EVALUATION OF PLANTATION TREE SPECIES FOR BIOMASS PRODUCTION AND NUTRIENT CYCLING IN WARM TEMPERATE NORTH WESTERN HIMALAYAS

Thesis

by

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CERTIFICATE - I

This is to certify that the thesis entitled **"Evaluation of plantation tree species for biomass production and nutrient cycling in warm temperate North Western Himalayas"** submitted in partial fulfillment of the requirements for the award of degree of **DOCTOR OF PHILOSOPHY (FORESTRY)** in the discipline of **SILVICULTURE** of Dr. Yashwant Singh Parmar University of Horticulture and Forestry (Nauni) Solan HP – 173230 India is a bonafide research work carried out by **Ms. Anuradha Thakur (F-2019-20-D)** daughter of **Shri Prithi Chand Thakur** under my guidance and supervision. No part of this thesis has been submitted for any other degree or diploma.

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

Place: Nauni, Solan
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CERTIFICATE-II

This is certified that the thesis titled **"Evaluation of plantation tree species for biomass production and nutrient cycling in warm temperate North Western Himalayas"** submitted by **Ms. Anuradha Thakur (F-2019-20-D)** daughter of **Shri Prithi Chand Thakur** to the Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan (Nauni) HP – 173 230 India in partial fulfilment of the requirement for the degree of **DOCTOR OF PHILOSOPHY (FORESTRY)** in the discipline of **SILVICULTURE** has been approved by Advisory Committee after the thesis viva-voice examination of the student in collaboration with an External Examiner.

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Place: Nauni, Solan
Dated: ...../..... **2024** **(Anuradha Thakur)**

CONTENTS

ABBREVIATIONS USED

%	:	Per cent
@	:	At the rate of
<	:	Less than
>	:	Greater than
°C	:	Degrees Celsius
µmol m^{-2} s^{-1}	:	Micro mole per second per square meter
AGB	:	Above ground biomass
ANOVA	:	Analysis of variance
BD	:	Bulk density
BGB	:	Below ground biomass
c mol (p+)	:	Centimol proton
CD	:	Critical Difference
CEC	:	Cation exchange capacity
cfu/g	:	colony-forming unit per gram
cm	:	Centimetre
cm^2	:	Centimetre square
CO_2	:	Carbon dioxide
CSP	:	Carbon sequestration potential
D	:	Depth
DBH	:	Diameter at Breast Height
dSm^{-1}	:	Deci Siemens per meter
EC	:	Electrical Conductivity
ESP	:	Exchangeable sodium percentage
et al.	:	Etalia (Co-workers)
FYM	:	Farm yard Manure
g	:	Gram
ha	:	Hectare
ha^{-1}	:	Per hectare
HWC	:	Hot water extractible carbon
i.e.,	:	*That is*
K	:	Potassium
Kg	:	Kilogram
LAI	:	Leaf Area Index

m	:	Meter
M	:	Management regimes
m asl	:	Meter above sea level
Mg	:	Megagrams
ml	:	Millilitres
mm	:	Millimeter
N	:	Nitrogen
NS	:	Non-Significant
OC	:	Organic Carbon
^{o}C	:	Degree Celsius
OM	:	Organic Matter
P	:	Phosphorus
PAR	:	Photosynthetically Active Radiation
PD	:	Particle Density
pH	:	Puissance d'Hydrogen
ppm	:	Parts per million
q	:	Quintal
q ha^{-1}	:	Quintal per hectare
SOC	:	Soil organic carbon
t	:	Tonnes
T	:	Treatment
t ha^{-1}	:	Tonnes per hectare
TB	:	Total biomass
UNFCCC	:	United Nations Framework Convention on Climate Change.
viz.	:	*Videlicet* (namely)
µm	:	Micro meter

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Chapter-1

INTRODUCTION

North western Himalaya represents a unique bio-region owing primarily to its varied topography and habitat heterogeneity along a wide elevation range. Warm temperate belt (1500-2500 m) in north western, western and central Himalaya are characterised by extensive grassy slopes with scattered trees and shrubs.

India has pledged to cut back total projected carbon emissions by up to one billion tons by 2030 with the exception of alternative formidable global climate change targets united within the recently command COP26 summit in Glasgow. Among totally different mitigation and adaption choices offered, trees will play a crucial role in international carbon flux and facilitate to store vast quantities of carbon for an extended amount of time (Panwar *et al.*, 2022).

At present, there is considerable interest of many countries in methods to estimate the biomass and carbon sequestration by terrestrial plant ecosystems. These estimates are required to satisfy the requirements of UNFCCC 1992, the Montreal protocol 1994 and the Kyoto protocol 1997.

Climate change requires significant mitigation actions. The main strategy should be preventive, i.e. by limiting greenhouse gas emission (Riahi *et al*., 2022). According to the latest Spanish national inventory, GHG emissions in 2020 were 274,743 kt CO_2 eq, a reduction of 12.5% compared to 2019, 37.9% compared to 2005, and 5.3% compared to 1990 (MITRED, 2022). However, the advanced results for 2021 point to an increase of 5.1% (MITRED, 2022). The sharp reduction in 2020 was in all probability due partly to the COVID-19 pandemic, and not solely to the mitigation measures adopted. Consequently, more efforts are required to cut back emissions. There are complementary mitigation actions, such as conserving and enhancing GHG sinks and reservoirs, including forests (Paris Agreement, 2022).

Plants have a crucial role in global climate change mitigation, as they're able to take atmospheric carbon from carbon dioxide through chemical changes of photosynthesis and fix it for an amount of your time that depends on their life. Carbon fixation is very vital in trees,

because of their size and longevity that permits them to carry it for an extended time (Korner C, 2017). Even when trees are felled, carbon remains sequestered in the wood (Tonn and Marland, 2007; Johnston and Radeloff, 2019); carbon persists in centuries-old wooden constructions and objects.

Carbon flows between the four major reservoirs; fossil and geological formations, the atmosphere, the oceans and terrestrial ecosystems including forests (Melillo *et al*., 1993; Siegenthaler and Sarmiento, 1993 and Prentice *et al.,* 2001). Transfer between these reservoirs occurs mainly as CO_2 in processes such as fuel combustion, chemical dissolution and diffusion, photosynthesis, respiration, decomposition, wildfires and burning of biomass in the open and in furnaces. If a component of the biosphere such as woody biomass expands, it becomes as a sink and thus removes carbon from the atmosphere and if it shrinks, it becomes the net source of CO_2.

The global CO_2 emissions and afterward its atmospheric concentration (418.90 ppm as on July 2022; CO_2 Earth 2022) have risen up drastically, particularly with the appearance of the commercial era, and are thought to be a primary driver of worldwide global climate change. Globally, about 1.5 trillion tonnes of CO_2 has been emitted since 1751 (Ritchie and Roser, 2020). With United Nations Framework Convention on Climate Change (UNFCCC) stressing on carbon sequestration, carbon capture and storage by trees and their wood merchandise are widely known as a climate mitigation strategy (Rathore *et al*., 2021).

Forests play an important role in global carbon (C) sequestration through the absorption of 35% of CO_2 emissions from fossil fuel and account for nearly 25% of global terrestrial ecosystem C sink. Hence, a far better understanding of the link between biodiversity and ecosystem functioning is crucial to sustaining forest ecosystem functions, like C storage, productivity, nutrient cycling, and global climate change mitigation. Forest productivity is a key ecosystem parameter for understanding carbon assimilation. A calculable 80% of the rise in the national C sink may be attributed to forest plantations.

Worldwide, Asia has the biggest space underneath plantations. Plantations cowl concerning 56.8 million hectares within the tropics (Kenzo *et al.*, 2020; Payn *et al.,* 2015). As plantations commonly have quick growth because of silvicultural practices and management, they often outweigh the natural forests for a few desired advantages (Arora *et al.*, 2014). In

terms of composition, *Pinus* spp. (20 percent) and *Eucalyptus* spp. (10 percent) remain dominant worldwide, although the overall diversity of species planted is continuously increasing (Carle *et al*., 2002). In India, a large variety of species are planted in the varied agro-climatic zones. *Acacia* spp., *Eucalyptus* spp., *Populus* spp. and *Tectona grandis* occupy the greatest areas in the plantations. Among conifers, *Cedrus deodara* and *Pinus roxburghii* occupy a major area (Pandey, 2000). However, in north India major plantation species are *Eucalyptus tereticornis*, *Populus* spp., *Pinus roxburghii* etc.

The mitigation potential of the forestry sector, supported by the biomass-demand situation, utilizing short or long-run industrial forestry possibility has been calculable to 122 Tg C for the period 2000–2012 (Ravindranath *et al.,* 2001). There is an importance of plantation forestry as a greenhouse gas mitigation option, as well as the need to monitor, preserve and enhance terrestrial carbon stocks (Updegraff *et al.,* 2004). Plantations outside forest area can reduce atmospheric CO_2 by storing carbon in biomass, soil and products and can be used as bio fuel offsetting fossil fuel (Birdsey and Heath, 2001). As trees grow and their biomass increases, they absorb carbon from the atmosphere and store it in the plant tissues (Mathews *et al*., 2000) resulting in growth of different parts. Active absorption of CO_2, from the atmosphere in photosynthetic process and its resultant storage within the biomass of growing trees or plants is that the carbon storage (Baes *et al*., 1977). Soil being a significant contributor to the carbon mitigation technology however, had numerous constrains like soil salinity and sodicity (Kumar *et al*., 2014; Felker *et al*., 2009).

Biomass production is an indication of the productivity of any plants and carbon capture is an indication of the reduction of atmospheric carbon dioxide which can mitigate the global warming. Tree plantations play an important role in global C-cycling as well as in preserving and enhancing the terrestrial C stocks. Maintenance of a thick litter layer along with rapid turnover time plays a significant role in plant nutrition as dense root systems of plants are developed inside such layers. The balance between litter fall inputs and decomposition determines soil C densities and leaching losses; ecosystem processes that are primarily controlled by the same environmental factors influencing biomass production. Biomass production systems embrace energy production from forest biomass or waste or biomass production on massive scale by short rotation forestry. Therefore, nutrient cycling in a forest ecosystem is influenced by decomposition of fine litter through soil assemblage that releases nutrients to the soil and influences forest productivity.

Leaf litter is one among the most internal flows of the continual vegetation–soil–fauna dynamic in forestry or agroforestry ecosystems, the subsequent decomposition method, and therefore the resultant incorporation of organic matter and nutrients, needed for growth, into the soil (Facelli and Pickett, 1991). Forest litter fall and subsequent decay are the major path-ways linking the biogeochemical processes of aboveground and belowground, acting as a critical factor in the regulation of nutrient cycling, soil fertility, and ecosystem carbon budgets (Hunt *et al.* 1988; Berg and Mc Claugherty, 2008; Staelens *et al*., 2011).

Litter is an important component of biomass in different plantations. The litter on the forest floor can act as an input-output system for nutrients (Das and Ramakrishnan, 1985). The rate at which the litter falls and subsequently decays regulate the energy flow, primary productivity and nutrient cycling in forest ecosystem (Waring and Schlesinger, 1985). Plant litter act as a temporary sink for nutrients and functions as 'a slow-release nutrient source' (White *et al*., 1988), thereby guaranteeing a permanent contribution of nutrients in the soil. It is estimated that litter nutrients released by litter decomposition make 70-90% of total nutrient requirement of plants (Waring and Schlesinger, 1985). The rate of decomposition conjointly plays a key role within the formation of organic matter and nutrient stock within the soil besides meeting the necessity for plant uptake (Isaac and Nair, 2005). Litter dynamics studies are very important in the nutrition budgeting on tropical ecosystem where vegetation depends on the recycling of the nutrients contained in the plant debris (Singh, 1968; Prichett and Fisher, 1987). The distribution of the regulation mechanism of the nutrient ratio in the leaf-litter-soil system and the effect of the nutrient return ratio of litter on soil nutrient cycling is important to understand.

Overall, leaf litter identify powerfully affected decomposition rates, and also the determined decomposition rates matched measures of metabolic activity and micro-organisms abundance.

Home field advantage (HFA) suggests that a specialization of soil microbial decomposers, bought up as "team players" for given plant litter (i.e., its chemical quality), referred to as "coaches of decomposition" since it dictates how briskly nutrient are often accessed by microbes, might occur through physiological diversification of the soil assemblage within the short term (Perez *et al*., 2013)

Soil microbic communities are a key part of the forest ecosystem; they're involved in basic processes, like decomposition and nutrient cycling, and perform a link role between plants and ecosystem functions (Zak *et al.*, 2003; Van der Heijden *et al*., 2008; Bardgett and Wardle, 2010). The influence of the tree type on microbic community structure and performance was supported by variety of various reports (Myers *et al.*, 2001; Hackl *et al*., 2004; Bastias *et al.*, 2007; Schweitzer *et al*., 2008; Berg and Smalla, 2009; Wubet *et al.*, 2012; Wang *et al*., 2013)

To increase the relative rate of decomposition and triggering the nutrient cycling process in forest soils the introduction of broad-leaved tree species was found beneficial.

From 1980's onwards a lot of plantation activity of tree species like *Populus* spp., *Eucalyptus* spp., *Alnus* spp., *Salix* spp. and *Robinia* spp. has been carried out on the experimental farm of the Regional Horticultural Research and Training Station, Bajaura and on common land of the villagers. The plantation established on the research farm is fully protected while; the plantation on the common land is subjected to limited degree of protection. Hitherto, no study has been carried out to compare these plantations managed under two different regimes for biomass productivity, nutrient cycling and microbial status. Hence the proposed study "**Evaluation of plantation tree species for biomass production and nutrient cycling in warm temperate North Western Himalayas**" will be carried out with the following objectives:

i) To study biomass production and carbon sequestration potential under different management regimes
ii) To assess nutrient dynamics of leaf litter (nutrient uptake, return through leaf litter) of plantation ecosystem
iii) To study the effect of different management regimes on soil physical, chemical and microbial properties

Chapter-2

REVIEW OF LITERATURE

Biomass of vegetation is a crucial ecological variable for understanding the evolution and potential future changes of the climate system. Vegetation biomass is a larger world store of carbon than the atmosphere and changes within the quantity of vegetation biomass already have an effect on the worldwide atmosphere by being a web source of carbon and having the potential either to sequester carbon within the future or to become an ever larger source. Depending on the amount of biomass, the vegetation cover will have an immediate influence on native, regional and even world climate notably on air temperature and humidity. Therefore, a global, regional and local assessment of biomass and carbon densities and their dynamics is an essential input to climate change forecasting models and mitigation and adaptation strategies.

In addition, there are two other emerging issues which contributes to the increasing importance of the biomass role as an essential climate variable: i) the growing use of biomass for energy production, so the increasing percentage of global greenhouse gases (GHG's) emitted from biomass consumption, and ii) the increasing concern on the possibility to significantly reduce global GHG's emission by avoiding biomass losses from deforestation, forest degradation and accounting for the effects of natural disturbances. The available literature pertinent to the present study is discussed below under the following heads:

2.1 BIOMASS AND CARBON DENSITY

2.2 CARBON SEQUESTRATION POTENTIAL IN BIOMASS POOL

2.3 NUTRIENT CONTENT OF LEAF LITTER

2.4 SOIL ORGANIC CARBON POOL

2.5 SOIL PHYSIO-CHEMICAL AND MICROBIAL PROPERTIES UNDER DIFFERENT PLANTATIONS.

2.1 BIOMASS AND CARBON DENSITY

Biomass is outlined as mass of live or dead organic matter. Changes in times of vegetation biomass per unit area (biomass density) can be used as an essential climate variable, because they are a direct measure of sequestration or release of carbon between

terrestrial ecosystems and the atmosphere. In this document, the term “biomass” we refer to the vegetation density i.e. mass per unit area of live or dead plant material. The carbon pools of terrestrial ecosystems involving biomass are conceptually divided into above- ground biomass, below ground biomass, dead mass and litter.

As tree grow and their biomass will increase, they absorb carbon from the atmosphere and store it in plant structure (Mathews *et al.,* 2000) leading to the growth of different parts. Active absorption of CO_2 from the atmosphere in photosynthetic process and its subsequent storage in the biomass of growing trees or plants is the carbon storage (Baes *et al*., 1977). In terms of atmospherical carbon reduction, trees in urban areas provide the double advantage of direct carbon storage and stability of natural ecosystem with escalated recycling of nutrient along with maintenance of climatic conditions by the biogeochemical processes.

Estimation of biomass is essential for determining the status and flux for biological material and for understanding the dynamics of forest ecosystem (Anderson, 1970). This information is utilized to quantitatively describe ecosystem and indicate the biomass resources available and hence elucidate nutrient cycling (Brown, 1997; Long and Turner, 1974), determining energy flow in the ecosystem (Satoo, 1968), to provide estimates of the carbon content in the forest (Brown, 1997) quantifying increment, growth and productivity in forests and to assess changes in forest and its structure (Brown, 1997).

Dewar and Cannell (1992) estimated carbon storage in UK plantations. Total carbon storage was found to be within the range 40-80 Mg C ha^{-1} in trees, 15-25 Mg C ha^{-1} in above and belowground litter, 70-90 Mg C ha^{-1} in soil organic matter and 20-40 Mg C ha^{-1} in wood product. The rate of carbon storage during the first rotation in most plantations was in the range 2-5 Mg C ha^{-1} yr^{-1}. Increasing the yield class from 6 to 24 m^3 ha^{-1} yr^{-1} increased the rate of carbon storage in the first rotation from 2.5 to 5.6 Mg C ha^{-1} yr^{-1} in unthinned plantations, whereas thinning reduced total carbon storage in *Picea sitchensis* plantations by about 15% and also lead to reduction in carbon storage in all plantation types.

Uri *et al.,* (2002) while studying the biomass production and nutrient accumulation in alder plantation on abandoned agricultural land stated that in the fifth year after planting, the biomass of the above ground part of the plantation was 15.9 t DM ha^{-1} and above ground biomass production was 6.4 t DM ha^{-1} each year. In the fourth year after planting, the

biomass of the below ground part was 2.7 t DM ha^{-1}, which accounted for 18% of total biomass. The biomass of the nodules was estimated at 169 ±76kg DMha^{-1} and the biomass of fine roots (d< 2mm) at 550 ±105 kg DM ha^{-1}.

According to Labrecque and Teodorescu (2005) poplar clones registered the highest aboveground biomass yield after 4 growing seasons (from 66.48 to 72.20 t DM ha^{-1}). The best willow biomass productivity was obtained from clones SX64 (67.58 t DM ha^{-1}) and clone SX61 (62.34 t DM ha^{-1}).

Fang *et al.,* (2006) studied biomass production and carbon storage in short-rotation poplar plantations over 10 years at the Hanyuan Forestry Farm, Baoying County, China. It was observed that at 10 years, the highest total biomass in the plantation of 1111 stems ha^{-1} reached about 146 t ha^{-1}, which was 5.3%, 11.6% and 24.2% higher than the plantations of 833, 625 and 500 stems ha^{-1}, respectively. The annual increment of biomass production over 10 years differed significantly among initial planting densities and stand ages ($p<0.01$), but no significant difference was observed from age 7 to 10.

Grunewald *et al.,* (2009) conducted the experiments with fast-growing tree species of *Populus* spp, *Robinia pseudoacacia* L and Salix for biomass production in Germany. The results revealed that the annual production of oven-dried biomass of *R. pseudoacacia* ranged between 3 and 10 t ha^{-1}, which was substantially greater than the biomass of poplar and willow clones established on the same site.

Ranabhat *et al.,* (2009) carried out a study to analyze the carbon content in different parts of *Alnus nepalensis,* and to assess the effect of aspect and altitude in the carbon storage *in Alnus nepalensis* in addition to quantify the overall carbon sequestration (stock) in *Alnus nepalensis* forest within the mid-hills of Kaski District. The analyses showed that mean carbon content in stem, branches, leaves and bark of *Alnus nepalensis* were found to be 40.52%, 33%, 9.56% and 16.4%, respectively. Total biomass carbon sequestered in northern aspect was 30.20 t ha^{-1} whereas for southern aspect it absolutely was 39.00 t ha^{-1}. In both the aspects higher carbon sequestration was observed at an elevation range of 1200-1300m i.e. 34.8 t ha^{-1} and 45.6 t ha^{-1} in northern and southern aspects, respectively. Soil carbon sequestration in northern and southern aspects was found to be 113.4 t ha^{-1} and 169.30 t ha^{-1},

respectively. The total carbon sequestration potential of *Alnus nepalensis* forest was estimated to be 186.05 t $ha^{-1.}$

Singh and Lodhiyal (2009) studied biomass and carbon allocation in Poplar agroforestry plantation in the Tarai region of central Himalaya, India and found that the Poplar agroforestry plantation in the region had a significant amount of biomass and carbon, which acts as an additional carbon sink in the region.

