover blocks the rays of light to reach the ground level. Therefore, the less crown cover facilitates the seedlings of Sal to receive more sunlight and trigger their growth and development. The maximum rays of light increase the ground temperature and also the rate of photosynthesis in seedlings (Sapkota *et al.*, 2009). Moreover, a better growth of root and shoot has been observed in open space area (Troup, 1986). The present result was supported by Troup (1986), Shrestha (1992), Sapkota and Oden (2009) and Awasthi *et al*. (2015). However, the number of saplings did not show any relationship with the crown cover. In contrast to it, Baral and Ghimire (2020) have reported a higher density of saplings in the open canopy. Seedlings may require higher light intensity for their growth and saplings may not have such requirements. Nonetheless, disturbances and grazing may also be the reasons for low density of saplings in the investigation.

Statistically, disturbance was positively correlated to the number of seedlings. The moderate disturbance enhances the advance regeneration of Sal seedlings and also affects their dispersion pattern (Sapkota *et al*., 2009). This moderate disturbance in low altitudinal range forest may be the reason of higher occurrence of seedlings. However, high disturbance might affect adversely to the number of seedlings resulting to a poor regeneration.

The density of seedlings had a positive relation with the altitudes. The variation in altitude brings a change in microclimate, temperature, rainfall and moisture (Chang *et al*., 2016). Lower elevation favored the number and growth of seedlings of Sal which may be due to the combined effect of higher temperature, higher rainfall, higher turnover of soil nutrients which results the lower nutrient in soil and moderate density. Moreover, loamy soil was very favorable for the growth of seedlings compared to silty loamy and sandy loamy. Gupta (1961) has also reported a better Sal regeneration in loamy texture of soil.

5.6. Edaphic and other selected factors

OM and N content in the study areas ranged from 1.79 to 4.11% and 0.08 to 0.2% respectively. OM and N were positively related with each other. OM and N content were positively associated with an altitude. Similar trend was observed in the study of Li *et al.* (2013b), Ram *et al.* (2015) and Bhattarai and Mandal (2016). Higher turnover and uptake of nutrients result in the low organic matter and nitrogen content in soil of Terai Sal forest (Bhattarai and Mandal, 2016). The decomposition rate of organic matter and nitrogen in hill Sal forest is very low (Bhattarai and Mandal, 2016), resulting in slow net uptake of nutrients. The fact that the Hill Sal forest has a larger quantity of soil organic matter storage might be related to lower soil temperature and moisture, which slows the breakdown of organic matter (Griffiths *et al.*, 2009). A similar slow rate of mineralization of nitrogen in Hill Sal forest results the higher availability of nitrogen content in soil (Bhattarai and Mandal, 2016). However, OM and N content was lowest in middle altitude forest. A high amount of moisture, higher temperature and sufficient rainfall in middle altitude may be the reasons higher decomposition rate and high turnover resulting to low OM and N in the soil. However, OM and N content recorded in the present study were very low in comparison to Ram *et al*. (2015), and closely similar to Bhattarai and Mandal (2012) and Poudel and Devkota, (2021). However, OM and N content was higher than the investigation of K.C *et al.* (2013). The N content ranging from 0.07 – 0.15% is considered as a good N content in the soil (NARC, 2012). N content in the present study is in a good condition according to the data provided by NARC (2012).

Phosphorous (P) content was similar in the forests of low and high altitude. P content did not have any relation with an altitude. Ram *et al*. (2015) have also reported no impact of altitude on P content. However, lower amount P in middle altitude forest might be due to the higher consumption of P by trees and other plants. It also may be due to the formation of aluminium phosphate and iron (Donahue, 1970). The P content in soil was higher than that of Paudel and Sah (2003), K.C *et al.* (2013), Ram *et al*. (2015). The value of Phosphorus is very high in the present investigation because NARC (2012) had mentioned good phosphorus content above 30 kg ha^{-1}. Among the studied factors in the investigation, phosphorus was not affected significantly by any of them. However, pH and disturbances showed slightly positive relationship with phosphorus.

Potassium (K) content in the soil was higher in low and middle altitudinal range and lower in high altitudinal range forest. It ranged from 125 – 209 kg ha^{-1}. Moreover, K content had a negative relation with an altitude. Potassium had a negative relationship with OM, N, P content and altitude. Similar trend for phosphorus and potassium was also reported by Richards and Wadleigh (1952) and Ram *et al.* (2015). Potassium content was very low in the study of Steiner *et al.* (2007) and K.C. *et al*. (2013) which was reported to be 0.3 – 2.8 kg ha^{-1} and 2.5 – 4.23 kg ha^{-1} respectively.