Uncertainties stay within the potential of forest plantations to sequestrate carbon. Liao *et al*., (2010) synthesized 86 experimental studies with paired-site design, to quantify the differences in ecosystem carbon pools between plantations and their corresponding adjacent primary and secondary forests (natural forests). Total ecosystem carbon stock in plant and soil pools was 284 Mg C ha^{-1} in natural forests and decreased by 28% in plantations. In comparison with natural forests, plantations decreased aboveground net primary production, litter fall, and rate of soil respiration by 11, 34, and 32% respectively. Fine root biomass, soil carbon concentration soil microbial carbon concentration decreased respectively by 66, 32, and 29% in plantations relative to natural forests.

Quinkenstein *et al.,* (2011) investigated C storage in biomass and soil under four SRC systems of *Robinia pseudoacacia* L. in the mining district of Lower Lusatia in 1995, 2005, 2006, and 2007. It was interpreted that average aboveground dry matter (DM) production ranged from 0.04 to 9.5 Mg ha^{-1} $year^{-1}$ for 1–14 years of growth, respectively. Total stocks of soil organic carbon (SOC) at 0–60 cm depth after 2 and 14 years of growth were 22.2±11.3 and 106.0±11.7 Mg ha^{-1}, respectively. The average rate of soil C sequestration within the 0–60 cm layer was 7.0 Mg ha^{-1} $year^{-1.}$ Hot water extractible carbon (HWC) that represents the labile fraction of SOC was highest within the oldest plantation (1.4 Mg ha^{-1} for the 0–30 cm layer).

Poplar based agroforestry systems are prevalent among farmers of Saharanpur (UP) and Yamunanagar (Haryana) districts of NW India. Rizvi *et al.,* (2011) stated that these systems are not only remunerative to the farmers, but also playing an important role in the assimilation of atmospheric carbon dioxide in the form of biomass carbon stocks. They made an assessment of carbon storage and CO_2 assimilation by poplar plantations in agroforestry in the above-mentioned districts. Contribution of poplar plantations to carbon storage was found to be 27– 32 t ha^{-1} in boundary system, whereas it had been 66– 83 t ha^{-1} in agrisilviculture system at a rotation period of 7 years in the 2 districts

Sheikh *et al.,* (2012) estimated carbon stocks of vegetation, forest floor and soils of a *Pinus roxburghii Sargent* Forest in the Garhwal Himalayas along a gradient to quantify changes in carbon stock due to differences in elevation at three sites. It was noticed that the above-ground biomass (AGB) and below-ground biomass (BGB) were highest at site I (184.46 and 46.386 t ha^{-1} respectively) at an elevation of 1300 m followed by site II (173.99 and 44.057 t ha^{-1} AGB and BGB respectively) at 1400 m and the lowest AGB and BGB were estimated at site III (161.72 and 41.301 t ha^{-1}) at 1500 m. The trend for SOC stock was the same as that of biomass. They suggested that carbon storage in both soil and biomass were negatively correlated with elevation.

Quinkenstein *et al.,* (2012) evaluate biomass production, C and N allocation patterns in *R. pseudoacacia* stands of one, two and twelve years old plantation, indicated that average dry matter production (DM) of the woody plant parts increased with plant age up to 7.45 t DM ha^{-1} yr^{-1} with a corresponding shoot increment of up to 4.77 t DM ha^{-1} yr^{-1} in the twelve-year-old stands. The shoot to root ratio modified from 0.2 for the one year-old trees to 2.0 in the twelve-year-old plantation, whereby a mean quantity of 3.4 t C ha^{-1} yr^{-1} and 0.1 t N ha^{-1} yr^{-1} was annually certain in the living woody plant components over the period of twelve years.

Aosaar *et al.,* (2012) reported that mean annual increment (MAI) of 20-year-old stands varied from 2.56 m3 ha^{-1} to 4.75 m3 ha^{-1} (dry matter). A rapid growth of alder stands and high biomass production was observed in favourable conditions. The highest woody biomass of annual production reported to 17 t ha^{-1} y^{-1}. Approximately 60 t ha^{-1} - 90 t ha^{-1} of stemwood can be produced during one rotation.

Aosaar *et al.,* (2013) reported the results of above and below-ground biomass production of the 17-year-old stand recorded AGB 120.8 t ha^{-1}; current annual increment of the stem mass was 5.7 t ha $year^{-1}$, calculated CRB was 22.3 t ha^{-1}, FRB was 81 ± 10 g m^{-2}, nodule biomass was 31 ± 19 g m^{-2}, fine root macro mass was 11 ± 2gm^{-2}, FRP was 53 g DM m^{-2} $year^{-1}$, fine root turnover rate was 0.54 $year^{-1}$ and fine root longevity was found to be 1.9 years. FRB was strongly correlated with the stand basal area and stem mass. Fine root efficiency was the highest at the age of 10 years but slightly reduced at the age of 17 years.

2.2 CARBON SEQUESTRATION POTENTIAL IN BIOMASS POOL

Devi *et al*., (2013) attempted a study to estimate biomass production and carbon sequestration potential of different plantation ecosystems in north western Himalaya, India.

Biomass, carbon density of biomass, soil, detritus, carbon sequestration and CO_2 mitigation potential were studied below different plantation forest ecosystems comprising of eight different tree species: *Quercus leucotrichophora, Pinus roxburghii, Acacia catechu, Acacia mollissima, Albizia procera, Alnus nitida, Eucalyptus tereticornis and Ulmus villosa*. It was reported that above (185.57±48.99t ha^{-1}) and below ground (42.47±10.38 tha^{-1}) biomass was maximum in *Ulmus villosa*. The vegetation carbon density was maximum in *Albizia procera* (118.37±1.49 tha^{-1}) and minimum (36.50±9.87 tha^{-1}) in *Acacia catechu* soil carbon density was maximum (219.86±10.34 tha^{-1}) in *Alnus nitida*, and minimum (170.83±20.60 tha^{-1}) in *Pinus roxburghii*. Detritus was higher in *Pinus roxburghii* (6.79±2.0 tha^{-1}). Carbon sequestration (7.91±3.4 tha^{-1}) and CO_2 mitigation potential (29.09±12.78 tha^{-1}) was maximum in *Ulmus villosa.*

Latifah and Sulistyiono (2013) conducted investigation to determine carbon sequestration potential of hybrid Eucalyptus. This study was conducted primarily to establish a carbon storage capacity forecast model for the Eucalyptus hybrid plantation forest in Aek Nauli, Simalungun District, North Sumatera. Models were checked and evaluated for statistical validity and accuracy in the forecasting of biomass and carbon based on the coefficient of determination (R) and the coefficient of correlation (r), the aggregative deviation percentage (AgD) and the average deviation percentage (AvD). The best general model to estimate the biomass of hybrid Eucalyptus was $Y= 1351.09\ x^{0.876}.\ e^{(0.094)}$. The results showed that the Eucalyptus hybrid had an average over-ground biomass up to year 3 in year 0 (land without eucalyptus trees) as high as that of year 3.1.36 t ha^{-1}, 5.2 t ha^{-1}. 19.43 t ha^{-1} and 28.73 t ha^{-1} while the carbon sequestration potential were, 2.23 t ha^{-1}, 19.08 t ha^{-1}, 71.31 t ha^{-1}, and 10.5.43 t ha^{-1} CO_2 respectively.

Pragasan and Karthick (2013) estimated capacity of carbon stock sequestered by two separate forms of tree plantations, Eucalyptus Plantation (EP) and Mixed Species Plantation (MP) at Bharathiar University Campus in Coimbatore, India. Total carbon stock (TCS) of all live trees (>- 9.5cm diameter at breast height) was determined by non-destructive method. Tree density and total biomass were 320 & 468 stems ha-1 and 48.05 & 39.64 tonne ha-1 at sites EP and MP, respectively. There was a positive association ($p>0.05$) between the tree density TCS and the total biomass at both sites. This shows that TCS increases with an increase in tree density and biomass, results showed that the carbon sequestration potential of

the fast growing Eucalyptus plantation is 11 per cent higher than the mixed species plantations in university.

Dhillon *et al*., (2014) carried out a research to study the effect of Poplar spacing and row direction, suitable crop rotation as well as the carbon sequestration potential of agroforestry as compared to sole agriculture. It was found that Poplar based agroforestry system at six years age was found to sequester 82 % more carbon than sole agriculture. The yearly rate of carbon storage was found to be 17.8 t ha^{-1} in Poplar based agroforestry system and 9.8 t ha^{-1} in sole agriculture. The carbon stock in the above-ground biomass and below-ground biomass contributed 37.3 t ha^{-1} at the age of six years

Murtaza *et al*., (2014) aimed to compare the C balances among various white willow (*Salix alba*) groves established across the four districts (viz. Anantnag, Bandipora, Baramulla and Ganderbal) of Kashmir valley. The maximum and minimum stem volume of 739.34 and 595.09 cum ha^{-1} and individual biomass production of 532.61 and 429.27 t ha^{-1} was recorded at Bandipora and Anantnag. The maximum soil carbon density of 68.07t ha^{-1} was recorded at Bandipora, followed by 67.93 t ha^{-1} at Baramulla, 66.86 t ha^{-1} at Ganderbal and 66.43t ha^{-1} at Anantnag. The results of this study further visualized that; on an average, white willow (*Salix alba*) can store up to 292.98 tons of C ha^{-1} and sequesters around 1075.24 CO_2 tons ha^{-1} from the atmosphere

Li *et al.,* (2015) studied two similar age-sequences of black locust forests *(Robinia pseudoacacia* L.) in the semi-arid and semi-humid zones of China's Loess Plateau to assess the variation in C stocks and age-related dynamics. The results demonstrated that C carrying capacity of plantations was166.4 Mg C ha^{-1} in the semi-humid zone, while the semi-arid zone had a capacity of only 79.4 Mg C ha^{-1}. Soil organic C (SOC) raised unceasingly with stand age in the semi-arid zone (R2 = 0.84, P = 0.010). However, in the semi-humid zone, SOC declined sharply by 47.8% after the initial stage (5 to 10 y). The C stock in trees raised unceasingly with stand age in the semi-humid zone (R_2 = 0.83, P = 0.011), however in the semi-arid zone, it reduced dramatically from 43.0 Mg C ha^{-1} to 28.4 Mg C ha^{-1} during the old forest stage (38 to 56 years).

Rytter *et al.,* (2015) examined 5-year-old replicated SRC plantations of willows (Salix spp.) on former arable land at five sites in Sweden for carbon sequestration in biomass and

soil. It was estimated that potential soil C sequestration rates ranged between 0.4 - 0.5 Mg ha^{-1} y^{-1} in willow plantations. The calculated SOC sequestration rates of 0.15 - 0.45 Mg ha^{-1} y^{-1} (30 cm soil depth) in the present study were based on input from willow litter, and thus dependent on the production level of the plantations.

Wang *et al.,* (2015) explored the effects of stand age on the carbon sequestration potential of *R. pseudoacacia* in a semi-arid, ecologically fragile area, parameters associated with carbon fixation were investigated in plots of three stand ages (5, 10, and 25 years). It was reported that the organic carbon density of *R. pseudoacacia*, understory vegetation and litter ranged from 3.4–16.8% and increased gradually with increasing stand age. Soil organic carbon increased with increasing stand age and accounted for 83.2–96.6% of the total carbon stored. Soil $CaCO_3$ content conjointly increased with increasing soil depth and stand age.

Kouchi *et al*., (2017) carried a study to investigate above-ground biomass of white poplar (*Populus alba* L.) plantations by four different plant spacing (0.5 × 0.5, 1 × 1, 2 × 2 and 4 × 4 m) in south west of Iran. The results showed that most biomass between the components is related to the bole wood and 2 × 2 m and 4 × 4 m planting spaces have the most quantity of the bole wood biomass between the four planting spaces (456.2 and 383.5 ton per hectare) and 0.5 × 0.5 m and 1 × 1 m planting spaces are after them (63.5 and 78.8 ton per hectare). Whereas, the most carbon sequestration is related to the 0.5 × 0.5 m planting space with 401.7 ton sequestered carbon per hectare and the lowest amount is related to 4 × 4 m planting space with 123.5 ton sequestered carbon per hectare.

Oliveira *et al.,* (2018) stated that when a mixed plantation of *Populus alba* L. genotype '111' (P) and the nitrogen-fixing species *Robinia pseudoacacia* L. genotype 'Nyirsegi' (R) was established with pure as well as mixtures with different proportions of the species 100P:0R; 75P:25R; 50P:50R; 25P:75R and 0P:100R), positive effect of the mixture 75P:25R in terms of biomass yield was obtained thus achieving a total yield of 13.66 Mg ha^{-1} yr^{-1} (26.83% higher than that of the *P. alba* monoculture and 89.99% higher than the *R. pseudoacacia* monoculture), with both species achieving a greater biomass yield per tree was estimated.

Cyamweshi *et al*., (2021) conducted tree inventory and destructive sampling in north-western Rwanda to understand carbon sequestration potential and other benefits of Alnus. It

was found that the largest biomass proportion was found in stems (70.5%) while branches and leaves stock about 16.5 and 13% of the total biomass, respectively. At farm level, aboveground biomass of Alnus trees was estimated to be 27.2 ± 0.7 Mg ha^{-1} representing 13.6 Mg of carbon (C) per hectare. Biomass carbon increased with tree size, from 7.1 ± 0.2 Mg C ha^{-1} in 3 years old trees to 34.4 ± 2.2 Mg C ha^{-1} in 10 years old trees. The converse was observed with elevation; biomass carbon decreased with increasing elevation from 21.4 ± 1.29 Mg C ha^{-1} at low (2011–2110 m) to 9.6 ± 0.75 Mg C ha^{-1} in the high elevation (>2510 m).

2.3 NUTRIENT CONTENT OF LEAF LITTER

One of the major recognized avenues of soil fertility improvements in forestry/ agroforestry systems is recycling of nutrients through decomposition of tree biomass-mainly leaf litter. The extent of benefits derived will, of course, depends on the nutrient content of the biomass added and the rate of decomposition.

The rate of nutrient release for decomposing leaf litter appears to be correlated with nutrient concentration in current litterfall. The concentration and absolute amount of N and P in leaf litter of all species increased with time. These studies also indicated that P levels can influence the mineralization or immobilization of other important nutrients. P and mg were rapidly released from the litter by leaching, Ca was released in such a way which indicated it is a structural component primarily released by decomposition (Gosz *et al*., 1973).

Hopman *et al*., (1980) found that the ammonification was higher in soils under eucalyptus than pine irrespective of soil moisture content and incubation period. Rapid decomposition of plant litter at the onset of the rainy season, however usually enhances major increase in nutrient accumulation over a relatively short period (Swift *et al.,* 1979).

Sharma and Ambasht (1987) made a comparison over 2 years in stands of 7,17,30,46 and 56 years in the Kalimpong forest division, Darjeeling, West Bengal. It was reported that seasonal decomposition rates were distinct with the highest rate in the 3 months of warm, rainy season. Among different stands decomposition rate was highest within the 30-year stand, i.e. at the time of canopy closure. The pattern of nutrient release (K > Ca > P > N) was a similar altogether the stands and also the actual quantity of nutrient release (30 > 17 >46 > 7 > 56-year stands) was associated with mass loss. The quantities of nutrients released per

unit area in twenty-four months were highest in the 30-year stand (nitrogen, 5 g m^{-2}; phosphorus 0.14 g m^{-2}; potassium, 1.17 g m^{-2}; and calcium, 0.59 g m^{-2}).

The nutrient content (especially N and P and the lignin and polyphenolic concentrations of litter strong influence its rate of decomposition and nutrient release into the soil (Szott *et al.,* 1991)

Bhardwaj *et al.,* (1992) studied the decomposition rates and carbon and nitrogen mineralization rates of leaf litter of four tree species- Leucaena, Populus, Eucalyptus and Prosopis. Decomposition rate in terms of CO_2 evolution was maximum for Leucaena leaves and lowest for eucalyptus leaves. Plant materials with high lignin and a wide C: N ratio decomposed slowly than the plant materials with low lignin and a narrow C: N ratio.

Ericsson (1994) examined willow plantations for growth and nutrient uptake dynamics within and between seasons, internal nutrient cycling, decomposition and mineralization of litter as well as nutrient losses due to harvest and leakage in energy forest plantations and concluded that the fertilizer need in well-established and high yielding (>>>12 tonnes stems, dry weight, ha^{-1} $year^{-1}$) stands is small, about 30 kg N ha^{-l} yr^{-l}, due to an efficient recycling of N from litter and the relatively low nutrient content in the harvested biomass (stems).

Palm (1995) reported that nutrient release patterns from organic material is determined by their chemical composition or quality. Leguminous materials release nitrogen immediately, unless they contain high levels of lignin or polyphenols. Non- leguminous and litter of both legumes and non- legumes generally immobilize nutrients initially.

Lodhiyal and Lodhiyal (1997) deal with the pattern of nutrient cycling and nutrient use efficiency in four (1-4 years old) poplar (*Populus deltoides* Marsh) plantations. The plantations were planted at 3 x 5 m spacing after clear felling of natural sal (*Shorea robusta* Dipterocarpaceae) mixed broad-leaved forests in central Himalayan Tarai. They revealed that the annual transfer of litter nutrients to the soil by vegetation was 91-148 N, 8-15 P and 70-99 K kg ha^{-1} yr^{-1}. The nutrient use efficiency of poplar plantations ranged from 151 to 174 kg ha^{-1} yc1 for N, 1338 to 1566 kg ha^{-1} yr^{-1} for P, and 313 to 318 kg ha^{-1} yr^{-1} for K.

Raj (1998) reported that nitrogen concentration in decomposing litter of *Populus deltoides* increased as the time elapsed while K and Ca concentration showed reverse trends. *P. deltoides* however, showed erratic trend throughout the study period. Ca release did not show any trend.

Sharma *et al.,* (2002) assessed the impact of stand age (5, 10,15,20,30 and 40 years) on the nutrient dynamics of mixtures of N_2 fixing (*Alnus nepalensis*) and non N_2 fixing (large cardamom) plants in eastern Himalaya. Annual N fixations increased from 5 year old stand (52kg ha^{-1}), peaking in the 15 years old stand (155kg ha^{-1}) and then deceased with increasing plantation age. Nitrogen and phosphorus uptake was lowest in 40 year old stand, and highest in the 15 years old stand respectively. Nutrient use efficiency was higher (with faster turnover times) in younger stands and decreased (with slower turnover times) in older plantations.

Philip *et al.,* (2003) observed varying degree of nitrogen immobilization during decomposition in a study conducted on nutrient release in a fifteen year old rubber plantation. The concentration of N in the decomposing litter was higher during the first two months and then a reduction was observed in the third month. Thereafter, an increase in N content was observed. As the decomposition preceded, P, Ca and Zn content in the leaf litter increased over the months with slight fluctuations, whereas the K and Mg content decreased markedly.

Meiresonne *et al*., (2006) observed 18-year-old poplar plantation on a well-drained silt loam soil during 2 consecutive years. Around 80% of the total nitrogen input (6.6 -6.5 kmol. ha^{-1} in both years 1 and 2, respectively) originates from litterfall. Total deposition of base cations originates from two processes, dry deposition (Mg^{2+} and Ca^{2+}) and canopy leaching (K^+ and Ca^{2+}). Litter input of Ca^{2+} represents about 83% of the total input (stand deposition + litterfall), Mg^{2+} about 61%, and K^+ less than 50%. Nutrient cycling in the poplar stand verified to be terribly efficient, with no significant nutrient losses.