Crown cover was highest in middle altitudinal range and lowest in high altitudinal range. Moreover, moisture content was also highest in middle altitudinal range forest. There was no significant difference between the moisture content of low and high altitude forests. Moisture content was positively related to the crown cover. Moreover, high percentage of crown cover blocks the sun rays and does not let easily to reach the ground surface which causes the moisture to be preserved in the soil. Moreover, silty loamy texture of soil in middle altitude range forest might have helped to bind more water molecules within it due to the large specific area (Brady and Weil, 2013) compared to sandy loamy in high altitude forest. The large specific area helps to bind more water molecules and other molecules (Brady and Weil, 2013). This may the reasons of high moisture content in middle altitudinal range. However, lower moisture in low altitudinal range forest may be due to the exposure of high temperature. Bhattarai (2016) has reported that the soil of Tarai Sal forest experiences a very high temperature in comparison to high altitude forest. Soil texture is the main factor for the movement of air, water and nutrients through it (Bhattarai and Mandal, 2016). Lower moisture content in hill forest may be due to the soil texture and slope. The slope was very high in hill Sal forest which increased the runoff rate of water. Moreover, sandy loamy texture may have helped penetration of water molecules to go deep level of soil and high moisture content was not seen within the depth of 30 cm. The moisture content in the present study was higher than the study of Gautam and Mandal (2013) which was just 8.2%. Low moisture content in their study might be due to the collection of soil in May. In Tarai region of Nepal, May is the month where the winter dry season has just come to an end. In the present study area climate data showed less than 200 mm rainfall was recorded in May. Therefore, one of the effects or combined effect of below and above soil temperature, precipitation, soil texture and slope of the land may the reason for the variation in the moisture in the forests' soil.

Bulk density in the study areas ranged from (1.26 - 1.35 g cm^{-3}). Bulk density was negatively correlated to an altitude which was also supported by Bhattarai and Mandal (2016). They reported the higher bulk density in Tarai Sal forest and lower in Hill Sal forest. The bulk density was close to the data reported by Gautam and Mandal (2013). Bhattari and Mandal (2016) have reported the bulk density of Sal forest in Jhapa to be 1.3-1.44 g cm^{-3}which was close to our study. However, hill Sal forest of Ilam had a low bulk density (1.03-1.13 g cm^{-3}) compared to the present investigation. Relatively higher and lower bulk density in low and high altitudinal range forests may be due to the presence of low and high percentage of organic matter respectively. A high percentage of organic matter results in the higher pore space which leads to low bulk density and vice versa (Bhattarai and Mandal, 2016).

The soil texture found in low, middle and high altitudinal range forests was loamy, silty loamy and sandy loamy respectively. Sandy loamy soil was described previously by Shrestha (1997) and Bhattarai and Mandal (2012) in mixed Sal forest and Tarai Sal forest respectively. The sandy loamy structure is common in Terai and tropical region and supports a healthy Sal forest (Shah, 1997).

The pH of all three forests was acidic in nature. However, the soil of low altitudinal range forest was less acidic than middle and high altitudinal range. Moreover, pH was negatively correlated to altitude in the present investigation. The pH range in the present study was more acidic than the pH range reported by Bhattarai and Mandal (2012) in Sal forest at an altitude of 62 m asl. However, the pH range of the present study is higher than that of Ram *et al.* (2015) which was carried out in Shivapuri Nagarjun National Park (1366 – 2732 m asl). The pH range (4.89 – 5.27) of the present study was relatively less compared to the pH (5.02-5.22) reported by Poudel and Devkota (2021) in Sal forest at an altitudinal range of 425 – 986 m asl. The pH trend in these literatures also shows the negative relation between the altitude and pH. Ram *et al.* (2015) have also reported in their study that the pH decreased with increasing altitude in both rainy and summer season. Some bacteria may also be responsible for higher acidic soil which produces carbon di-oxide, humic acids and other inorganic acids (Ram *et al.,* 2015). The availability of the nutrients was seen to be governed by pH in the present study which was also supported by Gaire (2003).

The overall variation in physical and chemical properties of soils may be due to the management practices (Chimdi *et al*., 2012), variation in rainfall and temperature, type of vegetation and microbial activities. The variation in physico-chemical properties of soil had been observed along an altitudinal gradient in the present study. Temperature, rainfall, and microclimates are all affected by changes in altitude (Chang *et al*., 2016). Moreover, variation in climate, temperature, rainfall and microclimate result in the formation of different kinds of microorganisms, which may be other reason for variation in soil physico-chemical properties along an altitudinal gradient (Bhattarai and Mandal, 2016). Burns *et al.* (1982) have also reported that the physico-hemical features of soils are intimately linked to altitudinal variation. Soil texture also plays a prominent role in availability of nutrients and their cycling (Robertson and Vitousek, 1981). This is because it plays a major role in the supply of air, water and nutrients (Bhattarai and Mandal, 2016).