Moshki and Lamersdorf (2011) studied a positive correlation between Robinia growth and soil organic carbon, total nitrogen, total phosphorus and cation exchange capacity (CEC) and negative relationship with soil inorganic carbon. With higher exchangeable Sodium Percentage (ESP) Robinia absorb a lot of exchangeable potassium than sodium as an adaptation mechanism against soil salinity. The concentration of nitrogen (N), sodium (Na) and calcium (Ca) of leaves was fairly good reflecting the variation in soil elements concentrations under Robinia plantation.

Hangs *et al*., (2014) examined the biomass production and attendant biogeochemical cycling of nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg) during the initial 4-year rotation of six willow varieties within Saskatchewan, Canada. It was observed that total above and below-ground biomass production during the rotation was approximately 40 Mg ha^{-1}, with calculated soil nutrient budget deficits (i.e., nutrient outputs > inputs + transfers) of 17, 39, 112, 271, and 74 kg ha^{-1} for N, P, K, Ca, and Mg, respectively, averaged across the varieties and sites, but soil S surplus of 60 kg ha^{-1} was observed.

Bani *et al.,* (2018) studied the effects of changed litter inputs on soil labile carbon and nitrogen pools in a eucalyptus- dominated forest. Leaf litter and deadwood have important role in the forest ecosystems, i.e. fungi produced the specific enzymes which help to increase nutrient uptake of the plant. The microbial community along with the environment determines the quality of substrates. Nitrogen content is influenced by the uptake of exogenous N by decomposers to meet their metabolic requirements.

Angst *et al.,* (2019) studied the effects of different tree species (alder, spruce, oak and willows) exert on litter decomposition by comparing decomposition patterns and microbial measures of both tree and understory litter which help to change the chemical properties of the soil.

Quichimbo *et al.,* (2019) investigated the diferences of nutrient dynamics between a native alder (*Alnus acuminata*) and an exotic pine *(Pinus patula*) tree species in this region. Results showed that total litterfall production in pine was double as high as in alder. The annual PNR of N and Ca were higher in alder, whereas those of K and Mn were higher in pine. Pine exhibited higher MRT values for C, N, P, S, Cu, and Zn, while alder showed the higher for Mg, K, Mn, and Ca. In soils, alder exhibited higher concentrations and stocks of nutrients, however not for C. Although, the soil microbial biomass was similar below each species, microbial activity was completely different. C and net N mineralization were higher in alder, and nitrification dominated over ammonification processes. In general, findings show a quicker cycling of nutrients in alder than in pine.

Wang *et al.,* (2019) reported influence of litter inputs on soil labile carbon and nitrogen pools in a eucalyptus-dominated forest of southeast Queensland, Australia. He

resulted that the litter input rates had no significant effects on litter decomposition at both sites ($P > 0.05$). After 15 months of decomposition, mean litter mass loss was 46.3% and 31.2% at the HQ and LQ sites, respectively.

Gonzalez *et al*., (2020) quantified the potential contribution of nutrients derived from leaf litter in a short rotation coppice plantation which includes monocultures of the species *Populus alba* (PA) and *Robinia pseudoacacia* (RP) as well as a mixture of 50PA:50RP, in the middle of the rotation. The *P. alba* monoculture provided the most leaf litter (3.37 mg ha^{-1} yr^{-1}), followed by the 50PA:50RP mixture (2.82 mg ha^{-1} yr^{-1}) and finally the *Robinia pseudoacacia* monoculture (2.55 mg ha^{-1} yr^{-1}). In addition to producing more litterfall, The carbon contribution derived from leaf fall was higher in the *Populus alba* monoculture (1.5 mg ha^{-1} yr^{-1}), intermediate in the mixed plot (1.3 mg ha^{-1} yr^{-1}) and slightly lower for the *Robinia pseudoacacia* monoculture (1.3 mg ha^{-1} yr^{-1}).

2.4 SOIL ORGANIC CARBON POOL

The organic carbon and soils of the world comprise bulk of the terrestrial carbon and serve as a major sink and source of atmospheric carbon. Increasing atmospheric concentrations of greenhouse gases may be mitigated by increasing carbon sequestration in vegetation and soil.

Soil organic C is the largest C reservoir in many terrestrial ecosystems including grasslands, savannas, boreal forests, tundra, some temperate forests, and cultivated systems, comprising as much as 98 per cent of ecosystem C stock in some systems (Schlesinger, 1977). Globally, the amount of C stored in soil is equal to the amount stored in vegetation and in the atmosphere combines (Schimel, 1995). A substantial portion of C mounted by vegetation is transferred to the soil annually (Raich and Nadelhoffer, 1989), some of that is refractory material with long turnover times (Falloon and Smith, 2000; Paul *et al.*, 1997) the rest decomposes relatively rapidly and is returned to the atmosphere as CO_2 (Falloon and Smith, 2000; Paul *et al*., 1997). Thus soil C is a large, respectively dynamic component of terrestrial C stock.

Turner and Lambert (2000) studied the effects of establishing *Pinus radiata* plantations on soil organic carbon by using paired plot and chronosequence techniques. One plot in each pair was located in relatively mature plantation and the other in adjacent existing

native forest. Soil organic carbon beneath plantation was less than beneath adjacent (original) native forest. Two chronosequences were studied; one located in a series of relatively fertile *Populus radiata* unthinned plantations, 0–24 years of age and the other in 0–35 year old *Eucalyptus grandis* plantations, also unthinned. The studies showed an apparent rapid decline in organic carbon in surface soil (0–10 cm) 12 years after plantation establishment. Soil organic carbon then stabilized with some indication of increases after 20 years of plantation establishment. There was a bigger loss of carbon from the deeper horizon (to 50 cm) within two years after plantation establishment and carbon continued to decline over the length of the two chronosequences.

Paul *et al.*, (2002) reviewed global data on changes in soil carbon following afforestation, available from 43 published or unpublished studies, encompassing 204 sites. Data was highly variable, with soil carbon either increasing or decreasing, particularly in young (<10 year) forest stands. On average, soil carbon in the <10 cm (or <30 cm) layers generally decreased by 3.46% yr^{-1} (or 0.63% yr^{-1}) relative to the initial soil carbon content during the first five years of afforestation, followed by a decrease in the rate of decline and eventually recovery to carbon contents found in agricultural soils at about age 30. In plantations older than 30 years, carbon content was similar to that under the previous agricultural systems within the surface 10 cm of soil, yet at other sampling depths, soil C had increased by between 0.50 and 0.86% y^{-1}. Furthermore, results suggested that most soil carbon was lost when softwoods, particularly *Pinus radiata* plantations, were established on ex-improved pastoral land in temperate regions. Accumulation of soil carbon was greatest when deciduous hardwoods or N_2-fixing species (either as an understorey or as a plantation), were established on ex-cropped land in tropical or subtropical regions. Accumulation was maximised by maintaining longer (20-50 year) forest rotations.

Kahle *et al.*, (2007) determined long-term effects of short rotation forestry on chemical, biochemical and physical soil properties we have investigated two former arable sites with willow and poplar clones (*Salix* and *Populus spp*.) in northeast Germany. The organic carbon and the total nitrogen contents of the sandy topsoil increased up to 4.0 g kg^{-1} and 0.2 g kg^{-1}, respectively after 12 years. The C/N ratio was higher under short rotation forestry caused by the stronger C than N accumulation. The contents and reserves of plant available phosphorus and potassium were reduced considerably from the 6th to the 12th year, however the plant supply was still sufficient without fertilization.

Ramachandran *et al.,* (2007) estimated 3.48 Tg soil carbon in the natural forests in Easter Ghats of Tamil Nadu, India. Forests show the best mitigation potential followed by agroforestry, plantation and agriculture. A projection of carbon stocks for small holder agroforestry systems in the tropics indicated C sequestration rates ranging from 1.5 to 3.5 Mg C ha^{-1} yr^{-1} and a tripling of C stocks in a twenty year period to 70 Mg ha^{-1} (Watson *et al.,* 2000)

Singh and Sharma (2007) reported that growth increment of poplar was markedly higher during April to October than October to April. Soil OC was considerably greater in older (6.83 g kg^{-1}) than the younger (5.35 g kg^{-1}) plantations. Accessible macronutrients in soil enhanced at sequential sampling times. The average Zn concentration at final sampling was 17% lower compared to initial sampling, whereas the other micronutrients tended to increase during April 2002 to October 2003 and the increase was higher in four year old plantations than one year due to higher inputs of organic matter.

Tangsinmankong *et al.,* (2007) examined carbohydrate in soil of mixed decidouous forest and teak plantation of 6, 15 and 24 years of age. The study was conducted in 2 areas; mixed deciduous forest at Huay Kha Khaeng Wildlife Sanctuary and teak plantation of Thai Plywood Co., Ltd. In Lansak District, Uthaithani Province. Results have showed that soil organic carbon from all sites has typically decreased with increasing depth. From the surface soil down to the level of 100 cm. the highest carbon stocks in the soil were recorded in the 6-year-old teak plantation, followed by the 24 and 15-years-old Teak plantations and mixed deciduous forest 157.03, 105.67, 78.78 and 70.96 t ha^{-1} respectively. The dissimilarity of organic soil carbon may be attributed to forest fire, forest management and topography.

Gupta *et al*., (2009) reported that popular based agroforestry system improves aggregation of soil through huge amounts of organic matter in the form of leaf biomass. The extent of improvement may be affected by the age of the popular trees and soil type. The surface and subsurface soil samples from agroforestry and adjoining non agroforestry sites with different years of popular plantation (1, 3 and 6 years) and varying soil textures (loamy and sandy clay) were analyzed for soil carbon increased from 0.36 in sole crop to 0.66 % in agroforestry soils. The increase was higher in loamy sand than sandy clay. The soil organic carbon increased with increased in tree age. The soil under agroforestry had 2.9-4.8 Mg ha^{-1}

higher soil organic carbon than in sole crop. The popular trees could sequester higher soil organic carbon in 0-30 cm profile during the first year of their plantation (6.07 Mg ha^{-1} yr^{-1}) than subsequent year (1.95 – 2.65 Mg ha^{-1} yr^{-1}). The sandy clay could sequester higher carbon (2.85 Mg ha^{-1} yr^{-1}) than in loamy sand (2.32 Mg ha^{-1} yr^{-1}).

Razakamanarivo *et al.,* (2010) conducted a study to evaluate and map the above ground biomass (ABG), below ground biomass (BLG) and soil organic carbon in the 30 cm top layer (SOC) in coppices of Eucalyptus plantations in the central highlands of Madagascar. Relationships between C stock and various biophysical and spatial factors that may affect C storage within each pool were investigated. Three different modelling methods have been evaluated and compared with different factor sets: (i) simple linear regression (SLM), (ii) multi linear regression (MLM) and (iii) boosted regression tree (BRT) models. The weights of the factors in the respective model were evaluated for the three pool specific models that provided the highest accuracy measurements. Regional spatial forecasts of carbon stocks have been made using spatial layers derived from a digital elevation model, remote sensing imaging and expert expertise. Results showed that BRT had the best predictive capacity for C stocks compared with the linear regression models. Accuracy assessment carried out using coefficient of determination (R^2) and ration of standard deviation to prediction error (RPD) showed satisfactory results, with 0.74 and 1.95 for ABG, 0.85 and 2.59 for BLG and 0.61 and 1.6 for SOC, respectively. Application of the best fitted models with spatial explanatory factors allowed to map and estimate C contained within each pool : 32$\pm$ 13 Gg C for ABG, 67$\pm$ 15 Gg C for BLG and, 139 $\pm$ 36 Gg C for SOC (1 Gg = 109g). A total of 238 $\pm$ 40Gg C was obtained for the entire study area by combining the three C maps.

Uri *et al.,* (2014) analysed the dynamics of the growth of 2–45-year-old grey alder stands (*Alnus incana*) growing at fertile sites as well as the dynamics of carbon (C) and nitrogen (N) accumulation in woody biomass and in the soil. The average stem-wood density found in this study was 396 ± 3.6 kg m^{-3} and the average density of the branches was 460 ± 2.9 kg m^{-3}. The average increase of the C pool in the 10 cm topsoil layer was in the range 1.1–1.2 t ha^{-1} yr^{-1} in young stands and 0.97–0.84 t ha^{-1} yr^{-1} in older stands. The average N accumulation in first-generation grey alder stands of the age of 14–35 years was 74 kg N ha^{-1} yr^{-1}.

Chimento *et al*., (2016) studied the effect of perennial woody (Poplar, Black locust, Willow) and herbaceous (giant reed, miscanthus, switchgrass) crops on SOC stock and its stabilization level after 6 years from plantation on an arable field. It was found that higher annual SOC sequestration rates were observed under woody species (120, 99, and 95 g C m^{-2} yr^{-1} for black locust, willow and poplar, respectively) than under herbaceous species (80 C m^{-2} yr^{-1} for switchgrass and miscanthus). The greater SOC accumulation rates observed under woody crops (105 g m^{-2} yr^{-1}) than under herbaceous crops (71 g m^{-2} yr^{-1}) were mainly driven by leaf-litter accumulation on the surface of the soil.

Globally carbon stock in soil exceeds carbon stocks in vegetation by a factor of about 5:1 in tropical forest to 5:1 in boreal forests and much larger factors in grasslands and wetlands (IPCC, 2000).

2.5 SOIL PHYSIO-CHEMICAL AND MICROBIAL PROPERTIES UNDER DIFFERENT PLANTATIONS

pH is the most commonly used method for expressing soil acidity or alkalinity. Most often forest soils have a pH range varying from 3.5-6.5 (Prithcett, 1979).

Shanmughavel and Francis (2001) studied the nutrient cycling in plantation forest of bamboo and acacia. A complete harvest of bamboo in 6 years removes 2341kg ha^{-1} of nitrogen, 22 kg ha^{-1} of phosphorus, 2653 kg ha^{-1} of potassium, 1211 kg ha^{-1} of calcium and 1356 kg ha^{-1} of magnesium. A total harvest of above ground biomass of Acacia in three years removes 91.74 N, 2.53 P, 73.41 K, 110.45 Ca, 14.06 Mg (kg ha^{-1}) and in four years removes 227.47 N, 7.34 P, 181.04 K, 284.15 Ca and 38.89 Mg (kg ha^{-1})

Noble *et al*., (2005) studied and compared the pedogenesis and other chemical attributes of a 49-year-old *Eucalyptus grandis* and *Pinus elliottii* plantations established on sandy textured soil along the Zululand coastal plain of South Africa. They investigated the changes in soil pH, exchangeable cations, organic carbon, extractable Fe and Al and the surface charge characteristics due to the plantations. In *Eucalyptus grandis* plantation the development of bleached A2e horizon within the surface 0-5 cm was confirmed through development of surface charge fingerprints, changes in organic carbon and Fe and Al mobilization for each of the pedogenetically distinct horizons was confirmed. Such development was not observed under the *P. elliottii* stand, suggesting that this pine species

has had less impact on the soil. It was argued that the rate of A2e horizon development is not dissimilar to that observed under native forest ecosystems in Australia, although considerably slower that those observed under reclaimed sand mining operations.

Nsabimana *et al.,* (2008) revealed that the composition of the plantation organisms had an effect on soil chemical properties. Complete soil C and N, C: N ratio, usable soil P, pH and cation exchange capacity (CEC) varied significantly between plantations of different species ($p<0.001$, N=54). Increase in soil C, total N, CEC and base saturation (BS) levels were observed mainly in mixed native species (MNS), *Polyscia fulva, Casuarina equisetifolia* and *Eucalyptus saligna.* The pH declined slightly in soil beneath some Eucalyptus species treatments and increased in others. The high nutrient uptake by fast-growing trees and the acidic parent material were involved in the acidification process. The findings suggest that the species used in afforestation maintain soil fertility and protect the environment.

Nampakdee *et al.,* (2010) studied biological, physical and chemical soil properties in Eucalyptus plantation under different soil series in Northern Thailand. The results indicated that microbial activity such as soil respiration, microbial biomass nitrogen and microbial biomass carbon in Eucalyptus plantation were from 3.95 to 5.91 mg c/day for microbial activity and 15.81 and 108.62 micro g N/g soil for microbial biomass nitrogen and 102.24 to 244.25 micro g c/g for soil microbial biomass carbon ($p<0.01$) respectively. The results showed that eucalyptus plantation has adverse effect on soil microbial activity in soil ecosystem and differ in each soil series.

Rahman *et al.,* (2012) studied the soil physical properties under plantation and deforested sites in a biodiversity conservation area of north-eastern Bangladesh. Forest plantation had a significant effect on soil binding process since a common trend of increament in soil particle density and bulk density were noticed; particle and bulk density of soil decreases if any land is deforested and remained deforested for a longer time. Deforested site contained lower mean soil organic matter than that of Garjan (*Dipterocarpus turbinatus*) and Sal (*Shorea robusta*) plantations. The highest value of organic matter was found at surface soil 0-10 cm depth) in both the Sal (2.24%) and Garjan (1.77%) plantations. The organic matter at both the plantations and deforested site decreased with the increase of soil

depth. The mean value of soil porosity was significantly less in deforested site (0.47gcc^{-1}) than that in Sal (0.48 gcc^{-1}) and Garjan plantation (0.49gcc^{-1})

Joshi and Negi (2015) studied the physio-chemical properties of soils of two dominant forest types in western Himalaya, viz, Oak (*Quercus leucotrichophora*) and Pine (*Pinus roxburghii*) were analysed in three depths in soil and in winters and rainy seasons. In general, all soil parameters, i.e. soil moisture, water holding capacity, organic carbon and total nitrogen decreased significantly with a rise in soil depth in both forests. However, pH did not show any trends with soil depth. All soil physio-chemical parameters were found to be significantly higher for Oak forests compared to Pine forests. The top soil layer (0-30 cm depth) of both the forest had high concentration of soil organic carbon and total N.

Mortimer *et al.,* (2015) analyzed N-fixing tree *Alnus nepalensis* (7 years old), into monoculture tea (*Camellia sinensis* var*., assamica*) plantations (32 years old) for basic soil properties and nutrients. It was found that biomass of soil fungi and bacteria were 41% and 10% higher in the tea + *Alnus nepalensis* sites than in the tea monoculture sites, respectively. Ectomycorrhizal biomass, as well as gram-positive, gram-negative and actinomycetes bacterial biomass, all increased ranging from 10% to 83%.

Murtaza *et al.,* (2017) investigated variation in microbial biomass carbon under the canopy of *Salix alba* plantations in temperate regions of Kashmir. The results revealed that the average value of soil microbial biomass carbon under *Salix alba* plantations at all locations was 0.402 t ha^{-1}. The higher mean microbial biomass carbon content of 190.51 µg C g^{-1} was recorded at Bandipora, followed by 186.10 µg C g^{-1} at Baramulla, 172.86 µg C g $^{-1}$ at Ganderbal and 167.70 µg C g^{-1} at Anantnag.

Baqir *et al*., (2018) evaluated the carbon sequestration efficiency of different tree species in Kahinaur plantations forest of district Mau, Uttar Pradesh. Moreover, improvement in nutrient status and other physio-chemical characteristics of soil due to plantation forest was also taken in consideration. The nutrient status of both plantation and wasteland soil decreased with increasing soil depth and bulk density. The soil microbial biomass carbon (SMBC), soil enzymes activities like soil dehydrogenase activity, acidic and alkaline phosphates and soil respiration were higher in the plantation forest soil as compared to the waste land soil. The highest SMBC (114.47µg g^{-1} soil 24h^{-1}) was reported in plantation forest

soil, but only 56.65µg g^{-1} soil $24h^{-1}$ in waste land soil. In addition, the acitivity of soil dehydrogenase (2.74 µg g^{-1} soil h^{-1}) was also highest in the plantation forest soil. Among the studied tree species, carbon accumulation was found maximum in *Prosopis juliflora, Putranjiva roxburghii, Pithecellobium dulce and Atrocarpus heterophyllus* depicting.

Tecimen *et al.,* (2018) revealed that pH was lower in natural plot than plantation at 20- year-old sites (no significant difference in other plots), EC did not show any significant difference between natural and plantation sites. Soil volume weight was higher in natural land which is in concordance with our hypothesis; and skeleton weight of natural sites was one third of plantation sites. The results showed that; soil chemical and physical properties do not alter instantly after the plantation of a natural site however is an efficient factor on soil.

Zhou *et al.,* (2018) investigated the effects of a 2-year N deposition treatment on litter decomposition, microbial activity, and nutrient release in two subtropical forests containing *Alnus cremastogyne* (AC, N-fxing) and *Liquidambar formosana* (LF, non-N-fixing). Nitrogen deposition significantly reduced soil microbial biomass C in the AC plantation. In the AC plantation, the mean microbial biomass C concentration was 347.4mg CKg^{-1}, 283.8mg C kg^{-1} and 225.4 mg C kg^{-1} in the N^0, N^1 and N^2 plots, respectively.

Xu Jie *et al.,* (2020) studied soil microbial biomass and enzyme activities in Eucalyptus plantations with different ages (1 and 5+ years) and species of trees *(E. urophylla×E. grandis, E. camaldulens and E. pellita*) in South China. The results revealed that the fungal biomass and the fungi-to-bacteria ratio significantly increased along with increasing plantation age. Similarly, the plantation age and eucalyptus species significantly affected the enzyme activities related to carbon cycling (β-xylosidase, β-d-glucuronidase, β-cellobiosidase and β-glucosidase). The activities of β-d-glucuronidase and β-glucosidase were significantly higher in the *Eucalyptus camaldulens* plantation. The enzymes involved in nitrogen (N-acetyl-glucosamidase) and sulfur (sulfatase) cycling were only affected by the eucalyptus plantation age and species, respectively.

Chapter-3

MATERIALS AND METHODS

The present study entitled **"Evaluation of plantation tree species for biomass production and nutrient cycling in warm temperate North Western Himalayas"** was conducted during 2021-2023 at the Regional Horticultural Research and Training Station, Bajaura, under Department of Silviculture and Agroforestry, UHF (Nauni), Solan. The details of the study, technique used and methodologies adopted in undertaking these studies are given below:

3.1 SITE DESCRIPTION

3.1.1 Location

The study was carried out at Regional Horticultural Research and Training Station, Jhiri; Bajaura- Himachal Pradesh (32^{o} 8' N latitude and 77^{o} 1' E longitude) with the elevation of 1090 m above mean sea level.

3.1.2 Climatic and edaphic factors

The climate of study area varies as the site "Regional Horticultural Research and Training Station, Bajaura" lies under temperate zone. The area is having extreme climate which varies from hot summer to severe cold winter, with heavy snowfall at upper ranges. Generally, 150 to 175 cm of average rainfall is recorded annually. The normal mean monthly maximum temperature is 31°C during June and minimum temperature is 16°C during January. The temperature may fall down to -5^{o}C in January and may rise to 38^{o}C in June.

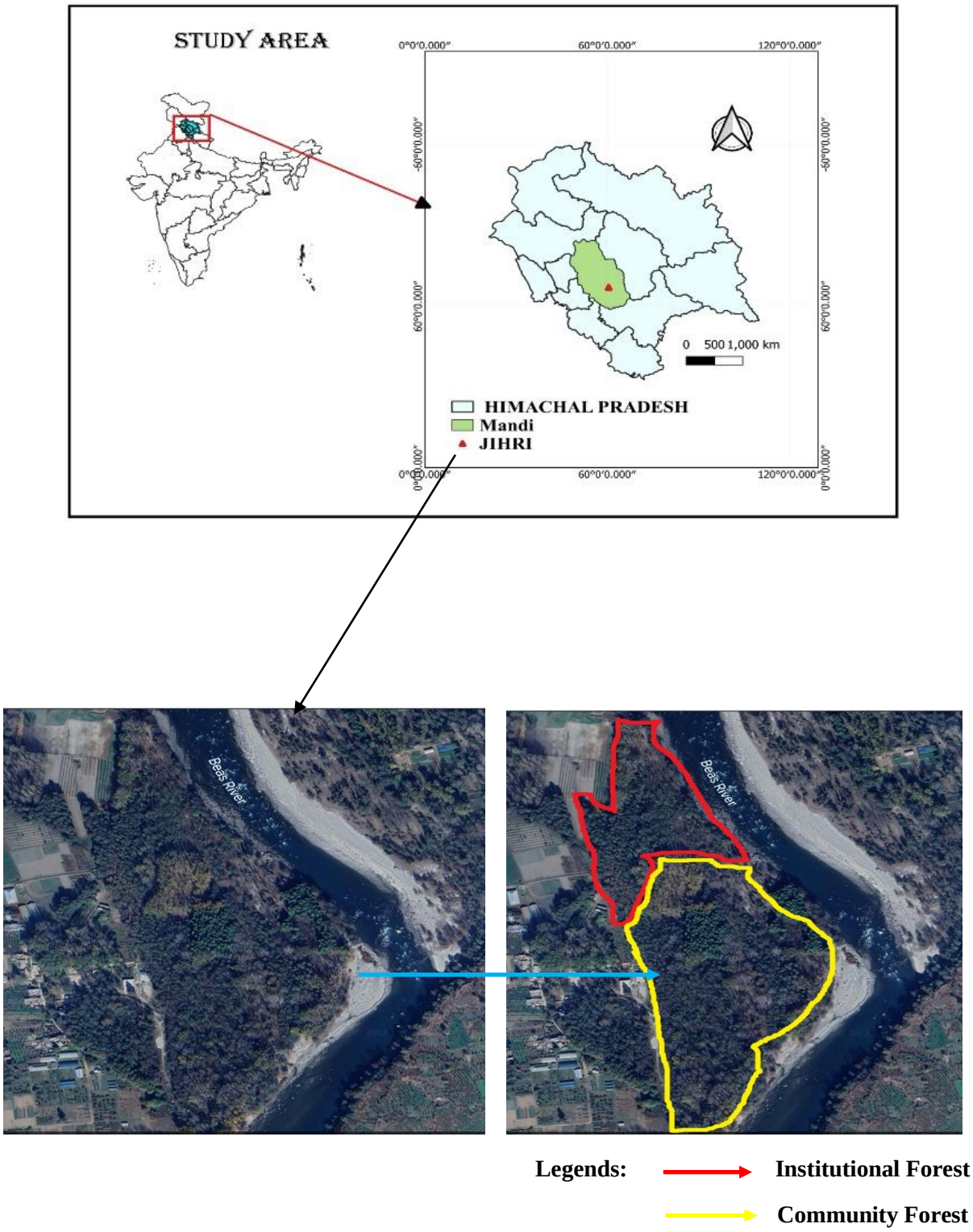


Figure 3.1: Study area map

Table 3.1: General description of plantation species, their site factors and distribution:

S. No	Species	Common Name	Family	Altitude (m above sea level)	Distribution	Silvicultural Characteristics
1	*Alnus nitida*	Kosh, koi, kunis	Betulaceae	1000-2900m	Commonly found along streams or planted as a roadside tree	Deciduous or semi deciduous tree, reaches upto 30m in height and 60 cm in diameter. Light demander, coppice fairly, moderately frost hardy and fire-resistant species which grows in moist soil.
2	*Eucalyptus tereticornis*	Blue gum, Forest Red gum	Myrtaceae	Upto 1700m	Grows under a wide range of climatic/ soil conditions from warm to hot, sub-humid to humid and from good to degraded soils	Evergreen species, widely planted in India, grows to a height of 20-50 m and 1-2 m in diameter. Strong light demander, good coppicer, wind firm in nature which grows in wide variety of soil such as alluvial soil, laterite soil, sandy loam soils, murum soils etc.
3	*Populus deltoides*	Poplar, Pahari pipal	Salicaceae	Upto 1600m	Estimated to range in forest life zones from warm temperate, dry to moist through cold temperate dry to moist.	Large, fast growing deciduous tree attaining a height of 30 m and with a trunk upto 1.8 m diameter. Light demander, pollards well, frost hardy, can withstand drought well, young trees are fire sensitive while old trees are tolerant to fire. It thrives best in ravines on well drained and porous soils with pH 5.5-7.5
4	*Salix tetrasperma*	White Willow	Salicaceae	Upto 2400m	Extensively cultivated in Western Himalaya along river streams, canal banks and around lakes. It is also reported to have been raised in dry temperate zone of Lahaul and Ladakh at a much higher altitude.	Moderate to large deciduous tree growing 10-30 m tall, with a trunk upto 60 cm in diameter. it tolerates a wide variety of soil types preferably sandy, silty or calcareous soils. It is strongly light demanding and does not tolerate shade. It can be pollarded or coppiced and reproduce from suckers or from adventitious roots.
5	*Robinia pseudocacia*	Black locust	Fabaceae	Upto 2000m	Grows in relatively humid conditions with mild winters and hot summers on a wide range of acidic to base rich soils on moist to dry soils	Deciduous, fast growing, multipurpose medium- sized tree, generally 12-18m tall and 30-76cm in stem diameter with open and irregular crown. Species matures early and growth rate decreases rapidly after 30 years on poor sites. Tolerates drought, wind, frost. Ability to produce suckers, ability to coppice and pollard, fixes nitrogen, regenerate rapidly. Very sensitive to competition and is classed as strong light demander.

To achieve the objectives, the present study was carried out under three experiments

3.2 EXPERIMENTAL DETAILS

Experiment I: To study biomass production and carbon sequestration potential under different management regimes

Treatment Details:

- **Type of Management Regimes:**

  M_1 - Institutional Forest

  M_2 - Community Forest

- **Tree Species: 5**

  T_1- *Robinia pseudocacia*

  T_2- *Populus deltoides*

  T_3- *Salix tetrasperma*

  T_4 -*Eucalyptus tereticornis*

  T_5 - *Alnus nitida*

- **Replications:** 3
- **Design:** Two way Anova
- **Date of Planting:** Jaunuary,1987
- **Plant Geometry:** Block Plantation
- **Spacing:** 3m x 3m
- **Treatment Combinations:** [2 (Management Regimes) X 5 (treatments) x 3 (replications)]
- **Sample plot size:**

  Trees: 20m × 20m

  Shrubs: 5m×5m

  Herbs: 1m×1m

Observations Recorded

I. Tree Parameters

- Tree height (m)
- Diameter at breast height (DBH)

- Form Factor
- Volume of standing trees

II. Biomass

- Tree above ground biomass (Mg ha^{-1})
- Below ground biomass (Mg ha^{-1})
- Total Biomass (Mg ha^{-1})
- Shrub biomass (Mg ha^{-1})
- Grass/herbage biomass (Mg ha^{-1})

III. Carbon and CO_2 estimation:

- **Carbon stock:** Biomass X 0.5 (IPCC default value)
- **Carbon sequestered (Mg ha^{-1}):** Carbon stock of study area – Carbon stock of adjoining barren land
- **Rate of carbon sequestered (Mg ha^{-1} yr^{-1}):** Carbon stock/ age of the plantation
- **CO_2 mitigated (Mg ha^{-1}):** Carbon stock X 3.67 (IPCC. 2006)

Experiment 2: To assess nutrient dynamics of leaf litter (nutrient uptake, return through leaf–litter) of plantation ecosystem

❖ **Treatment Combinations:** [2 (Management Regimes) ×5 (treatments) ×3 (replications)]

Observations Recorded

I. Nutrient estimation in plants (leaf, stem, branches, roots)

- Total N (kg ha^{-1})
- Total P (kg ha^{-1})
- Total K (kg ha^{-1})
- Total Ca and Mg (kg ha^{-1})

II. Nutrient Dynamics (Nutrient uptake, return through leaf - litter and retention)

Experiment 3: To study the effect of different management regimes on soil physico-chemical and microbial properties

❖ **Type of Management Regimes:**

M_1 - Institutional Forest

M_2 - Community Forest

❖ **Tree Species: 5**

T_1- *Robinia pseudocacia*

T_2- *Populus deltoides*

T_3- *Salix tetrasperma*

T_4 - *Eucalyptus tereticornis*

T_5 – *Alnus nitida*

Soil depths (Verma *et al*., 2023)**:** **D_1**: 0-20cm

D_2: 20-40cm

Replications: 3

Treatment Combinations: [2 (Management Regimes) x 5(treatments) x 2 (depths)]

Design: Three way Anova

3.3 EXPERIMENTAL METHODOLOGY

During the present study, following observations were recorded to quantify the biomass of different plantation species, effect of different plantation species on nutrient status of soil and to quantify the different plant nutrients and carbon content in plantation species in order to work out the nutrient cycling and carbon sequestration potential of plantation species.

3.3.1 Vegetation Analysis

I. Tree Parameters:

a) Tree Height (m)

Tree height of a standing tree refers to total distance along the stem between base of the stem at ground level and tip of the leading shoot. Tree sample plots of 20m× 20m were marked in each plantation of different management regimes for analyzing structural and functional parameters of tree vegetation. Height was measured with the help of by Ravi multimeter (Blue Leiss Hypsometer).

b) Diameter at Breast Height (m)

Two diameter measurements of the stem (at major and minor axis) at the breast height (1.37m) were taken with tree calliper and their mean was taken as dbh of a tree. Whenever,

meter tape was used for diameter measurement, the following formula was applied to convert circumference (c) to diameter at breast height.

$$DBH = c/\pi$$

Where, c stands for circumference /girth at breast height.

c) Form Factor

Form factor was calculated using Spiegel Relascope to find out the tree volume using the formula given by Pressler's (1865) and Bitterlich (1984).

$$f=2h_1/3h$$

Where, f = Form factor

h_1 = Height at which diameter is half of dbh

h = Total height

d) **Volume of standing trees:** Volume was calculated by Pressler's formula (1865)

V: f x h x g

Where, **V:** Volume

f: Form factor

h: Total height

g: Basal area = πr^2 or $\pi(dbh/2)^2$

Where, **r** = radius

dbh = diameter at breast height

II) Shrubs

The shrub characteristics were studied by laying out sub-plots of size 5m x 5m in each sample plot. Density of shrubs was calculated by counting plants of different species in each sub-plot. Stratified sampling of each shrub species was done by grouping them into three categories by visual appearance viz., a) large b) medium and c) small on the basis of size and number of stems in each of them. In each category, numbers of plants were counted. Basal area of stem was determined by Vernier Calliper.

III) Herbs

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

3.3.2. Biomass Estimation

3.3.2.1 Tree biomass

Volume of trees was transformed into biomass by multiplying it with specific gravity. Belowground biomass of trees was calculated following IPCC (1996) guidelines. The sum of aboveground and belowground biomass added up to determine total biomass of tree. The total biomass of trees in each elevation and aspect was calculated by adding up the biomass of every tree in it.

a. Stem biomass (Mg ha^{-1})

Stem biomass was calculated by multiplying specific gravity of stem wood with stem volume.

Specific gravity: Specific gravity was determined from the available literature (Appendices I)

Stem biomass = Average specific gravity of stem wood × Stem volume

b. Above ground tree biomass (Mg ha^{-1})

The total tree above ground biomass was calculated by multiplying the stem biomass with the biomass expansion factor of the species (Appendices I).

c. Below ground tree biomass (Mg ha^{-1})

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

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

d. Tree biomass (Mg ha^{-1})

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

e. Leaf litter biomass

Leaf litter was collected by placing nylon trap of 1m ×1 m mounted on a wooden frame randomly under each species. The samples were weighted in the field and thereafter dried in oven for dry weight estimation.

f. Shrub biomass

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

g. Herbaceous biomass

The different species in each quadrate were packed in paper bags separately. Whole plants were uprooted with their root systems. In laboratory, these plants were segregated into shoot and root portion. The shoot portion was packed in paper bag and oven dried. The roots of different species were then washed in running water using fine mesh, packed in paper bags, oven dried at 70^{o}C for 72 hours till constant dry weight is attained and weighed to determine their dry weight. Total biomass was calculated by adding aboveground and belowground biomass of each species. The crop biomass was converted into carbon by multiplying with a factor of 0.5 (IPCC default value).

h. Vegetation Biomass (Mg ha^{-1})

Vegetation biomass = tree biomass (Mg ha^{-1}) + shrub biomass (Mg ha^{-1}) + herb biomass (Mg ha^{-1})

3.3.2.2 Carbon and CO_2 estimation:

a. Carbon

Carbon stock = Biomass x 0.5 (IPCC default value)

b. Carbon density (Mg ha^{-1})

Carbon density = Carbon in megagrams per hectare

c. Carbon sequestered = Carbon stock of study area – carbon stock of adjoining barren land

d. Rate of Carbon sequestration (Mg ha^{-1} yr^{-1})

Carbon sequestered **=** Carbon stock/ age of the plantation

e. CO_2 mitigated (Mg ha^{-1} yr^{-1})

Carbon stock content was multiplied by 44/12 to estimate CO_2 mitigated as given by IPCC (2006).

f. Vegetation carbon density (Mg C ha^{-1})

Vegetation carbon density = Tree carbon density (Mg C ha^{-1}) + Shrub carbon density (Mg C ha^{-1}) + herb carbon density (Mg C ha^{-1})

3.3.3 Nutrient Estimation in Plants (leaf and leaf litter)

3.3.3.1 Collection of plant samples

A representative sample composite sample of stem, leaf, branch, rhizomes, root and leaf litter was collected from each sample plot. Leaf samples were collected as per the procedure adopted by Verma *et al.* (1992).

3.3.3.2 Preparation of plant samples

The plant sample collected were immediately weighted and brought to the laboratory in paper bags. All the samples were washed in series, first with tap water, than 0.1 N HCL followed by distilled water. The washed samples were allowed to dry in air and subsequently in oven at 60±5°C till constant weight. The dried samples were then ground in a grinder and stored in butter paper bags for chemical analysis.

3.3.3.3 Plant chemical analysis

For the estimation of total nitrogen, plant material was digested in the concentrated sulphuric acid in the presence of a digestion mixture of following composition:

K_2SO_4 400 parts

$CuSO_4$ 20 parts

HgO_3 parts

Selenium Powder 2 parts

After digestion, the N was determined by Micro-Kjeldahl method (Jackson, 1973)

For the estimation of total P, K, Ca and Mg, wet digestion of the plant sample was carried out in di-acid mixture consisting nitric acid and perchloric acid in the ratio of 4:1 and the final volume of the digest was made to 100 ml with distilled water. Total P in the digest was determined by Vanado-molybdate yellow method using Ultra Spectophotometer while K, Ca and Mg were estimated using Atomic Absorption Spectophotometer.

3.3.3.4. Plant nutrient uptake Nutrient uptake in different biomass yielding components was worked out according by the formula given by Embaye *et al.*, 2005:

$$\text{Nutrient uptake} = \frac{\text{Nutrient content} \times \text{dry weight}}{100}$$

Nutrient uptake by leaf and leaf litter was added to calculate the total nutrient uptake.

3.3.3.5. Nutrient cycling

Nutrient cycling was worked out on an annual basis, by calculating plant nutrient uptake, returns of nutrient through leaf litter and nutrients retention in plant parts (Shanmughavel and Frances, 2001).

3.3.4 Soil Physico-chemical and Microbial Analysis

3.3.4.1 Collection and preparation of soil samples

The composite soil samples were collected from different layers viz; 0-20 cm and 20-40 cm for studying the soil physical analysis and depth–wise distribution of nutrient elements from each site. The composite soil samples were dried, ground with mortar and pestles and sieved with 2 mm mesh sieve before analysis. Soil chemical and microbial analysis and laboratory studies were conducted in the Department of Silviculture and Agroforestry of Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (HP). Details of methodologies employed for estimating different soil physico-chemical parameters are given in table 2 as below:

Table 3.2: Soil physical, chemical and microbial analysis: methods and instruments used

Sr. No	Parameters	Methods employed	Instrument/ apparatus used
1	EC ($dS\ m^{-1}$)	1:2 soil water suspension	
2	pH (1:2)	1:2 soil water suspension (Jackson, 1973)	pH meter
3.	Bulk Density ($g\ cm^{-3}$)	Core method	Core method
4.	Organic Carbon (%)	Wet Combustion method (Walkley and Black, 1934)	-----
5.	Available Nitrogen ($kg\ ha^{-1}$)	Alkaline potassium permanganate method (Subbiah and Asija, 1956)	Kjeldahl distillation unit
6.	Available Phosphorus ($kg\ ha^{-1}$)	Olsen *et al.* (1954)	Specrtronnic 20 D^{+}
7.	Available Potassium ($kg\ ha^{-1}$)	Neutral 1 N ammonium acetate solution method (Merwin and Peach, 1951)	Flame photometer
8.	Exchangeable Calcium (c mol (p+)/kg)	Neutral 1N ammonium acetate solution (Merwin and Peech,1951)	Flame photometer
9.	Exchangeable Magnesium (c mol (p+)/kg)	Neutral 1N ammonium acetate solution (Merwin and Peech,1951)	Flame photometer
10.	Microbial Count ($\times 10^5$ cfu g^{-1} soil)	Pore Plate method (Subbarao, 1999)	Laminar and Incubator

3.3.4.2 Soil organic carbon density inventory (Mg ha^{-1})

Soil Organic Carbon **(**SOC) density was calculated by multiplying organic carbon ($g\ kg^{-1}$) with bulk density ($g\ cm^{-1}$) and soil depth.