6. Conclusion and recommendation

6.1. Conclusion

- The forests were dominated by *S. robusta* in all three altitudinal ranges. High altitudinal range *S. robusta* forest was more diverse in compared to low and mid altitudinal range forest.

- Tree species were distributed accordingly with respect to altitude, moisture, pH and phosphorus content.

- *S. robusta* had the highest IVI and density in all three sites.

- The value of estimated carbon stock varied between the forests. *S. robusta* made the highest proportion of carbon stock among the tree species in all altitudinal ranges.

- The carbon stock in the forests was affected by different factors. Potassium content and pH were positively correlated to the carbon stocks. However, organic matter, nitrogen content and altitude had a negative relation with carbon stock.

- The regeneration status of seedlings and trees of *S. robusta* in all three altitudinal ranges was good. However, it was very poor in terms of saplings in low and middle ranges.

- The density of saplings, seedlings and trees were significantly different among three different altitudinal ranges.

- The density of seedlings were negatively correlated with altitude.

- The density of saplings and trees were positively correlated with altitude.

6.2. Recommendation

- Regeneration of *S. robusta* is very crucial in all three altitudinal range for high potential of carbon stock and sustainable life too. Community forest user groups have failed to develop saplings from seedlings, which is very necessary for sustainable forest and seems a great problem in lower and middle altitudinal ranges. In lower and middle altitudinal ranges, grazing, firewood collection, looping and human encroachments had caused destruction of saplings ultimately affecting the tree density. Moreover, it can negatively affect in potential of carbon sequestration by the forests. Therefore, the community forest user groups should control such anthropogenic disturbances and should make a proper management plans to establish seedlings to sapling phase.

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Annexes

Annex 1. Referenced literatures were used for the standard tree density of the particular tree species

Tree species	**References**
Adina cordifolia (Roxb.) Brandis	Jackson (1994)
Albizia lebbeck (L.) Benth.	Jackson (1994)
Albizia lucidior (Steud.) I.C.Nielson ex H.Hara	Reyes *et al*. (1992)
Albizia odoratissima (L.f.) Benth.	Reyes *et al*. (1992)
Albizia sp.	Reyes *et al*. (1992)
Alnus nepalensis D.Don	Jackson (1994)
Bombax ceiba L.	Jackson (1994)
Casearia graveolens Dalzell	Reyes *et al*. (1992)
Cassia fistula L.	Jackson (1994)
Castanopsis indica (Roxb. ex Lindl.) A.DC.	Jackson (1994)
Dalbergia sissoo Roxb. ex DC.	Jackson (1994)
Dillenia pentagyna Roxb.	Reyes *et al*. (1992)
Elaeocarpus angustifolius Blume	Jackson (1994)
Falconeria insignis Royle	Reyes *et al*. (1992)
Ficus benghalensis L.	Reyes *et al*. (1992)
Ficus semicordata Buch.-Ham. ex J.E.Sm.	Reyes *et al*. (1992)
Heynea trijuga Roxb.	Reyes *et al*. (1992)
Lagerstroemia parviflora Roxb.	Jackson (1994)
Lannea coromandelica (Houtt.) Merr.	Reyes *et al*. (1992)
Litsea monopetala (Roxb. ex Baker) Pers.	Jackson (1994)
Lyonia ovalifolia (Wall.) Drude	Karki *et al.* (2016)
Machilus odoratissima (Nees) Kosterm.	Karki *et al.* (2016)
Madhuca longifolia (J.Koenig ex L.) J.F.Macbr.	Reyes *et al*. (1992)
Mallotus philippensis (Lam.) Mull.Arg	Reyes *et al*. (1992)
Mangifera indica L.	Reyes *et al*. (1992)

Neolamarckia cadamba (Roxb.) Bosser	Jackson (1994)
Phyllanthus emblica L.	Jackson (1994)
Pyrus pyrifolia (Burm.fil.) Nakai	Karki *et al.* (2016)
Rhus chinensis Mill.	Karki *et al.* (2016)
Schima wallichi (DC.) Korth.	Jackson (1994)
Schleichera oleosa (Lour.) Oken	Reyes *et al.* (1992)
Semecarpus anacardium L.fil.	Reyes *et al.* (1992)
Senegalia catechu (L.f.) P.J.H.Hurter and Mabb.	Jackson (1994)
Shorea robusta Gaertn.	Jackson (1994)
Syzygium cumini (L.) Skeels	Jackson (1994)
Syzygium nervosum DC.	Reyes *et al.* (1992)
Tectona grandis L.f.	Jackson (1994)
Terminalia alata B.Heyne ex Roth	Jackson (1994)
Terminalia anogeissiana Gere and Boatwr.	Jackson (1994)
Terminalia bellirica (Gaertn.) Roxb.	Jackson (1994)
Terminalia chebula Retz.	Jackson (1994)
Toona ciliata M.Roem.	Jackson (1994)
Zanthoxylum sp.	Carsan *et al.* (2012)

Annex 2. Plant species of low altitudinal range forest with the analysis of community attributes like basal area (B), relative basal area (RB), frequency (F), relative frequency (RF), density (D), relative density (RD) and important value index (IVI).