SOC density ($Mg\ ha^{-1}$) = SOC ($g\ kg^{-1}$) X bulk density ($g\ cm^{-1}$) X soil depth (cm)

3.5 STATISTICAL ANALYSIS

Descriptive statistics and histograms were made directly from a spreadsheet in window excel 2007**.** Analysis of variance (ANOVA) and correlation coefficients were assessed by using procedure outlined by Gomez and Gomez (1984) and R programming language version 4.2.0 software. The least significant difference at 5 per cent level (<0.05) was used for testing the significant differences among treatments.

Chapter-4

RESULTS AND DISCUSSION

The results emerging out of present investigation entitled **"Evaluation of plantation tree species for biomass production and nutrient cycling in warm temperate North Western Himalayas"**, were carried out under two different management regimes i.e. a.) Institutional forest b.) Community forest. Plantation forest ecosystem due to their nature of origin, structure, function, tree species and management to which each plantation is subjected to reflect a wide variability in terms of biomass production, carbon storage and carbon sequestration potential. The results so obtained with respect to various plant growth and biomass, plant nutrients, carbon sequestration, soil physico-chemical and microbial count have been elaborated in this chapter with a view to find out the cause and effect relationship among different plantation species and management regimes for sorting out the information of practical value under the following broad headings:

4.1 Tree Parameters

4.2 Biomass and Biomass Carbon Density (Mg C ha^{-1})

4.3 Detritus Carbon Density

4.4 Soil Carbon Density

4.5 Ecosystem Carbon Density

4.6 Carbon Sequestration

4.7 Rate of Carbon Sequestration and CO_2 Mitigation

4.8 Leaf Litter Dynamics

4.9 Plant Nutrient Estimation

4.10 Nutrient Dynamics

4.11 Soil Physico- chemical Characteristics

4.12 Soil Microbial Count (10^5 cfu g^{-1})

4.13 Correlation Studies

4.1 TREE PARAMETERS:

Five different plantations namely, *Robinia pseudoacacia* (T_1), *Populus deltoides* (T_2), *Salix tetrasperma* (T_3), *Eucalyptus tereticornis* (T_4) and *Alnus nitida* (T_5) under two different management regimes i.e. Institutional forest (M_1) and Community forest (M_2) were assessed for their influence on tree parameters. The data pertaining to diameter at breast height (cm),

height (m), tree basal area (m^2 ha^{-1}) and volume (m^3 ha^{-1}) of various tree species under different management regimes have been presented in table 4.1 and table 4.2.

4.1.1 Diameter at Breast Height (cm)

The data presented in table 4.1 clearly indicates significant variation in the diameter at breast height (dbh) for different plantation tree species managed under different regimes. Amongst the tree species, *Populus deltoides* exhibited the highest dbh of 34.09 cm, which was notably larger than the dbh of all other tree species. Conversely, *Robinia pseudoacacia* had the lowest dbh of 24.64 cm, while *Salix tetrasperma* dbh was statistically at par with that of *Alnus nitida*.

Additionally, it was observed that the dbh value (34.61 cm) in institutional forest significantly differed from the dbh value in community forest.

The interaction effect between the plantation tree species (T) and the management regimes (M) revealed significant variations in dbh under different management conditions. In institutional forest, *Populus deltoides* displayed the highest dbh of 38.21 cm. *Salix tetrasperma* exhibited a dbh of 36.84 cm, which was statistically at par with dbh (36.25 cm) of *Alnus nitida*. In contrast, under community forest, *Salix tetrasperma* dbh (25.81 cm) was statistically similar to *Eucalyptus tereticornis* (25.02 cm) and *Alnus nitida* (25.63 cm). Minimum dbh of 28.71 cm for institutional forest and 20.56 cm for community forest was recorded for *Robinia pseudoacacia*.

4.1.2 Height (m)

The data presented in table 4.1 evidently showed that tree height exhibited significant variations based on the plantation tree species and the management regimes employed. The tallest trees were observed for *Populus deltoides*, with a height of 17.84 meters, while *Robinia pseudoacacia* displayed the shortest trees at 13.22 meters.

The interaction analysis between plantation tree species (T) and management regimes (M) revealed that in this context, *Populus deltoides* (19.77 meters) demonstrated maximum value which was found to be statistically at par with *Salix tetrasperma* (19.17 meters). Furthermore, within the institutional forest, *Salix tetrasperma* and *Alnus nitida* were found to have statistically equivalent tree heights.

In the case of community forest, the results echoed those of the diameter at breast height (cm) findings.

Table 4.1: Diameter at breast height (cm) and height (m) of different plantation tree species under different management regimes

Management Regimes / Treatments	Diameter at breast height (cm)			Height (m)		
	M_1	M_2	Mean	M_1	M_2	Mean
***T_1* (*R. pseudoacacia*)**	28.71	20.56	24.64	15.29	11.14	13.22
***T_2* (*P. deltoides*)**	38.21	29.99	34.09	19.77	15.92	17.84
***T_3* (*S. tetrasperma*)**	36.84	25.81	31.32	19.17	14.15	16.66
***T_4* (*E. tereticornis*)**	33.06	25.02	29.04	16.99	13.12	15.05
***T_5* (*A. nitida*)**	36.25	25.63	30.94	18.23	13.25	15.74
Mean	34.61	25.40		17.89	13.51	
$CD_{0.05}$ M: Management Regimes T: Tree species M× T	: 0.52 : 0.81 : 1.15			0.49 0.78 1.11		

4.1.3 Basal Area (m^2 ha^{-1})

The data presented in table 4.2 clearly demonstrates significant variation in basal area among different tree species and management regimes. The highest basal area was recorded for *Populus deltoides* as 12.82 $cm^2 ha^{-1}$, which was statistically equivalent to *Salix tetrasperma* i.e. 10.91 m^2 ha^{-1}.

Furthermore, the basal area significantly differed across various management regimes, with the maximum basal area of 12.39 cm^2 ha^{-1} observed in institutional forest (M_1).

Analyzing the interaction between plantation tree species (T) and management regimes (M), it was found that *Robinia pseudoacacia* (8.77 m^2 ha^{-1}) was statistically similar to *E. tereticornis* (8.51 m^2 ha^{-1}) in institutional forest. Likewise, *Salix tetrasperma* (14.61 m^2 ha^{-1}) and *Alnus nitida* (14.10 m^2 ha^{-1}) displayed comparable basal areas under institutional forest conditions. These trends were consistent in community forest as well.

4.1.4 Volume of a standing tree (m^3 ha^{-1})

The results concerning the volume of standing trees which was measured in cubic meters per hectare, m^3 ha^{-1} exhibited significant variations based on different tree species and

management regimes. Notably, the highest volume was observed for *Populus deltoides* as 84.21 m^3 ha^{-1}, followed by *Salix tetrasperma* at 67.39 m^3 ha^{-1}. In contrast, *Robinia pseudoacacia* displayed the lowest volume of standing trees as 32.18 m^3 ha^{-1}.

In terms of management regimes, the volume of standing trees was significantly highest as 84.20 m^3 ha^{-1} under institutional forest conditions.

The interaction analysis between management regimes (M) and tree species (T) revealed the highest volume for *Populus deltoides* which was 114.93 m^3 ha^{-1} under institutional forest management. In the case of community forests, *Salix tetrasperma* (36.03 m^3 ha^{-1}) displayed a statistically similar volume to *Eucalyptus tereticornis* (31.97 m^3 ha^{-1}) and *Alnus nitida* (32.88 m^3 ha^{-1}).

Table 4.2: Basal area (m^2 ha^{-1}) and volume (m^3 ha^{-1}) of different plantation tree species under different management regimes

Management Regimes / Treatments	Basal Area (m^2 ha^{-1})			Volume (m^3 ha^{-1})		
	M_1	M_2	Mean	M_1	M_2	Mean
T_1 (R. pseudoacacia)	8.77	4.64	6.70	46.09	18.27	32.18
T_2 (P. deltoides)	16.00	9.65	12.82	114.93	53.49	84.21
T_3 (S. tetrasperma)	14.61	7.22	10.91	98.75	36.03	67.39
T_4 (E. tereticornis)	8.51	6.84	7.67	71.51	31.97	51.74
T_5 (A. nitida)	14.10	7.08	10.59	89.73	32.88	61.30
Mean	12.39	7.08		84.20	34.53	
$CD_{0.05}$						
Management Regimes (M)	:1.33			2.14		
Tree Species (T)	:2.11			3.38		
M×T	:2.96			4.78		

4.2 BIOMASS AND BIOMASS CARBON DENSITY (Mg C ha^{-1})

This experiment evaluated the biomass, biomass carbon density and carbon sequestration potential of different tree species viz; *Robinia pseudoacacia*, P*opulus deltoides, Salix tetrasperma, Eucalyptus tereticornis* and *Alnus nitida* exhibited on different management regimes i.e. Institutional forest (M_1) and Community forest (M_2) of Regional Horticutlural Research &Training Station, Bajaura, Kullu – Himachal Pradesh the results of the same have been presented from table 4.3 and table 4.5.

***Salix tetrasperma* plantation under institutional forest**

***Salix tetrasperma* plantation under community Forest**

Plate 1: *Salix tetrasperma* plantation under different management regimes

4.2.1 Tree Biomass

4.2.1.1 Tree Above Ground Biomass (Mg ha^{-1})

The perusal of the data presented in table 4.3 reveals that tree above ground biomass varied significantly with the plantation tree species and management regimes. Maximum above ground biomass (62.53 Mg ha^{-1}) was displayed by *Alnus nitida* followed by *Eucalyptus tereticornis* (48.00 Mg ha^{-1}) which was found to be statistically at par with *Populus deltoides* (47.04 Mg ha^{-1}). Minimum quantity of above ground biomass (37.04 Mg ha^{-1}) was recorded for *Robinia pseudoacacia,* which was found to be significantly lower than all other plantation tree species. Under management regimes, above ground biomass was recorded higher for institutional forest (67.00 Mg ha^{-1}). Interaction between plantation tree species (T) and management regimes (M) shows that above ground biomass significantly found maximum (91.52 Mg ha^{-1}) for *Alnus nitida* followed by *Eucalyptus tereticornis* (65.57 Mg ha^{-1}) which was found to be statistically at par with *Populus deltoides* (64.20 Mg ha^{-1}) under institutional forest (M_1). In case of community forest, maximum value (33.54 Mg ha^{-1}) was recorded for *Alnus nitida* which was significantly at par with *Eucalyptus tereticornis* (30.44 Mg ha^{-1}) whereas; *Salix tetrasperma* (22.70 Mg ha^{-1}) was significantly at par with *Robinia pseudoacacia* (22.57 Mg ha^{-1})**.**

4.2.1.2 Tree Below Ground Biomass (Mg ha^{-1})

It was evident from the data presented in table 4.3 that tree below ground biomass varied significantly with the plantation tree species and management regimes. Maximum and minimum values for plantation tree species as well as for management regimes followed the same trend as of tree above ground biomass. Interaction between plantation tree species (T) and management regimes (M) showed that below ground biomass significantly found maximum (43.95 Mg ha^{-1}) for *Alnus nitida* followed by *Eucalyptus tereticornis* (32.60 Mg ha^{-1}) which was found to be statistically at par with *Populus deltoides* (31.88 Mg ha^{-1}) and *Salix tetrasperma* (31.17 Mg ha^{-1}) under institutional forest (M_1). For community forest, maximum value (18.07 Mg ha^{-1}) was recorded for *Alnus nitida. Eucalyptus tereticornis* (16.54 Mg ha^{-1}) was evaluated to be significantly at par with *Populus deltoides* (16.34 Mg ha^{-1}) along with *Salix tetrasperma* (12.77 Mg ha^{-1}) which was significantly at par with *Robinia pseudoacacia* (22.57 Mg ha^{-1})**.**

4.2.1.3 Tree Total Biomass (Mg ha^{-1})

Perusal of the data presented in table 4.3 represented that total biomass (above + below) for tree varied significantly with the plantation tree species and management regimes. Trends observed were similar as off tree above ground biomass and below ground biomass for the observed maximum and minimum values. Interaction between the parameters reflected that *Eucalyptus tereticornis* (98.18 Mg ha^{-1}) was found to be statistically at par with *Populus deltoides* (96.08 Mg ha^{-1}) which was further found to be statistically at par with *Salix tetrasperma* (31.17 Mg ha^{-1}) for institutional forest. For the total biomass under community forests, the same trends as off tree below ground biomass was observed.

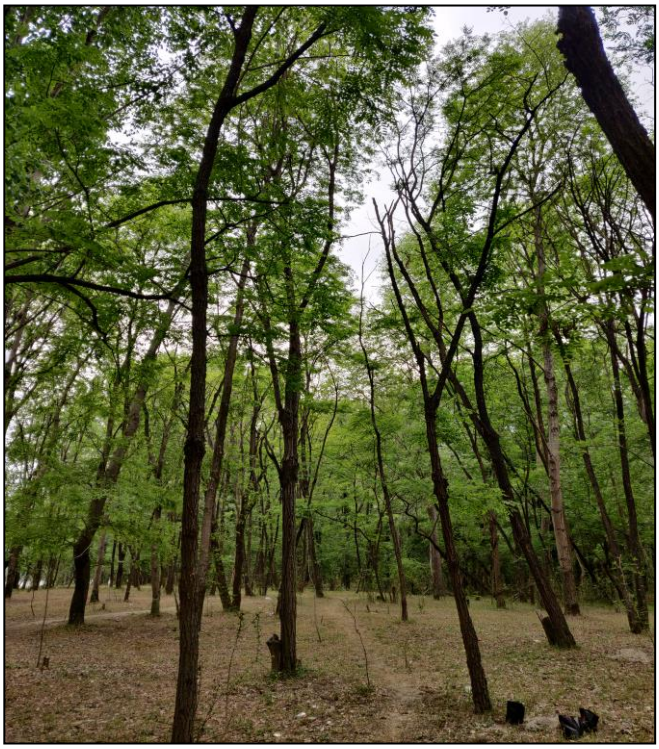
Table 4.3: AGB (Mg ha^{-1}), BGB (Mg ha^{-1}) and TB (Mg ha^{-1}) of different plantation tree species under different management regimes

Management Regimes / Treatments	AGB (Mg ha^{-1})			BGB (Mg ha^{-1})			TB (Mg ha^{-1})		
	M_1	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**
T_1 (R. pseudoacacia)	51.52	22.57	37.04	26.53	12.63	19.58	78.06	35.20	56.63
T_2(P. deltoides)	64.20	29.88	47.04	31.88	16.34	24.11	96.08	46.22	71.15
T_3 (S. tetrasperma)	62.21	22.70	42.46	31.17	12.77	21.97	93.39	35.47	64.43
T_4 (E. tereticornis)	65.57	30.44	48.00	32.60	16.54	24.57	98.18	46.98	72.58
T_5 (A. nitida)	91.52	33.54	62.53	43.95	18.07	31.01	135.47	51.61	93.54
Mean	67.00	27.82		33.23	15.27		100.23	43.10	
$CD_{0.05}$ Management Regimes (M) : 1.47 Tree Species (T) : 2.33 M×T : 3.29				0.65 1.02 1.45			2.11 3.34 4.73		

4.2.2 Shrub Biomass (Mg ha^{-1})

Table 4.4 represented shrub biomass (Mg ha^{-1}) which varies significantly with the plantation tree species (T) and management regimes (M). Maximum shrub biomass was recorded under *Alnus nitida* (0.65 Mg ha^{-1}) in the descending order for *Salix tetrasperma* > *Populus deltoides* > *Eucalyptus tereticornis* > and minimum was for *Robinia pseudoacacia* (0.29 Mg ha^{-1}). Institutional forest reflects higher value (0.48 Mg ha^{-1}) of shrub biomass (Mg ha^{-1}). Interaction between both the parameters reflected that shrub biomass under the entire plantation tree species were significantly different with the shrub biomass of *Alnus nitida*

Robinia pseudoacacia **plantation under institutional forest**



Robinia pseudoacacia **plantation under community forest**

Plate 2: ***Robinia pseudoacacia*** **plantation under different management regimes**

(0.75 Mg ha^{-1}) under institutional forest. Same pattern has been observed for shrub biomass under community forest.

4.2.3 Herb Biomass (Mg ha^{-1})

The data depicted in table 4.4 reveals herb biomass (Mg ha^{-1}) for plantation tree species (T) and management regimes (M) varied significantly with the maximum value reported for *Alnus nitida* (5.89 Mg ha^{-1}) and minimum (3.67 Mg ha^{-1}) for *Robinia pseudoacacia*. Institutional forest was reported with higher value (5.41 Mg ha^{-1}) for herb biomass. Maximum herb biomass (Mg ha^{-1}) was examined for *Alnus nitida* (6.75 Mg ha^{-1}) under institutional forest and was reported to be significantly different for other tree species. Herb biomass under *Salix tetrasperma* and *Populus deltoides* was found to be statistically at par with each other for community forest, reflecting interaction effect between plantation tree species (T) and management regimes (M).

Table 4.4: Shrub and herb total biomass (Mg ha^{-1}) under different plantation tree species of different management regimes

Management Regimes / Treatments	Shrub biomass (above+below) (Mg ha^{-1})			Herb biomass (above+ below) (Mg ha^{-1})		
	M_1	M_2	Mean	M_1	M_2	Mean
T_1 (R. pseudoacacia)	0.30	0.29	0.29	3.41	3.94	3.67
T_2 (P. deltoides)	0.44	0.40	0.42	4.99	4.32	4.65
T_3 (S. tetrasperma)	0.52	0.35	0.44	6.23	4.46	5.34
T_4 (E. tereticornis)	0.38	0.31	0.35	5.66	3.35	4.50
T_5 (A. nitida)	0.75	0.56	0.65	6.75	5.05	5.89
Mean	0.48	0.38		5.41	4.22	
$CD_{0.05}$						
Management Regimes (M)	:0.03			0.08		
Tree Species (T)	:0.05			0.12		
M×T	:0.08			0.18		

It was observed that *Salix tetrasperma* (4.46 Mg ha^{-1}) was significantly at par with *Populus deltoides* (4.32 Mg ha^{-1}) under community forest.

4.2.4 Vegetation Biomass (Mg ha^{-1})

Data presented in table 4.5 demonstrated that the vegetation biomass varied significantly among the different plantation tree species for institutional forest. It was found that vegetation biomass was found to be maximum for *Alnus nitida (*142.97 Mg ha^{-1})

followed by *Eucalyptus tereticornis* (104.22 Mg ha^{-1}) and minimum value was displayed by *Robinia pseudoacacia* (81.77 Mg ha^{-1}) for institutional forest. Results pertaining to vegetation biomass for community forest also varied significantly for plantation tree species. Trends followed were same as for institutional forest in terms of maximum and minimum values.

In the present study it was observed that the tree above ground biomass, below ground biomass and vegetation biomass density varied significantly among the different plantation tree species tree. Biomass and carbon stock in forest vegetation differs based on factors such as geographical location, plant species composition, and stand age (Van Noordwizk *et al.,* 1997). The structural characteristics we have noted in the current low-statured forest align with findings from other research conducted on dry forests. To illustrate, the range of basal area (BA) we have observed is similar to the ranges documented in previous studies. Specifically, Singh and Singh (1991) reported ranges of 3.84–10.36 m^2 ha^{-1}, while Jha and Singh (1990) documented ranges of 6.58–23.21 m^2 ha^{-1} for various dry tropical communities in the Vindhyan region. Variation in leaf structure and photosynthetic efficiency can influence biomass production. To improve the accuracy of total carbon calculations (Hamberg, 2000), it is necessary to estimate above-ground tree biomass, below-ground biomass, as well as biomass of shrubs and herbaceous/grass vegetation in plantation ecosystems of warm temperate western Himalayas has been presented in table 4.1 to table 4.5, respectively.

The variation in volume observed at different sites can be attributed to differences in factors such as tree growth, tree density, and soil conditions at each location. Singh and Gupta (2008) have also suggested that as the diameter at breast height (dbh) and height of trees increase, their volume tends to increase as well. Walsh *et al.,* (2008) have reported that an increase in growth parameters like dbh, height, and basal area corresponds to an increase in tree volume. They further observed that for certain *Eucalyptus* species, the volume ranges from 9.5 to 125.9 m^3 per hectare for various diameter classes up to the age of 10 years. Wong *et al.,* (2000) have advocated that for similar species, the stem volume ranges from 167 to 232 m^3 per hectare (equivalent to a M.A.I of 8.4 - 11.6 m^3 per hectare per year) when the plantations reach an age of 20 years.

The study investigated the vegetation biomass of different plantation tree species in two types of management regimes: community forest and institutional forest.

Table 4.5: Biomass and biomass carbon density (Mg ha^{-1}) of different plantation tree species under different management regimes

Management Regimes / Treatments	Tree above ground biomass		Tree below ground biomass		Tree biomass (above + below)		Shrub biomass (above + below)		Herb/grass biomass (above + below)		Vegetation biomass (above + below)		Vegetation carbon density	
	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2
T_1 (*R. pseudoacacia*)	51.52	22.57	26.53	12.63	78.06	35.20	0.30	0.29	3.41	3.94	81.77	39.44	38.84	18.73
T_2 (*P. deltoides*)	64.20	29.88	31.88	16.34	96.08	46.22	0.44	0.40	4.99	4.32	101.51	50.95	48.22	24.20
T_3 (*S. tetrasperma*)	62.22	22.71	31.17	12.77	93.39	35.47	0.52	0.35	6.23	4.46	100.14	40.29	47.57	19.13
T_4 (*E. tereticornis*)	65.58	30.44	32.60	16.54	98.18	46.98	0.38	0.31	5.66	3.35	104.22	50.64	49.50	24.06
T_5 (*A. nitida*)	91.52	33.54	43.95	18.07	135.47	51.61	0.75	0.56	6.75	5.05	142.97	57.22	67.91	27.18
MEAN	67.00	27.83	33.23	15.27	100.23	43.10	0.48	0.38	5.41	4.22	106.12	47.71	50.41	22.66
$CD_{0.05}$	3.30		1.45		4.73		0.08		0.18		4.68		2.22	

The vegetation biomass of plantation tree species varied, with a range of 39.44 to 57.22 Mg ha^{-1} for community forest and 81.77 to 142.97 Mg ha^{-1} for institutional forest. The data indicated that the biomass of all types of plantations was significantly influenced by the management strategies employed.

Among all the tree species maximum height and dbh was recorded for *Populus deltoides* which can be attributed to high growth rate and better adaptability of the species while comparatively poor performance of *Robinia pseudoacacia, Pinus roxburghii* and *Dalbergia sisoo* can be attributed to slow growth rate of these species in the riverain areas as reported by Thakur and Chauhan (2008).

Across both management regimes, the species *Alnus nitida* exhibited the highest vegetation biomass. Certain species of *Alnus* (alder) are known for their rapid growth rates, especially during their early growth stages. This fast growth can result in substantial biomass accumulation in a shorter time frame. While poplar trees are among the fastest growing species in temperate zones, achieving high productivity appears to be dependent on the availability of both belowground and aboveground resources. Some studies (Monclus *et al*., 2006; Stanturf and Oosten, 2014; Stettler and Bradshaw, 1996; Vítková *et al.*, 2017) suggest that these high growth rates can be realized when resources are abundant both in the soil and in the surrounding environment. However, it is important to note that such highly productive hybrid species used in short rotation coppice (SRC) systems are often susceptible to drought stress (González-González *et al.,* 2017; Monclus *et al*., 2006). This means that while these hybrids can achieve impressive growth rates, they may face challenges when water availability is limited.

In summary, the study underscores the influence of management practices on plantation tree species' biomass. It also highlights the rapid growth potential of certain species like *Alnus nitida* and specific other species, as well as the resource dependent productivity of fast-growing species like poplars in temperate zones.

In natural reclamation areas, yields are typically diminished due to the presence of unfavourable soil and growth conditions. Nevertheless, findings from various field experiments suggest that *Robinia pseudoacacia* (black locust) has the potential for improved performance when planted in more favourable sites. For instance, in a study involving 5-year-

old energy plantations situated on sandy soils in Hungary, Rédei *et al.,* (2008) documented annual biomass yields ranging from 6.5 to 8.0 Mg DM ha^{-1} $year^{-1}$ for different *Robinia pseudoacacia* clones.

The biomass of shrubs and herbaceous vegetation (as presented in table 4.4) constitutes a significant portion of the overall biomass within plantation ecosystems. These components are frequently excluded from biomass calculations in research due to the absence of a universally applicable method and the intricate nature of estimation (Karki, 2002). The data further indicate that there were substantial variations in the biomass of shrubs and herbs/grasses across both types of management regimes, influenced by the types of plantation tree species or vegetation present. These variations can be attributed to differences in factors such as light interception, moisture levels, nutrient dynamics, and more.

In general, the biomass of shrubs and herbs/grasses was highest in treatments with elevated humus content density, observed in both the regimes. Similar variations in shrub and herb/grass density have also been observed in studies conducted by Adhikari *et al.,* (1995) for temperate ecosystems in the Indian Himalayas and by Zhu *et al.,* (2010) for temperate regions in China. These findings emphasize the multifaceted nature of factors influencing the biomass distribution of shrubs and herbaceous vegetation in various ecosystems.

Within our research, the density of vegetation biomass exhibited a range of 81.77 to 142.97 Mg ha^{-1} in institutional forests and 39.44 to 57.22 Mg ha^{-1} in community forests, as outlined in table 4.5. This trend was consistent across both management regimes. Notably, the impact of treatments on vegetation carbon density was statistically significant within both management systems. Across both regimes, *Alnus nitida* emerged as the species with the highest vegetation carbon density. The reported ranges of vegetation carbon density in our study align closely with those documented by Sharma *et al.,* (2010), Tiwari and Singh (1987), and Singh *et al.,* (1985) in the neighbouring Himalayan regions.

This investigation highlights the prevalence of a greater number of woody species along with ground vegetation in forests managed institutionally, in contrast to those under community management. Moreover, a negative correlation was observed between species richness and the distance from the nearest village, as well as with increasing levels of anthropogenic disturbances. Interestingly, these findings deviate from the conclusions

presented by Maren *et al.,* (2013), which suggested that community forests generally exhibited lower levels of degradation compared to government-managed forests, providing support for the principles of common pool resource management. Forests subject to grazing and/or cutting displayed distinct patterns in vegetation biomass when compared to the other forest types, as noted by Gautam (2005).

King *et al*., (2006) elaborated that greater penetration of light into gaps and favourable conditions for growth over most of the year may allow more smaller-statured species to co-exist with canopy trees in tropical vs. temperate forests.

The interspecific variation in growth performance for various tree species has been reported by earlier workers (Bisht and Tokey, 1993; Thakur and Mishra, 1998.)

The results of this study have been supported by Mir *et al.,* (2021) reporting the level of disturbance, species diversity, stand characteristics, biomass and C stock taking three traditional forests: sacred forests (SF), restricted forests (RF)and village forests (VF). It was reported that there was a 30% reduction of AGB in RFs and 70% in VFs as compared to the SFs. The mean AGBC stock was 129 $\pm$26.3, 92.49 $\pm$ 15.2 and 39$\pm$ 5.7 Mg C ha^{-1} in SF, RF and VF.

4.2.5 Carbon Density (Mg C ha^{-1})

A perusal of the data presented in tables 4.5- 4.10 of vegetation carbon density for different management regimes evinced that carbon density varied significantly with plantation tree species.

4.2.5.1 Tree carbon density (Mg C ha^{-1})

Furthermore, data in table 4.6 presents carbon stock, carbon sequestration, carbon mitigation and O_2 liberation of different plantation tree species under different management regimes.

It was found that *Alnus nitida* had maximum contribution for carbon stock (44.43 Mg C ha^{-1}), carbon sequestration (1.23 Mg C ha^{-1} yr^{-1}) and carbon mitigation (163.07 Mg C ha^{-1}). Contribution by different management regimes (table 4.6) reveal that under institutional forest carbon stock of 47.61 Mg C ha^{-1}, carbon sequestration of 1.32 Mg C ha^{-1} yr^{-1} and carbon mitigation of 174.74 Mg C ha^{-1} was recorded which was statistically different with community forest.

Table 4.6: Plantation tree species wise carbon stock (Mg C ha^{-1}), carbon sequestration (Mg C ha^{-1} $tree^{-1}$) and carbon mitigated (Mg C ha^{-1}) under different management regimes

Management Regimes / Treatments	Carbon stock (Mg C ha^{-1})			Carbon sequestration (Mg C ha^{-1} yr^{-1})			Carbon mitigated (Mg C ha^{-1})		
	M_1	M_2	Mean	M_1	M_2	Mean	M_1	M_2	Mean
T_1 (R .pseudoacacia)	37.08	16.72	26.90	1.03	0.46	0.75	136.07	61.37	98.72
T_2 (P. deltoides)	45.64	21.95	33.79	1.27	0.61	0.93	167.50	80.58	124.04
T_3 (S. tetrasperma)	44.35	16.85	30.60	1.23	0.47	0.85	162.80	61.84	112.32
T_4 (E. tereticornis)	46.63	22.31	34.47	1.29	0.62	0.96	171.15	81.90	126.52
T_5 (A. nitida)	64.35	24.52	44.43	1.79	0.68	1.23	236.17	89.98	163.07
MEAN	47.61	20.47		1.32	0.57		174.74	75.13	
$CD_{0.05}$									
Management Regimes (M)	: 1.00				0.03			3.69	
Tree Species (T)	: 1.59				0.04			5.83	
M×T	: 2.25				0.06			8.25	

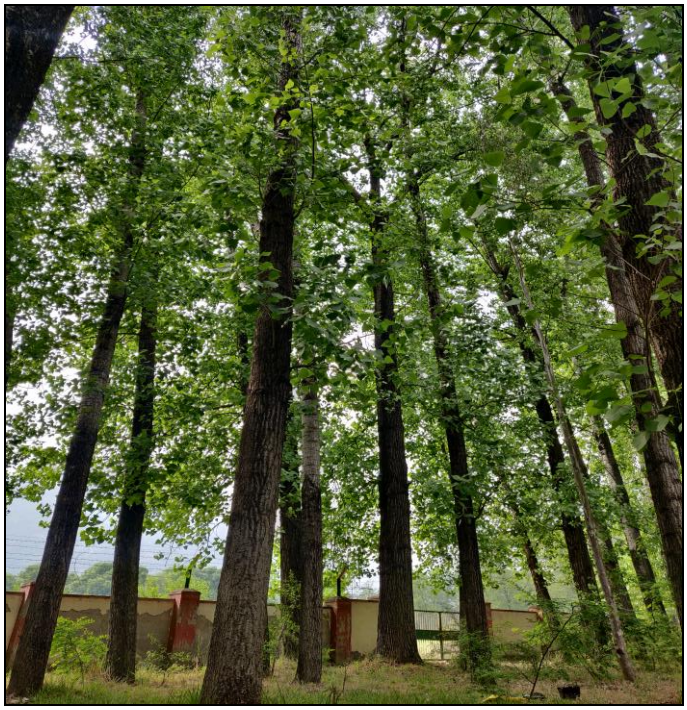
Interaction between plantation tree species and management regimes (table 4.6) in terms of carbon stock delineated that *Eucalyptus tereticornis* (46.63 Mg C ha^{-1}) and *Salix tetrasperma* (44.35 Mg C ha^{-1}) was found to be statistically at par with *Populus deltoides* (45.64 Mg C ha^{-1}) for institutional forest. Under community forest, *Alnus nitida* (24.52 Mg C ha^{-1}) was statistically at par with *Eucalyptus tereticornis* (22.31 Mg C ha^{-1}) which was further found to be at par with *Populus deltoides* (21.95 Mg C ha^{-1}).

Carbon sequestration (Mg C ha^{-1} yr^{-1}) and carbon mitigation (Mg C ha^{-1}) varied statistically for different plantation species under different regimes (table 4.6). For carbon sequestration, *Eucalyptus tereticornis* (1.29 Mg C $ha^{-1}yr^{-1}$) was found to be statistically equal to *Salix tetrasperma* (1.23 Mg C ha^{-1} yr^{-1}) and statistically at par with *Populus deltoides* (1.27 Mg C ha^{-1} yr^{-1}) under institutional forest. Whereas; *A*lnus *nitida* (0.68 Mg C ha^{-1} yr^{-1}) was found to be statistically equal to *Eucalyptus tereticornis* (0.62 Mg C ha^{-1} yr^{-1}) furthermore; *Salix tetrasperma* (0.47 Mg C ha^{-1} yr^{-1}) was statistically at par with *Robinia pseudoacacia* (0.46 Mg C ha^{-1} yr^{-1}) for community forest.

Carbon mitigation was found maximum for *Alnus nitida* (163.07 Mg C ha^{-1} yr^{-1}) and minimum for *Robinia pseudoacacia* (98.72 Mg C ha^{-1} yr^{-1}). For interaction between tree species and management regimes, trend followed was same as of carbon sequestration.

4.2.5.2 Shrub carbon density (Mg C ha^{-1})

Significantly maximum shrub carbon density (table 4.7) was found in *Alnus nitida* (0.31 Mg C ha^{-1}) followed by *Salix tetrasperma* (0.21 Mg C ha^{-1}), which was ascertained to be statistically at par with *Populus deltoides* (0.20 Mg C ha^{-1}). Whereas, *Robinia pseudoacacia* (0.14 Mg C ha^{-1}) had minimum value and remained statistically at par with *Eucalyptus tereticornis* (0.16 Mg C ha^{-1}). Institutional forest recorded higher (0.23 Mg C ha^{-1}) shrub carbon density. Interaction between both the parameters showed that *Salix tetrasperma* (0.25 Mg C ha^{-1}) and *Eucalyptus tereticornis* (0.18 Mg C ha^{-1}) remained statistically equal to *Populus deltoides* (0.21 Mg C ha^{-1}) and *Robinia pseudoacacia* (0.14 Mg C ha^{-1}), respectively for institutional forest and under community forest maximum value was recorded for *Populus deltoides* (0.19 Mg C ha^{-1}) which was reported to be statistically equals to *Eucalyptus tereticornis* (0.15 Mg C ha^{-1}). Further, *Eucalyptus tereticornis* (0.15 Mg C ha^{-1}) has been reported to be statistically superior to *Salix tetrasperma* (0.17 Mg C ha^{-1}) and *Robinia pseudoacacia* (0.14 Mg C ha^{-1}).



***Populus deltoides* plantation under institutional forest**

***Populus deltoides* plantation under community forest**

Plate 3: *Populus deltoides* plantation under different management regimes

4.2.5.3 Herb carbon density (Mg C ha^{-1})

For herb carbon density (table 4.7), the maximum value was recorded for *Alnus nitida* (2.80 Mg C ha^{-1}) and the lowest value was documented for *Robinia pseudoacacia* (1.74 Mg C ha^{-1}). *Populus deltoides* (2.21 Mg C ha $^{-1}$) was identified to be statistically at par with *Eucalyptus tereticornis* (2.14 Mg C ha^{-1}). Interaction between tree species and management regimes reflected that maximum value for herb carbon was found in *Alnus nitida* (3.20 Mg C ha^{-1}) under institutional forest and minimum value was recorded for *Eucalyptus tereticornis* (1.59 Mg C ha^{-1}), which remained statistically at par with *Populus deltoides* (2.05 Mg C ha $^{-1}$) under community forest.

4.2.5.4 Vegetation carbon density (Mg C ha^{-1})

Vegetation carbon density for institutional forest (table 4.5) revealed that maximum value was recorded for *Alnus nitida (*67.91 Mg C ha^{-1}) followed by *Eucalyptus tereticornis* (49.50 Mg C ha^{-1}), *Populus deltoides* (48.22 Mg C ha^{-1}), *Salix tetrasperma* (47.57 Mg C ha^{-1}) and minimum was found for *Robinia pseudoacacia* (38.84 Mg C ha^{-1}). In community forest (table 4.5), maximum contribution for carbon density was reported by *Alnus nitida (*27.18 Mg C ha^{-1}) followed by *Populus deltoides* (24.20 Mg Cha^{-1}), *Eucalyptus tereticornis* (24.06 Mg C ha^{-1}), *Salix tetrasperma* (19.13 Mg C ha^{-1}) and minimum was found for *Robinia pseudoacacia* (18.73 Mg C ha^{-1}).

Table 4.7: Shrubs and herbs carbon density (Mg C ha^{-1}) under different plantation tree species of different management regimes

Management Regimes / Treatments	Shrubs carbon density (Mg C ha^{-1})			Herb carbon density (Mg C ha^{-1})		
	M_1	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**
T_1 (R. pseudoacacia)	0.14	0.14	0.14	1.62	1.87	1.74
T_2 (P. deltoides)	0.21	0.19	0.20	2.37	2.05	2.21
T_3 (S. tetrasperma)	0.25	0.17	0.21	2.96	2.12	2.54
T_4 (E. tereticornis)	0.18	0.15	0.16	2.69	1.59	2.14
T_5 (A. nitida)	0.36	0.27	0.31	3.20	2.39	2.80
MEAN	0.23	0.18		2.57	2.29	
$CD_{0.05}$						
Management Regimes (M)	:0.02				0.04	
Tree Species (T)	:0.03				0.06	
M×T	:0.04				0.09	

4.3 DETRITUS CARBON DENSITY (Mg C ha^{-1})

Detritus biomass and carbon density present in different tree plantations under different regimes are depicted in table 4.8 and table 4.9.

4.3.1 Detritus Biomass (Mg ha^{-1})

4.3.1.1 Leaf litter (Mg ha^{-1})

A perusal of data presented in table 4.8 show the litter biomass under different management regimes for tree plantations. Maximum value (2.66 Mg ha^{-1}) was recorded for *Alnus nitida* and minimum (1.53 Mg ha^{-1}) for *Robinia pseudoacacia.* Interaction between both the parameters showed that *Alnus nitida* (2.94 Mg ha^{-1}) was statistically at par with *Salix tetrasperma* (2.86 Mg ha^{-1}) which was statistically at par with *Populus deltoides* (2.80 Mg ha^{-1}) under institutional forest.

4.3.1.2 Dead twigs and branches (Mg ha^{-1})

The dead twigs and branches biomass shown in table 4.8 reveals that maximum value (0.83 Mg ha^{-1}) was reported by *Alnus nitida* which remains statistically at par with *Robinia pseudoacacia* (0.80 Mg ha^{-1}) followed by *Populus deltoides* (0.76 Mg ha^{-1}) and *Salix tetrasperma* (0.75 Mg ha^{-1}). It was observed that *Robinia pseudoacacia* (0.80 Mg ha^{-1}) remained statistically at par with *Populus deltoides* (0.76 Mg ha^{-1}) and *Salix tetrasperma* (0.75 Mg ha^{-1}), whereas; *Populus deltoides* (0.76 Mg ha^{-1}) and *Salix tetrasperma* (0.75 Mg ha^{-1}) was found to be statistically at par with each other. Whereas, the lowest value was recorded for *Eucalyptus tereticornis* (0.46 Mg ha^{-1}).

4.3.1.3 Dead tree (Mg ha^{-1})

Dead tree biomass shown in table 4.8 depicts that the maximum value (0.50 Mg ha^{-1}) was recorded for *Alnus nitida* and minimum for *Robinia pseudoacacia* (0.21 Mg ha^{-1}) which remained statistically at par with *Eucalyptus tereticornis* (0.27 Mg ha^{-1}) whereas; *S. tetrasperma* (0.42 Mg ha^{-1}) and *Populus deltoides* (0.41Mg ha^{-1}) was found to be statistically at par with each other. Interaction between species and regimes showed that *Robinia pseudoacacia* (0.20 Mg ha^{-1}) remained statistically at par with *Eucalyptus tereticornis* (0.29 Mg ha^{-1}). *Populus deltoides* (0.60 Mg ha^{-1}) was determined to be statistically at par with *Salix tetrasperma* (0.59 Mg ha^{-1}) and *Alnus nitida* (0.67 Mg ha^{-1}).