Tree species	**B (m^2 ha^{-1})**	**RB**	**F (%)**	**RF**	**D (pl ha^{-1})**	**RD**	**IVI**
Adina cordifolia	0.881333	1.714289	3.3	1.323176	2.166472	0.260415	3.29788
Albizia lucidior	1.5	2.917664	10	4.009623	6.499415	0.781245	7.708532
Dillenia pentagyna	0.133333	0.259348	3.3	1.323176	2.166472	0.260415	1.842939
Falconeria insignis	0.645333	1.255244	10	4.009623	12.99883	1.562491	6.827358
Lagerstroemia parviflora	0.164333	0.319646	3.3	1.323176	2.166472	0.260415	1.903237
Lannea	0.176333	0.342988	3.3		2.166472	0.260415	1.926578

coromandelica							
Mallotus phillipensis	0.089667	0.174411	3.3	1.323176	2.166472	0.260415	1.758002
Mangifera indica	0.133333	0.259348	3.3	1.323176	2.166472	0.260415	1.842939
Phyllanthus emblica	0.102	0.198401	3.3	1.323176	4.332943	0.52083	2.042407
Schleichera oleosa	0.2348	0.456712	6.6	2.646351	6.499415	0.781245	3.884308
Shorea robusta	35.06267	68.20071	96.6	38.73296	593.6132	71.35375	178.2874
Syzygium cumini	0.220333	0.428572	3.3	1.323176	2.166472	0.260415	2.012163
Syzygium nervosum	0.077667	0.15107	3.3	1.323176	2.166472	0.260415	1.734661
Terminalia alata	7.937967	15.44021	70	28.06736	171.1513	20.5728	64.08037
Terminalia anogeissiana	2.325333	4.523027	16.6	6.655974	12.99883	1.562491	12.74149
Terminalia bellirica	1.603667	3.119307	6.6	2.646351	4.332943	0.52083	6.286488
Terminalia chebula	0.123	0.239248	3.3	1.323176	2.166472	0.260415	1.822839

Annex 3. Plant species of middle altitudinal range forest with the analysis of community attributes like basal area (B), relative basal area (RB), frequency (F), relative frequency (RF), density (D), relative density (RD) and important value index (IVI).

Tree species	**B (m^2 ha^{-1})**	**RB**	**F (%)**	**RF**	**D (pl ha^{-1})**	**RD**	**IVI**
Albizia lebbeck	0.090233	0.221196	6.6	2.204409	4.332	0.381674	2.807279
Albizia odoratissima	0.011167	0.027374	6.6	2.204409	4.332	0.381674	2.613457
Albizia sp.	0.095567	0.23427	20	6.680027	28.158	2.480881	9.395178
Casearia graveolens	0.0173	0.042409	6.6	2.204409	4.332	0.381674	2.628492
Cassia fistula	0.182867	0.448276	10	3.340013	6.498	0.572511	4.3608
Falconeria insignis	0.0379	0.092907	13.3	4.442218	8.664	0.763348	5.298473

Ficus benghalensis	0.798	1.956202	3.3	1.102204	2.166	0.190837	3.249243
Heynea trijuga	0.040533	0.099363	13.3	4.442218	12.996	1.145022	5.686602
Machilus odoratissima	0.178333	0.437163	3.3	1.102204	2.166	0.190837	1.730204
Neolamarckia cadamba	0.478	1.17176	6.6	2.204409	4.332	0.381674	3.757843
Schima wallichi	5.478	13.42866	70	23.38009	93.138	8.205991	45.01475
Semecarpus anacardium	1.327933	3.25527	16.6	5.544422	10.83	0.954185	9.753878
Shorea robusta	30.6865	75.2243	100	33.40013	937.878	82.63242	191.2569
Syzygium cumini	0.2994	0.733943	10	3.340013	6.498	0.572511	4.646468
Tectona grandis	0.017533	0.042981	6.6	2.204409	4.332	0.381674	2.629064
Terminalia alata	0.020567	0.050417	3.3	1.102204	2.166	0.190837	1.343458
Terminalia bellirica	1.034667	2.536362	3.3	1.102204	2.166	0.190837	3.829404

Annex 4. Plant species of high altitudinal range forest with the analysis of community attributes like basal area (B), relative basal area (RB), frequency (F), relative frequency (RF), density (D), relative density (RD) and important value index (IVI).

Tree species	**B (m^2 ha^{-1})**	**RB**	**F (%)**	**RF**	**D (pl ha^{-1})**	**RD**	**IVI**
Adina cordifolia	0.718067	2.000186	10	2.387205	6.4992	0.348427	4.735817
Albizia lebbeck	0.004233	0.011792	3.3	0.787778	2.1664	0.116142	0.915712
Albizia sp.	0.1366	0.380501	13.3	3.174982	15.1648	0.812995	4.368479
Alnus nepalensis	0.035567	0.099071	3.3	0.787778	4.3328	0.232284	1.119133
Bombax ceiba	0.277333	0.772516	10	2.387205	6.4992	0.348427	3.508147
Casearia graveolens	0.1519	0.42312	33.3	7.949391	34.6624	1.858275	10.23079
Cassia fistula	0.1529	0.425905	13.3	3.174982	12.9984	0.696853	4.29774
Castanopsis indica	0.332433	0.925998	16.6	3.96276	21.664	1.161422	6.05018
Dalbergia sissoo	0.0576	0.160446	10	2.387205	6.4992	0.348427	2.896077
Elaeocarpus	0.0715	0.199164	6.6	1.575555	4.3328	0.232284	2.007004

angustifolius							
Falconeria insignis	0.007167	0.019963	3.3	0.787778	2.1664	0.116142	0.923883
Ficus semicordata	0.007167	0.019963	3.3	0.787778	2.1664	0.116142	0.923883
Lagerstroemia parviflora	0.1637	0.455989	10	2.387205	10.832	0.580711	3.423904
Litsea monopetala	0.0057	0.015877	3.3	0.787778	2.1664	0.116142	0.919797
Lyonia ovalifolia	0.016	0.044568	3.3	0.787778	2.1664	0.116142	0.948488
Madhuca longifolia	0.204633	0.570009	6.6	1.575555	4.3328	0.232284	2.377849
Mallotus phillipensis	0.0577	0.160724	6.6	1.575555	15.1648	0.812995	2.549274
Mangifera indica	0.010333	0.028784	3.3	0.787778	2.1664	0.116142	0.932703
Pyrus pyrifolia	0.0463	0.128969	3.3	0.787778	2.1664	0.116142	1.032889
Rhus chinensis	0.005333	0.014856	3.3	0.787778	2.1664	0.116142	0.918776
Schima wallichi	4.62	12.86908	56.6	13.51158	121.3184	6.503962	32.88462
Semecarpus anacardium	0.616333	1.716806	16.6	3.96276	12.9984	0.696853	6.376419
Senegalia catechu	0.124067	0.34559	6.6	1.575555	6.4992	0.348427	2.269571
Shorea robusta	27.04163	75.32488	96.6	23.0604	1490.53	79.90833	178.2936
Syzygium cumini	0.433033	1.206221	33.3	7.949391	25.9968	1.393706	10.54932
Terminalia alata	0.073367	0.204364	13.3	3.174982	10.832	0.580711	3.960057
Terminalia anogeissiana	0.272733	0.759703	23.3	5.562187	28.1632	1.509848	7.831738
Toona ciliate	0.056	0.155989	3.3	0.787778	4.3328	0.232284	1.176051
Zanthoxylum sp.	0.203033	0.565552	3.3	0.787778	4.3328	0.232284	1.585614

Annex 5. Tree carbon stock in low altitudinal range

Tree species	**Carbon stock (t ha^{-1})**
Adina cordifolia	5.154862
Albizia lucidior	7.158328
Dillenia pentagyna	0.296729

Falconeria insignis	4.158545
Lagerstroemia parviflora	0.70392
Lannea coromandelica	0.346545
Mallotus philippensis	0.357375
Mangifera indica	0.205761
Phyllanthus emblica	0.595625
Schleichera oleosa	1.613602
Shorea robusta	266.645
Syzygium cumini	0.790557
Syzygium nervosum	0.119125
Terminalia alata	61.20858
Terminalia anogeissiana	13.27702
Terminalia bellirica	5.653021
Terminalia chebula	3.8

Annex 6. Tree carbon stock in middle altitudinal range

Tree species	**Carbon stock (t ha^{-1})**
Albizia sp.	0.120208
Albizia lebbeck	0.283734
Albizia odoratissima	0.008664
Cassia fistula	1.216158
Casearia graveolens	0.011912
Falconeria insignis	0.024908
Ficus benghalensis	1.516136
Heynea trijuga	0.030323
Machilus odoratissima	0.855534
Neolamarckia cadamba	2.40849
Schima wallichi	18.2781
Semecarpus anacardium	3.635478
Shorea robusta	159.4314