***Eucalyptus tereticornis* plantation under institutional forest**

***Eucalyptus tereticornis* plantation under community forest**

Plate 4: *Eucalyptus tereticornis* plantation under different management regimes

Table 4.8: Detritus biomass (Mg ha^{-1}) of different plantation tree species under different management regimes

Management Regimes / Treatments	Leaf litter (Mg ha^{-1})			Dead twigs and branches (Mg ha^{-1})			Dead tree biomass (Mg ha^{-1})			Total detritus biomass (Mg ha^{-1})		
	M_1	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**
T_1 (R. pseudoacacia)	1.73	1.33	1.53	0.91	0.70	0.80	0.20	0.22	0.21	2.85	2.26	2.55
T_2 (P. deltoides)	2.80	1.47	2.13	0.85	0.68	0.76	0.60	0.22	0.41	4.26	2.37	3.32
T_3 (S. tetrasperma)	2.86	1.90	2.38	0.97	0.53	0.75	0.59	0.25	0.42	4.43	2.68	3.56
T_4 (E. tereticornis)	1.93	1.70	1.82	0.53	0.39	0.46	0.29	0.26	0.27	2.76	2.36	2.56
T_5 (A. nitida)	2.94	2.38	2.66	0.99	0.67	0.83	0.67	0.34	0.50	4.60	3.40	4.00
Mean	2.45	1.76		0.85	0.59		0.47	0.26		3.78	2.62	
$CD_{0.05}$												
Management Regimes (M)	:0.06			0.07			0.07			0.33		
Tree Species (T)	:0.09			0.10			0.10			0.20		
M×T	:0.13			0.15			0.14			0.29		

Furthermore, *Salix tetrasperma* (0.59 Mg ha^{-1}) was statistically at par with *Alnus nitida* (0.67 Mg ha^{-1}) under institutional forest. Community forest represents that each tree species was statistically at par with each other. Albitely, *Robinia pseudoacacia* (0.22 Mg ha^{-1}) was statistically equal to *Populus deltoides* (0.22 Mg ha^{-1}).

4.3.1.4 Total detritus biomass (Mg ha^{-1})

Total detritus biomass for different tree species (table 4.8) revealed that the maximum value (4.00 Mg ha^{-1}) was recorded for *Alnus nitida* is followed by *Salix tetrasperma* (3.56 Mg ha^{-1}), which remains statistically at par with *Populus deltoides* (3.32 Mg ha^{-1}). Further, *Robinia pseudoacacia* (2.55 Mg ha^{-1}) was recorded with minimum value and statistically at par with *Eucalyptus tereticornis* (2.56 Mg ha^{-1}). Interaction between species and regimes showed that *Robinia pseudoacacia* (2.85 Mg ha^{-1}) remained statistically at par with *Eucalyptus tereticornis* (2.76 Mg ha^{-1}). *Populus deltoides* (4.26 Mg ha^{-1}) was found to be statistically at par with *Salix tetrasperma* (4.43 Mg ha^{-1}) which was further found to be statistically at par with *Alnus nitida* (4.60 Mg ha^{-1}) under institutional forest. Whereas, *Robinia pseudoacacia* (2.26 Mg ha^{-1}) remained statistically at par with *Eucalyptus tereticornis* (2.36 Mg ha^{-1}) and *Populus deltoides* (2.37 Mg ha^{-1}) which was found to be statistically at par with each other for community forest. The data pertaining table 4.8 reveals that institutional forest showed higher value in of leaf litter (2.45 Mg ha^{-1}), dead twigs and branches (0.85 Mg ha^{-1}), dead tree (0.47 Mg ha^{-1}) and total detritus biomass (3.78 Mg ha^{-1}) in comparison with community forest.

4.3.2 Detritus carbon density (Mg C ha^{-1})

Detritus carbon density under different tree plantations is shown in table 4.9 which depicts significantly maximum value (1.90 Mg C ha^{-1}) for *Alnus nitida* and minimum value (1.22 Mg C ha^{-1}) for *Robinia pseudoacacia* which remained statistically equal to *Eucalyptus tereticornis* (1.22 Mg C ha^{-1}). Institutional forest was recorded with higher detritus C density (1.80 Mg C ha^{-1}) when compared to community forest. Interaction between management regimes and tree species showed that *Alnus nitida* (2.19 Mg C ha^{-1}) was statistically at par with *Salix tetrasperma* (2.11 Mg C ha^{-1}). Further, *Salix tetrasperma* (2.11 Mg C ha^{-1}) remained statistically at par with *Populus deltoides* (2.02 Mg ha^{-1}). *Eucalyptus tereticornis* (1.31 Mg C ha^{-1}) was also found to be statistically at par with *R. pseudoacacia* (1.35 Mg C ha^{-1}) under institutional forest. *Robinia pseudoacacia* (1.08 Mg C ha^{-1}) under community forest were found to be statistically at par with *Populus deltoides* (1.13 Mg C ha^{-1}) and *E.*

tereticornis (1.12 Mg C ha^{-1}). Whereas, *Populus deltoides* (1.13 Mg C ha^{-1}) and *Eucalyptus tereticornis* (1.12 Mg C ha^{-1}) were found to be statistically at par with each other.

4.4 SOIL CARBON DENSITY (Mg C ha^{-1})

Data in table 4.10 demonstrate that soil carbon density ((Mg C ha^{-1}) of different soil layers viz; humus, 0-20, 20-40 cm and humus + soil (0-40 cm) varied significantly for different tree plantations among different management regimes.

In humus layer, maximum carbon density (0.65 Mg C ha^{-1}) has been recorded for *Alnus nitida*, which was followed by *Salix tetrasperma*, *Populus deltoides*, *Eucalyptus tereticornis* and *Robinia pseudoacacia* respectively, in descending order. *Populus deltoides* (0.41 Mg C ha^{-1}) was found to be statistically at par with *Eucalyptus tereticornis* (0.40 Mg C ha^{-1}). Minimum value was recorded under *Robinia pseudoacacia*.

For 0-20 cm layer, maximum soil carbon density was displayed by *Salix tetrasperma* (27.96 Mg C ha^{-1}), which, however remained statistically at par with *Alnus nitida* (26.28 Mg C ha^{-1}) and also *Populus deltoides* (24.80 Mg C ha^{-1}) remained statistically at par with *Eucalyptus tereticornis* (24.26 Mg C ha^{-1}). Among both the management regimes, trend followed was same as of humus for soil carbon density. Interaction between both the factors were found to be non-significant.

Carbon density in 20-40 cm soil layer varied significantly for management regimes and plantation tree species but the interaction between both these factors did not vary significantly. In 20-40 cm soil layer, highest value of soil carbon density was recorded in *Salix tetrasperma* (24.82 Mg C ha^{-1}) which however remained statistically at par with *Alnus nitida* (24.74 Mg C ha^{-1}) and *Populus deltoides* (24.56 Mg C ha^{-1}). Minimum value of soil carbon density was displayed by *Eucalyptus tereticornis* (20.61 Mg C ha^{-1}) which remained statistically at par with *Robinia pseudoacacia* (20.69 Mg C ha^{-1}).

For soil layer 0-40 cm, maximum soil carbon density (52.78 Mg C ha^{-1}) was recorded for *Salix tetrasperma* which was found to be statistically at par with *Alnus nitida* (51.02 Mg C ha^{-1}), this further was found to be statistically at par with *Populus deltoides* (49.36 Mg C ha^{-1}). Minimum value was recorded for *Robinia pseudoacacia* (43.51 Mg C ha^{-1}) which was found to be statistically at par with *Eucalyptus tereticornis* (44.86 Mg C ha^{-1}). Further, institutional forest was recorded with higher soil carbon density (53.82 Mg C ha^{-1}). Interaction between these factors was found to be statistically non-significant for soil carbon density.

Table 4.9: Detritus carbon density (Mg C ha^{-1}) of different plantation tree species under different management regimes

Management Regimes / Treatments	Leaf litter (Mg C ha^{-1})			Dead twigs and branches (Mg C ha^{-1})			Dead trees (Mg C ha^{-1})			Total detritus (Mg C ha^{-1})		
	M_1	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**
T_1 (R. pseudoacacia)	0.83	0.63	0.73	0.43	0.33	0.38	0.10	0.11	0.10	1.35	1.08	1.22
T_2 (P. deltoides)	1.33	0.70	1.02	0.40	0.32	0.36	0.29	0.11	0.20	2.02	1.13	1.58
T_3 (S. tetrasperma)	1.36	0.90	1.13	0.46	0.25	0.36	0.28	0.12	0.20	2.11	1.28	1.69
T_4 (E. tereticornis)	0.92	0.81	0.87	0.26	0.19	0.22	0.14	0.12	0.13	1.31	1.12	1.22
T_5 (A. nitida)	1.40	1.13	1.26	0.47	0.32	0.40	0.32	0.16	0.24	2.19	1.61	1.90
MEAN	1.17	0.84		0.41	0.28		0.23	0.13		1.80	1.24	
$CD_{0.05}$												
Management Regimes (M)	: 0.03			0.03			0.03			0.06		
Tree Species (T)	: 0.05			0.05			0.05			0.10		
M×T	: 0.07			0.07			0.07			0.14		

In total [Humus + soil layers (0-40 cm)], soil carbon density varied significantly for management regimes and plantation tree species but the interaction between both these factors were found to be non- significant. Maximum value for soil carbon density (53.33 Mg C ha^{-1}) was recorded for *Salix tetrasperma* which was found to be statistically at par with *Alnus nitida* (51.67 Mg C ha^{-1}). Whereas, minimum value (43.68 Mg C ha^{-1}) of soil carbon density was observed for *Robinia pseudoacacia* which followed the same trend as of 0-40 cm soil layer.

4.5 ECOSYSTEM CARBON DENSITY (Mg C ha^{-1})

A perusal of data presented in table 4.11 reveals that the carbon density for plantation tree species and under different management regimes varied significantly.

Vegetation carbon density for institutional forest (table 4.11) revealed that maximum value was recorded for *Alnus nitida (*67.91 Mg C ha^{-1}) followed by *Eucalyptus tereticornis* (49.50 Mg C ha^{-1}), *Populus deltoides* (48.22 Mg C ha^{-1}), *Salix tetrasperma* (47.57 Mg C ha^{-1}) and minimum was found for *Robinia pseudoacacia* (38.84 Mg C ha^{-1}).

For community forest (table 4.11) maximum contribution of carbon density was reported by *Alnus nitida (*27.18 Mg C ha^{-1}) followed by *Populus deltoides* (24.20 Mg C ha^{-1}), *Eucalyptus tereticornis* (24.06 Mg C ha^{-1}), *Salix tetrasperma* (19.13 Mg C ha^{-1}) and minimum was found for *Robinia pseudoacacia* (18.73 Mg C ha^{-1}).

Detritus carbon density under different tree plantations is shown in table 4.9 which depicts significantly maximum value (1.90 Mg C ha^{-1}) for *Alnus nitida* and minimum value (1.22 Mg C ha^{-1}) for *Robinia pseudoacacia* which remained statistically equal to *Eucalyptus tereticornis* (1.22 Mg C ha^{-1}). Institutional forest was recorded with maximum value (1.80 Mg C ha^{-1}) when compared to community forest. Interaction between management regimes and tree species showed that *Alnus nitida* (2.19 Mg C ha^{-1}) was statistically at par with *Salix tetrasperma* (2.11 Mg C ha^{-1}). Further, *Salix tetrasperma* (2.11 Mg C ha^{-1}) remained statistically at par with *Populus deltoides* (2.02 Mg ha^{-1}). *Eucalyptus tereticornis* (1.31 Mg C ha^{-1}) was also found to be statistically at par with *Robinia pseudoacacia* (1.35 Mg C ha^{-1}) under institutional forest. *Robinia pseudoacacia* (1.08 Mg C ha^{-1}) under community forest was found to be statistically at par with *Populus deltoides* (1.13 Mg C ha^{-1}) and *Eucalyptus tereticornis* (1.12 Mg C ha^{-1}). Whereas, *Populus deltoides* (1.13 Mg C ha^{-1}) and *Eucalyptus tereticornis* (1.12 Mg C ha^{-1}) were found to be statistically at par with each other.

Table 4.10: Soil carbon density (Mg C ha^{-1}) of different plantation tree species under different management regimes

Management Regimes / Treatments	Humus			0-20 cm			20-40 cm			0-40 cm			Total [Humus + soil layers (0-40 cm)]		
	M_1	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**
T_1 (R. pseudoacacia)	0.19	0.15	0.17	25.16	20.48	22.82	23.62	17.76	20.69	48.77	38.24	43.51	48.96	38.39	43.68
T_2 (P. deltoides)	0.47	0.35	0.41	27.37	22.22	24.80	27.29	21.83	24.56	54.67	44.05	49.36	55.14	44.40	49.77
T_3 (S. tetrasperma)	0.58	0.51	0.55	31.09	24.83	27.96	26.98	22.65	24.82	58.08	47.48	52.78	58.66	47.99	53.33
T_4 (E. tereticornis)	0.41	0.39	0.40	28.53	19.99	24.26	23.97	17.25	20.61	52.49	37.23	44.86	52.89	37.62	45.26
T_5 (A. nitida)	0.77	0.54	0.65	28.65	23.89	26.28	26.42	23.05	24.74	55.08	46.95	51.02	55.85	47.48	51.67
MEAN	0.48	0.39		28.16	22.82		25.66	20.51		53.82	42.79		54.30	43.18	
$CD_{0.05}$															
Management Regimes (M)	: 0.02			1.13			1.13			1.69			1.69		
Tree Species (T)	: 0.02			1.78			1.79			2.67			2.68		
M×T	: 0.04			NS			NS			NS			NS		

Data presented in table 4.10 demonstrate that soil carbon density in total i.e. humus + soil (0-40 cm layer) did not varied significantly among plantation tree species and different management regimes.

For both the management regimes, highest ecosystem carbon density (125.94 Mg C ha^{-1}) was displayed by *Alnus nitida*, followed by *Salix tetrasperma* (108.33Mg C ha^{-1}) which remained statistically at par with *Populus deltoides* (105.38 Mg C ha^{-1}), which further found to be statistically at par with *Eucalyptus tereticornis* (103.71 Mg C ha^{-1}). Whereas, minimum value of total carbon density under plantation was displayed by *Robinia pseudoacacia* (89.15 Mg C ha^{-1}). Same trend was displayed by community forest (table 4.11) for carbon density of plantation tree species under different management regimes.

Table 4.11: Carbon density (Mg C ha^{-1}) of different plantation tree species under different management regimes

Management Regimes / Treatments	Vegetation		Soil		Detritus		Ecosystem		Soil: Vegetation ratio	
	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2
T_1 (R. pseudoacacia)	38.84	18.73	48.96	38.39	1.35	1.08	89.15	58.20	1.26	2.06
T_2 (P. deltoides)	48.22	24.20	55.14	44.40	2.02	1.13	105.38	69.73	1.14	1.83
T_3 (S. tetrasperma)	47.57	19.13	58.66	47.99	2.11	1.28	108.33	68.41	1.23	2.52
T_4 (E. tereticornis)	49.50	24.05	52.89	37.62	1.31	1.12	103.71	62.80	1.07	1.56
T_5 (A. nitida)	67.91	27.18	55.85	47.48	2.19	1.61	125.94	76.28	0.82	1.75
MEAN	50.41	22.66	54.30	43.18	1.80	1.24	106.51	67.08	1.11	1.94
$CD_{0.05}$	2.22		NS		0.14		4.58		0.25	

Results pertaining to soil: vegetation ratio (table 4.11) in plantation forest ecosystem varied significantly. Highest ratio was displayed by *Robinia pseudoacacia* (1.26 Mg C ha^{-1}). Whereas minimum value was recorded for *Alnus nitida* (0.82 Mg C ha^{-1}), under institutional forest.

Further, under community forest, highest ratio was displayed by *Salix tetrasperma* (2.52 Mg C ha^{-1}). Whereas, minimum value was reported for *Eucalyptus tereticornis* (1.56 Mg C ha^{-1}) followed by *Alnus nitida* (1.75 Mg C ha^{-1}).

The study presented in table 4.6 highlights substantial variations in carbon density or carbon stock among different plantation tree species under diverse management practices, ranging from 15 to 70 Megagrams per hectare (Mg/ha). This observation is consistent with previous research by Joshi and Dhyani (2018), Chaturvedi *et al*., (2011), and Russell *et al.*, (2000).

Carbon stocks are highly dependent on the tree density (Pragasan LA, 2014) and carbon concentration in each and every component of tree species. Research conducted in Central India's tropical dry deciduous forests revealed a range of total tree carbon density between 48.97 and 214.97 Mg carbon per hectare (C/ha). Notable species such as *Diospyros melanoxylon, Butea monosperma, Shorea robusta, Senegalia catechu, Spondias pinnata, and Lagerstroemia parviflora* played a significant role in higher carbon storage within these forests (Dimobe *et al*., 2019). In another tropical dry forest study, carbon accumulation was primarily found in mature trees. Species like *Acacia catechu*, *Buchanania lanzan, Hardwickia binata, Shorea robusta* and *Terminalia tomentosa* exhibited elevated carbon density (Wang *et al.,* 2018). Carbon stock assessments of tree vegetation within India's Bodamalai hills tropical forests fell within the global range of 3.53 to 38.92 tons of carbon per hectare (t C/ha). Among these, mixed-deciduous forests exhibited the highest carbon stock at 30.81 tC/ha, particularly in the lower size class (30-90 cm girth at breast height), as reported by Pragasan (2015). In the context of reforestation efforts around Mountain and Lake Batur, Sujarwo and Darma (2011) conducted a study involving the planting of diverse tree species on previously bare land. Their findings revealed an above-ground carbon stock of 28.06 tons per 0.24 hectares (ha), indicating a total carbon stock of 46,778.17 tons across a 400-hectare area of secondary forests surrounding Mountain and Lake Batur.

The examination of extensive native shrub and herb species contribution to the carbon reservoir (as shown in table 4.7) involved the analysis of biomass spanning from 0.14 to 3.20 Megagrams of carbon per hectare (Mg C/ha). These findings align with a study conducted in the Iberian dehesas, where the total carbon content stored in shrubs, encompassing both above- and belowground biomass, varies between 1.8 and 11.2 Mg C/ha for *Cistus ladanifer* and ranges from 2.6 to 8.6 Mg C/ha for *Retama sphaerocarpa*, as indicated by Roig *et al*., (2013). The carbon storage of individual shrub species within the Iberian dehesas fluctuates between 1.8 and 11.2 Mg C/ha. Lufafa *et al.,* (2008) have quantified the carbon stocks in shrub biomass, demonstrating a range of 0.9 to 2.0 Mg C/ha in native shrub communities within Senegal's Peanut basin.

The carbon density of vegetation, encompassing trees, shrubs, and herbs (as presented in table 4.5 and table 4.7), displays a range spanning from 15.75 to 70 Megagrams per hectare (Mg/ha), which concurs with the findings of Wang *et al.,* (2004) and Jhariya (2017).

The storage of carbon within shrubs and forests holds significant potential to contribute to the overall carbon pool within ecosystems. The combined carbon density of vegetation (comprising herbs, shrubs, and trees) and soil reaches its peak in the *U. villosa* plantation, totaling 86.21 tons per hectare (t ha^{-1}), with soil accounting for 49.13 t ha^{-1}. A descending order of carbon density (including both vegetation and soil) across systems is observed as follows: *U. villosa* (135.34 t ha^{-1}) > Mixed Forest (97.63 tha-1) > *E. tereticornis* (96.51 t ha^{-1}) > *A. mollissima* (88.37 t ha^{-1}) > *Q. leucotricophora* (86.72 t ha^{-1}) > *P. roxburghii* (85.94 t ha^{-1}) > grassland (45.61 t ha^{-1}), as detailed in Gupta *et al.,* (2015), aligning quite closely with the present study. These quantities collectively account for a significant proportion, ranging from 20% to 30%, of the entire plant biomass within the respective systems. Consequently, the carbon density of vegetation exhibits variability influenced by the distinct characteristics of each ecosystem and the composition of plant species present.