Syzygium cumini	0.92376
Tectona grandis	0.01841
Terminalia alata	0.032489
Terminalia bellirica	3.476283

Annex 7. Tree carbon stock in high altitudinal range

Tree species	**Carbon stock (t ha^{-1})**
Adina cordifolia	2.234135
Albizia sp.	0.474334
Albizia lebbeck	0.002166
Alnus nepalensis	0.021659
Bombax ceiba	0.6671
Cassia fistula	0.481915
Casearia graveolens	0.159194
Castanopsis indica	0.676846
Dalbergia sissoo	0.064977
Elaeocarpus angustifolius	0.07689
Falconeria insignis	0.007581
Ficus semicordata	0.001083
Lagerstroemia parviflora	0.301061
Litsea monopetala	0.006498
Lyonia ovalifolia	0.01083
Madhuca longifolia	1.061295
Mallotus philippensis	0.064977
Mangifera indica	0.004332
Pyrus communis	0.054148
Rhus chinensis	0.003249
Schima wallichi	11.59627
Semecarpus anacardium	1.97964
Senegalia catechu	0.249079

Shorea robusta	110.2025
Syzygium cumini	1.632012
Terminalia alata	0.947585
Terminalia anogeissiana	0.439679
Toona ciliata	0.04765
Zanthoxylum sp.	0.71475

Annex 8. Physico-chemical properties of soil of low (RKCF), middle (PCF) and high altitudinal range forest (KMCF).

Site	OM (%)	N (%)	P (kg ha^{-1})	K (kg ha^{-1})	pH	Sand (%)	Silt (%)	Clay (%)
RKCF	1.19	0.06	14.5	235.8	5	30	40	30
RKCF	1.26	0.06	15.5	301.3	5.3	34	36	30
RKCF	2.36	0.12	12.5	265.6	5.2	42	40	18
RKCF	3.15	0.16	14.5	360.8	5.3	42	36	22
RKCF	2.84	0.14	15.5	229.8	5.4	42	34	24
RKCF	2.91	0.15	18.6	277.5	5.5	40	42	18
RKCF	1.88	0.09	30.7	200.1	5.3	42	48	10
RKCF	1.71	0.09	22.6	206.0	5.3	38	48	14
RKCF	1.60	0.08	15.5	164.4	5.1	48	42	10
RKCF	1.64	0.08	18.6	200.1	5.2	42	48	10
RKCF	2.26	0.11	16.5	188.2	5.1	28	48	24
RKCF	1.64	0.08	20.6	253.7	5.2	30	36	34
RKCF	2.36	0.12	25.7	182.2	5.2	42	44	14
RKCF	1.12	0.06	32.7	200.1	5.3	42	40	18
RKCF	1.81	0.09	28.7	200.1	5.5	34	54	12
RKCF	1.36	0.07	30.7	146.5	5.6	52	36	12
RKCF	2.12	0.11	15.5	164.4	5.4	38	44	18
RKCF	1.88	0.09	38.8	223.9	5.3	32	44	24
RKCF	1.46	0.07	28.7	170.3	5.4	34	50	16
RKCF	1.43	0.07	25.7	229.8	5	38	40	22
RKCF	1.88	0.09	18.6	206.0	5.1	54	38	8
RKCF	2.84	0.14	59.6	200.1	4.9	19.7	62	18.3
RKCF	2.53	0.13	11.5	247.7	5.1	27.7	62	10.3

RKCF	3.60	0.18	5.2	212.0	5.6	21.7	64	14.3
RKCF	3.36	0.17	12.5	229.8	5.4	35.7	52	12.3
RKCF	2.22	0.11	65.9	194.1	5.1	27.7	56	16.3
RKCF	3.26	0.16	3.1	325.1	5.5	25.7	60	14.3
RKCF	2.57	0.13	3.1	122.7	5.6	29.7	56	14.3
RKCF	1.40	0.07	3.1	69.1	5.1	11.7	68	20.3
RKCF	1.36	0.07	3.2	70.2	5.1	13.2	65	23.1
PCF	2.51	0.13	2.0	134.6	4.9	33.7	46	20.3
PCF	2.69	0.13	5.2	207.4	4.8	35.7	48	16.3
PCF	2.76	0.14	3.1	189.6	4.8	43.7	42	14.3
PCF	3.00	0.15	9.4	267.0	4.8	41.7	48	10.3
PCF	0.77	0.04	3.1	201.5	5	37.7	36	26.3
PCF	2.37	0.12	3.1	380.0	5.1	47.7	30	22.3
PCF	2.58	0.13	5.2	267.0	5	49.7	36	14.3
PCF	2.02	0.10	2.0	177.7	4.9	41.7	36	22.3
PCF	0.59	0.03	12.5	201.5	5.1	39.7	48	12.3
PCF	0.42	0.02	15.6	195.5	4.9	47.7	40	12.3
PCF	0.42	0.02	9.4	159.8	4.7	37.7	48	14.3
PCF	3.25	0.16	12.5	219.3	4.8	39.7	42	18.3
PCF	1.26	0.06	3.1	124.1	4.9	43.7	48	8.3
PCF	2.09	0.10	5.2	284.8	5.1	39.7	40	20.3
PCF	2.34	0.12	9.4	231.2	4.9	49.7	36	14.3
PCF	1.61	0.08	3.1	219.3	4.9	39.7	34	26.3
PCF	1.64	0.08	12.5	142.0	4.9	37.7	38	24.3
PCF	1.81	0.09	24.0	255.0	5	48	42	10
PCF	0.98	0.05	19.8	142.0	5.1	42	46	12
PCF	1.64	0.08	9.4	207.4	5	30	52	18
PCF	2.16	0.11	13.6	213.4	4.9	32	54	14
PCF	2.44	0.12	15.6	249.1	5	32	52	16
PCF	0.59	0.03	5.2	207.4	5.1	30	58	12
PCF	1.64	0.08	9.4	177.7	5	44	48	8
PCF	1.64	0.08	11.5	177.7	5	36	44	20
PCF	2.69	0.13	9.4	189.6	5.1	40	44	16
PCF	1.33	0.07	24.0	243.1	5.2	62	28	10
PCF	1.47	0.07	19.8	249.1	5.2	42	44	14
PCF	1.64	0.08	13.6	219.3	5.2	56	36	8
PCF	1.64	0.08	13.6	142.0	5.1	30	44	26

KMCF	4.79	0.24	20.6	81.9	4.7	64	28	8
KMCF	6.08	0.30	25.7	135.9	4.8	76	20	4
KMCF	5.62	0.28	17.6	99.9	4.6	68	24	8
KMCF	4.85	0.24	12.5	153.9	5	70	20	10
KMCF	2.07	0.10	15.5	51.9	4.9	78	16	6
KMCF	5.46	0.27	15.5	123.9	4.8	76	18	6
KMCF	3.77	0.19	12.5	153.9	4.7	74	16	10
KMCF	3.61	0.18	43.9	135.9	4.7	70	22	8
KMCF	3.92	0.20	12.5	123.9	4.8	68	24	8
KMCF	4.42	0.22	15.5	152.5	4.6	62	30	8
KMCF	3.61	0.18	12.5	122.7	4.4	68	22	10
KMCF	5.46	0.27	12.5	140.6	4.7	70	22	8
KMCF	4.14	0.21	15.5	146.5	4.9	74	18	8
KMCF	2.99	0.15	14.5	93.0	5	76	18	6
KMCF	4.29	0.21	15.5	110.8	5.2	76	20	4
KMCF	2.69	0.13	16.5	87.0	5.2	78	16	6
KMCF	3.18	0.16	18.6	87.0	5	78	16	6
KMCF	3.21	0.16	19.6	90.4	4.8	76	15	5
KMCF	5.09	0.25	20.6	146.5	4.9	78	18	4
KMCF	3.55	0.18	15.5	104.9	5	76	20	4
KMCF	5.31	0.27	15.5	170.3	5.3	74	20	6
KMCF	4.08	0.20	17.6	110.8	5.2	78	16	6
KMCF	2.19	0.11	96.5	93.0	5.3	68	24	8
KMCF	4.23	0.21	25.7	104.9	5.1	76	18	6
KMCF	3.30	0.17	15.5	247.7	5	74	20	6
KMCF	5.28	0.26	13.5	110.8	5	78	16	6
KMCF	2.99	0.15	14.5	63.2	4.6	68	24	8
KMCF	5.31	0.27	53.0	241.8	4.9	76	20	4
KMCF	4.50	0.22	24.6	128.7	4.8	70	24	6
KMCF	3.60	0.18	13.5	140.6	5	80	14	6

Annex 9. Bulk density and moisture of low altitudinal range forest

Plot	**Fresh weight (g)**	**Dry weight (g)**	**Moisture (g)**	**Moisture (%)**	**Bulk density (g cm^{-3})**
1	87	70	17	24.28571	1.346801

2	90	69	21	30.43478	1.327561
3	89	76	13	17.10526	1.462241
4	91	74	17	22.97297	1.423761
5	89	68	21	30.88235	1.308321
6	86	68	18	26.47059	1.308321
7	87	72	15	20.83333	1.385281
8	76	58	18	31.03448	1.115921
9	109	90	19	21.11111	1.731602
10	95	78	17	21.79487	1.500722
11	86	70	16	22.85714	1.346801
12	76	58	18	31.03448	1.115921
13	80	66	14	21.21212	1.269841
14	94	78	16	20.51282	1.500722
15	86	70	16	22.85714	1.346801
16	53	40	13	32.5	0.769601
17	87	66	21	31.81818	1.269841
18	87	66	21	31.81818	1.269841
19	84	66	18	27.27273	1.269841
20	75	62	13	20.96774	1.192881
21	82	76	6	7.894737	1.462241
22	78	66	12	18.18182	1.269841
23	92	76	16	21.05263	1.462241
24	94	79	15	18.98734	1.519962
25	88	76	12	15.78947	1.462241
26	74	64	10	15.625	1.231361
27	70	60	10	16.66667	1.154401
28	92	80	12	15	1.539202
29	90	84	6	7.142857	1.616162
30	91	85	6	7.058824	1.635402

Annex 10. Bulk density and moisture of middle altitudinal range forest

Plot	**Fresh weight**	**Dry weight**	**Moisture (g)**	**Moisture**	**Bulk density (g cm^{-3})**

	(g)	(g)		(%)	
1	91	72	19	26.38889	1.385281
2	95	80	15	18.75	1.539202
3	101	80	21	26.25	1.539202
4	93	76	17	22.36842	1.462241
5	102	90	12	13.33333	1.731602
6	86	72	14	19.44444	1.385281
7	104	84	20	23.80952	1.616162
8	68	55	13	23.63636	1.058201
9	100	82	18	21.95122	1.577682
10	77	64	13	20.3125	1.231361
11	82	68	14	20.58824	1.308321
12	88	68	20	29.41176	1.308321
13	95	82	13	15.85366	1.577682
14	80	68	12	17.64706	1.308321
15	87	72	15	20.83333	1.385281
16	92	80	12	15	1.539202
17	106	58	48	82.75862	1.115921
18	100	84	16	19.04762	1.616162
19	97	72	25	34.72222	1.385281
20	87	36	51	141.6667	0.692641
21	100	56	44	78.57143	1.077441
22	80	52	28	53.84615	1.000481
23	86	62	24	38.70968	1.192881
24	83	64	19	29.6875	1.231361
25	102	74	28	37.83784	1.423761
26	97	50	47	94	0.962001
27	83	58	25	43.10345	1.115921
28	108	76	32	42.10526	1.462241
29	83	64	19	29.6875	1.231361
30	92	78	14	17.94872	1.500722

Annex 11. Bulk density and moisture of high altitudinal range forest

Plot	Fresh weight (g)	Dry weight (g)	Moisture (g)	Moisture (%)	Bulk density(g cm^{-3})
1	84	62	22	35.48387	1.192881
2	75	48	27	56.25	0.923521
3	85	74	11	14.86486	1.423761
4	86	62	24	38.70968	1.192881
5	90	75	15	20	1.443001
6	73	46	27	58.69565	0.885041
7	92	68	24	35.29412	1.308321
8	85	68	17	25	1.308321
9	86	72	14	19.44444	1.385281
10	65	47	18	38.29787	0.904281
11	80	66	14	21.21212	1.269841
12	86	72	14	19.44444	1.385281
13	74	62	12	19.35484	1.192881
14	84	74	10	13.51351	1.423761
15	62	48	14	29.16667	0.923521
16	92	84	8	9.52381	1.616162
17	76	70	6	8.571429	1.346801
18	76	66	10	15.15152	1.269841
19	79	68	11	16.17647	1.308321
20	74	72	2	2.777778	1.385281
21	84	76	8	10.52632	1.462241
22	76	64	12	18.75	1.231361
23	79	68	11	16.17647	1.308321
24	81	68	13	19.11765	1.308321
25	73	60	13	21.66667	1.154401
26	83	68	15	22.05882	1.308321
27	65	48	17	35.41667	0.923521
28	91	76	15	19.73684	1.462241
29	79	68	11	16.17647	1.308321
30	83	78	5	6.410256	1.500722

Photo plates

Plate 1. Measuring tree DBH

Plate 2. Using clinometer to measure angle of inclination for tree height

Plate 3. Taking field notes

Plate 4. Making quadrat

Plate 5. Local people collecting firewood

Plate 6. Measuring bulk density

Plate 7. *Ficus semicordata*

Plate 8. Collecting soil samples

Plate 9. Field team with the forest authorities of PCF