Leaf litter, decaying trees, and twigs (table 4.8 and table 4.9) originating from detritus play a crucial role in determining the carbon density within forest tree plantations of broadleaved species. The transition from natural forests to these plantations has the potential to modify the quantity and composition of organic matter entering the soil, subsequently impacting the decomposition of soil organic matter (SOM), as noted by Lyu *et al*., in 2018. Variations in carbon content are notable among different tree species, with trunks and stems having the highest carbon content, followed by leaves and roots, as observed by丁访军 Ding *et al.,* in 2015. The carbon storage potential of fast-growing tree species like *Alnus subcordata, Populus deltoides,* and *Taxodium distichum* encompasses live biomass, the forest floor, and soil organic matter, according to findings by Eslamdoust and Sohrabi in 2018. The quality of litter and soil characteristics, encompassing pH, organic carbon levels, nutrient availability, and microbial activity, diverges across tree species, thus exerting influence over carbon density and cycling within mixed forest stands, as highlighted by Kooch *et al.,* in 2017.

The soil carbon density within plantation tree species exhibits a range spanning from 38.39 to 58.66 Mg/ha, as documented in table 4.10. Notably, the concentration of soil organic carbon (SOC) beneath sizable tree trunks was discovered to be approximately fourfold greater than the concentration found between trees, as outlined by Dean *et al*., 2020. In a

study conducted within a soil-water conservation area in southeastern China, Xu *et al*., (2019) reported a significant increase in carbon density, rising from 20.14 Mg C/ha in 1981 to 43.57 Mg C/ha in 2015. Likewise, Guan *et al.,* (2019) conducted research in Gansu Province, China, estimating a soil organic carbon density (SOCD) of 175.3 Mg C/ha for the 0-100 cm layer on a regional scale. The dynamics of the soil carbon pool were intricately influenced by factors such as vegetation composition and the spatial distribution of carbon within the soil profile. Examining the soil organic carbon pool (expressed in Mg C ha^{-1}): it ranged from 7.383 to 4.923 (0-15 cm); 6.693 to 4.183 (15-30 cm); 4.166 to 3.335 (30-45 cm); and 3.590 to 2.500 (45-60 cm). It's worth noting that within the 0-30 cm soil depth, the soil organic carbon pool comprised 54.73% to 64.52% of the total organic carbon pool encompassing the 60 cm soil depth, according to Singh *et al*., (2017) study.

Various factors influence the carbon density within ecosystems dominated by broadleaf plantations. Research has indicated that compared to natural forests, these plantations tend to exhibit lower soil carbon concentrations. This is often accompanied by reductions in aboveground net primary production, litterfall, and soil respiration rates, as observed by Shunbao *et al*., (2019). The carbon storage in these ecosystems is notably impacted by forest management practices, while soil carbon storage is primarily governed by moisture-related factors. Studies by Liao *et al*., (2010) found decreases in fine root biomass, soil carbon concentration, and soil microbial carbon concentration in plantation settings compared to natural forests. Notably, the distribution of carbon storage between vegetation and soil differs across various forest types. For instance, plant carbon storage ranges from 68.09 t ha^{-1} in aspen-white birch forests to 117.81 t ha^{-1} in mixed Korean pine-broadleaved hardwood forests, while soil carbon storage ranges from 153.23 t ha^{-1} in mixed Korean pine-broadleaved hardwood forests to 261.58 t ha^{-1} in aspen-white birch forests, as concluded by Ma *et al*., in 2015. Bin *et al*., (2017) emphasized in that both forest management practices and moisture-related factors significantly shape the division of carbon allocation between vegetation and soil in diverse forest types. Guo *et al*., noted in 2016 that carbon storage varies across different tree components, with stems holding the highest carbon storage capacity.

These findings collectively underscore the intricate and multifaceted nature of carbon density in broadleaf plantation ecosystems. It highlights the necessity of accounting for a wide array of environmental factors in the management of carbon within these ecosystems.

4.6 CARBON SEQUESTRATION (Mg C ha $^{-1}$)

Carbon sequestration potential is calculated by carbon density of components of ecosystem (soil, plantation and total) located just adjoining to the established plantation of the respective tree species from the plantation tree species components. The same has been reported in table 4.12 and discussed under following heads and sub-heads.

4.6.1 Carbon Density Under Plantation Ecosystem

4.6.2 Carbon Density Outside Plantation Ecosystem

4.6.3 Carbon Sequestration

4.6.1 Carbon Density Under Plantation Ecosystem (Mg C ha^{-1})

A perusal of data presented in table 4.12 reveal that the carbon density of plantation tree species under different management regimes in vegetation and total (vegetation + soil) varied significantly. Whereas, soil carbon density did not vary significantly among plantation tree species and management regimes.

In institutional forest (table 4.12), maximum plant carbon density was observed by *Alnus nitida* (70.10 Mg C ha^{-1}) followed by *Eucalyptus tereticornis* (50.81 Mg C ha^{-1}), which remained statistically at par with *Populus deltoides* (50.24 Mg C ha^{-1}) and *Salix tetrasperma* (49.67 Mg C ha^{-1}). Minimum value of plant carbon density was recorded for *Robinia pseudoacacia* (40.19 Mg C ha^{-1}).

In community forest (table 4.12) maximum plant carbon density was observed by *Alnus nitida* (28.80 Mg C ha^{-1}) followed by *Populus deltoides* (25.33 Mg C ha^{-1}), which remained statistically at par with *Eucalyptus tereticornis* (25.18 Mg C ha^{-1}). Minimum value of plant carbon density was recorded for *Robinia pseudoacacia* (19.81 Mg C ha^{-1}) which remained statistically at par with *Salix tetrasperma* (20.41 Mg C ha^{-1}).

Total carbon density also varied significantly among plantation tree species with the highest value was recorded in *Alnus nitida* (125.95 Mg C ha^{-1}), followed by *Salix tetrasperma* (108.33Mg C ha^{-1}) which remained statistically at par with *Populus deltoides* (105.38 Mg C ha^{-1}), which further found to be statistically at par with *Eucalyptus tereticornis* (103.71 Mg C ha^{-1}). The lowest value of total carbon density under plantation was displayed by *Robinia pseudoacacia* (89.15 Mg C ha^{-1}). The community forest also exhibited a similar pattern in terms of carbon density among plantation tree species for total (vegetation + soil) components, as shown in table 4.12.

Table 4.12: Carbon Sequestration (Mg C ha^{-1}) of different plantation tree species under different management regimes

Treatments \ Management Regimes	Carbon density under plantation ecosystem						Carbon density outside plantation ecosystem						Carbon sequestration					
	Plant		Soil		Total		Plant		Soil		Total		Plant		Soil		Total	
	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2
T_1 (*R. pseudoacacia*)	40.19	19.81	48.96	38.39	89.15	58.20	4.12	2.74	1.40	1.47	5.52	4.21	36.07	17.07	47.56	36.93	83.63	53.99
T_2 (*P. deltoides*)	50.24	25.33	55.14	44.40	105.38	69.73	4.19	4.58	1.65	1.06	5.84	5.63	46.06	20.76	53.49	43.34	99.55	64.09
T_3 (*S. tetrasperma*)	49.67	20.41	58.66	47.99	108.33	68.41	2.90	3.05	0.91	1.08	3.81	4.13	46.77	17.36	57.75	46.91	104.52	64.28
T_4 (*E. tereticornis*)	50.81	25.18	52.89	37.62	103.71	62.80	3.40	5.18	1.12	1.12	4.52	6.30	47.42	20.00	51.78	36.50	99.20	56.50
T_5 (*A. nitida*)	70.10	28.80	55.85	47.48	125.95	76.28	3.57	2.92	0.77	0.45	4.34	3.37	66.53	25.88	55.08	47.04	121.60	72.91
MEAN	52.20	23.91	54.30	43.18	106.51	67.08	3.64	3.69	1.17	1.04	4.81	4.73	48.57	20.21	53.13	42.14	101.70	62.36
$CD_{0.05}$	2.25		NS		4.58		1.01		0.87		1.29		2.58		NS		5.26	

4.6.2 Carbon Density Outside Plantation Ecosystem (Mg C ha^{-1})

A perusal of data presented in table 4.12 reveal that carbon density outside plantation ecosystem in plant, soil and total (plant + soil) varied slightly but significantly for plantation tree species under different management regimes. Maximum value for plant carbon density (4.19 Mg C ha^{-1}) was recorded for *Populus deltoides*. The carbon density of other plantation tree species viz; *Robinia pseudoacacia* (4.12 Mg C ha^{-1}), *Salix tetrasperma* (2.90 Mg C ha^{-1}), *Eucalyptus tereticornis* (3.40 Mg C ha^{-1}) and *A*lnus *nitida* (3.57 Mg C ha^{-1}) remained statistically at par with one another. Minimum amount of carbon density was recorded for *Salix tetrasperma* (2.90 Mg C ha^{-1}) under institutional forest.

Data presented in table 4.12 exhibits that soil carbon density outside plantation ecosystem varied slightly (0.87), but significantly among plantation tree species under both the management regimes. For institutional forest (table 4.12) maximum value of soil carbon density (1.65 Mg C ha^{-1}) was recorded for *Populus deltoides*, which however remained statistically at par with *Robinia pseudoacacia* (1.40 Mg C ha^{-1}), *Salix tetrasperma* (0.91 Mg C ha^{-1}) and *Eucalyptus tereticornis* (1.12 Mg C ha^{-1}). Whereas, minimum value (0.77 Mg C ha^{-1}) was displayed by *Alnus nitida*, which was also found to be statistically at par with *Robinia pseudoacacia* (1.40 Mg C ha^{-1}), *Salix tetrasperma* (0.91 Mg C ha^{-1}), *Eucalyptus tereticornis* (1.12 Mg C ha^{-1}). For community forest (table 16), maximum value of soil carbon density (1.47 Mg C ha^{-1}) was recorded for *Robinia pseudoacacia* which however remained statistically at par with *Populus deltoides* (1.06 Mg C ha^{-1}), *Salix tetrasperma* (1.08 Mg C ha^{-1}) and *Eucalyptus tereticornis* (1.12 Mg C ha^{-1}). Further, minimum value (0.45 Mg C ha^{-1}) was displayed by *Alnus nitida*, which was observed to be statistically different from *Robinia pseudoacacia* (1.47 Mg C ha^{-1}) and were statistically at par with *Populus deltoides* (1.06 Mg C ha^{-1}), *Salix tetrasperma* (1.08 Mg C ha^{-1}) and *Eucalyptus tereticornis* (1.12 Mg C ha^{-1}).

As perusal of data presented in table 4.12 reveal that total carbon density outside the plantation varied significantly. Maximum value of total carbon density outside the plantation (5.84 Mg C ha^{-1}) was reported for *Populus deltoides* which remained statistically at par with *Robinia pseudoacacia* (5.52 Mg C ha^{-1}). The carbon density in other tree species remained statistically at par with one another. Whereas, minimum value (3.81 Mg C ha^{-1}) was recorded for *Salix tetrasperma*.

Data presented in table 4.12 for total total carbon density outside the plantation also varied significantly for community forest. *Eucalyptus tereticornis* (6.30 Mg C ha^{-1}) was recorded with maximum value for total carbon density viz; vegetation + soil and found to be statistically different from other tree species but statistically at par with *Populus deltoides* (5.63 Mg C ha^{-1}). Minimum value (3.37 Mg C ha^{-1}) was observed under *Alnus nitida.*

4.6.3 Carbon Sequestration (Mg C ha^{-1})

Data in table 4.12 demonstrates that carbon sequestration potential (CSP) varied significantly with plantation tree species, vegetation and vegetation + soil combined together.

Vegetation carbon sequestration as presented in table 4.12 demonstrated that *Alnus nitida* (66.53 Mg C ha^{-1}) displayed highest value of vegetation carbon sequestration. *Populus deltoides, Salix tetrasperma* and *Eucalyptus tereticornis* displayed statistically at par values with each other for vegetation carbon sequestration. Whereas, minimum value of vegetation carbon sequestration was displayed by *Robinia pseudoacacia* (36.07 Mg C ha^{-1}) under institutional forest. Among the plantation tree species in the community forest (as indicated in table 4.12), *Alnus nitida* demonstrated the highest vegetation carbon sequestration value at 25.88 Mg C ha^{-1}. The remaining plantation tree species exhibited minor yet statistically significant variations in this aspect.

A perusal of data presented in table 4.12 reveal that carbon sequestration in soil did not vary significantly among plantation tree species and management regimes.

Total carbon sequestration (Vegetation + Soil) also varied among plantation types. For institutional forest, maximum value of total carbon sequestration (121.60 Mg C ha^{-1}) was recorded for *Alnus nitida*. Whereas, minimum value of total carbon sequestration (83.63 Mg C ha^{-1}) was recorded for *Robinia pseudoacacia*. Further, *Populus deltoides* (99.55 Mg C ha^{-1}) was found to be statistically at par with *Salix tetrasperma* (104.52 Mg C ha^{-1}) and *Eucalyptus tereticornis* (99.20 Mg C ha^{-1}).

Maximum value (72.91 Mg C ha^{-1}) for total carbon sequestration under community forest was found for *Alnus nitida*. *Robinia pseudoacacia* (53.99 Mg C ha^{-1}) and *Eucalyptus tereticornis* (56.50 Mg C ha^{-1}) found to be significantly at par with each other. Whereas, *Populus deltoides* (64.09 Mg C ha^{-1}) varied significantly at par with *Salix tetrasperma* (64.28 Mg C ha^{-1}).

4.7 RATE OF CARBON SEQUESTRATION AND CO_2 MITIGATION

Carbon sequestration and carbon dioxide (CO_2) mitigation potential in vegetation, soil and total (Vegetation + Soil) presented in table 4.13 varied significantly with plantation tree species and management regimes and the same has been discussed under following heads:

4.7.1 Rate of Carbon Sequestration (Mg C ha^{-1} yr^{-1})

4.7.2 Rate of Carbon Dioxide mitigation (Mg C ha^{-1} yr^{-1})

4.7.1 Rate of Carbon Sequestration (Mg C ha^{-1} yr^{-1})

Highest amount of carbon sequestration rate in vegetation (table 4.13) was obtained (1.85 Mg C ha^{-1}) for *Alnus nitida*. Whereas, *Populus deltoides* (1.28 Mg C ha^{-1}) varied significantly with *Salix tetrasperma* (1.30 Mg C ha^{-1}) and *Eucalyptus tereticornis* (1.32 Mg C ha^{-1}). Further, the later species were found to be significantly at par with each other. Minimum value (1.00 Mg C ha^{-1}) of rate of carbon sequestration was displayed by *Robinia pseudoacacia* under institutional forest. Same trend was followed by different plantation tree species for rate of carbon sequestration potential under community forest.

A perusal of data presented in table 4.13 demonstrated that rate of carbon sequestration potential for soil did not vary significantly for different plantation tree species under both the management regimes.

Maximum (3.38 Mg C ha^{-1}) rate of carbon sequestration (vegetation + soil) potential was recorded in *Alnus nitida* plantation. *Populus deltoides* (2.77 Mg C ha^{-1}) was found to be statistically at par with *Salix tetrasperma* (2.90 Mg C ha^{-1}) and *Eucalyptus tereticornis* (2.76 Mg C ha^{-1}) and both the species were found to be statistically at par with each other. Minimum value (2.32 Mg C ha^{-1}) was found in *Robinia pseudoacacia* plantation under institutional forest.

Rate of carbon sequestration potential for *Populus deltoides* (1.78 Mg C ha^{-1}) and *S. tetrasperma* (1.78 Mg C ha^{-1}) plantation were found statistically equal to each whereas, *Robinia pseudoacacia* (1.50 Mg C ha^{-1}) was found to be statistically at par with *Eucalyptus tereticornis* (1.57 Mg C ha^{-1}). Minimum value (1.50 Mg C ha^{-1}) was found in *Robinia pseudoacacia* plantation under community forest.

Table 4.13: Rate of carbon sequestration (Mg C ha^{-1} yr^{-1}) and carbon mitigation (Mg C ha^{-1} yr^{-1}) potential of different plantation tree species under different management regimes

Treatments \ Management Regimes	Rate of carbon sequestration						Rate of carbon mitigation					
	Plant		Soil		Total		Plant		Soil		Total	
	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2	M_1	M_2
T_1 (*R. pseudoacacia*)	1.00	0.47	1.32	1.03	2.32	1.50	3.68	1.74	4.85	3.77	8.53	5.51
T_2 (*P. deltoides*)	1.28	0.58	1.48	1.20	2.77	1.78	4.70	2.12	5.45	4.42	10.15	6.53
T_3 (*S. tetrasperma*)	1.30	0.48	1.60	1.30	2.90	1.78	4.77	1.77	5.89	4.78	10.66	6.55
T_4 (*E. tereticornis*)	1.32	0.56	1.44	1.02	2.76	1.57	4.83	2.04	5.28	3.72	10.11	5.76
T_5 (*A. nitida*)	1.85	0.72	1.53	1.31	3.38	2.03	6.78	2.64	5.61	4.79	12.40	7.43
MEAN	1.35	0.56	1.48	1.17	2.83	1.73	4.95	2.06	5.42	4.30	10.37	6.36
$CD_{0.05}$	0.07		NS		0.15		0.26		NS		0.54	

4.7.2 Rate of Carbon Dioxide Mitigation (Mg C ha^{-1} yr^{-1})

A perusal of data presented in table 4.13 reveal that rate of carbon dioxide mitigation in vegetation varied among plantation tree species under management regimes. Maximum value (6.78 Mg C ha^{-1}) was displayed by *Alnus nitida*. Whereas, *Populus deltoides* (4.70 Mg C ha^{-1}), *Salix tetrasperma* (4.77 Mg C ha^{-1}) and *Eucalyptus tereticornis* (4.83 Mg C ha^{-1}) were found to be statistically at par with each other under institutional forest.

Maximum value (2.64 Mg C ha^{-1}) under community forest (table 4.13) was reported by *Alnus nitida*. *Populus deltoides* (2.12 Mg C ha^{-1}) was found to be statistically at par with *Eucalyptus tereticornis* (2.04 Mg C ha^{-1}). Whereas, minimum value was displayed by *Robinia pseudoacacia* (1.74 Mg C ha^{-1}) which varied significantly at par with *Salix tetrasperma* (1.77 Mg C ha^{-1}).

Rate of carbon dioxide mitigation in soil found not to be significant among different plantation tree species for both the management regimes.

Data presented in table 4.13 for institutional forest exhibits that maximum value of total carbon dioxide mitigation rate (12.40 Mg C ha^{-1}) was recorded in *Alnus nitida*. Same trend as off vegetation carbon mitigation potential was followed for other plantation tree species. Whereas, for community forest again maximum value of total carbon dioxide mitigation rate (7.43 Mg C ha^{-1}) was recorded in *Alnus nitida* plantation. All the other species were found to be statistically at par with each other. Minimum value (5.51 Mg C ha^{-1}) was recorded for *Robinia pseudoacacia.*

Carbon stock refers to the total amount of carbon present at the time of measurement, whereas carbon sequestration rate pertains to the process of extracting carbon from the environment and storing it in a reservoir (Takimoto *et al*., 2009). Consequently, the total carbon sequestration potential (as shown in table 4.14) and the carbon sequestration rate (as indicated in table 4.13) of all the components contributing to carbon sequestration were higher in *Alnus nitida* for both management regimes, followed by *Salix tetrasperma* and *Populus deltoides.*

When considering only the woody components for long-term carbon storage, these findings align with the results of Wang and Fenz (1995) and Chesney and Nygren (2002) for

Populus deltoides and *Eucalyptus tereticornis*. They also coincide with studies showing similar results for various tree species of *Poplar* and *Eeythrina poeppigiana*. Carbon storage can be notably high in complex agroforestry land use systems, with productivity influenced by factors such as tree age, structure, and the management of the planting system (Swamy and Puri, 2005; Oelbermann *et al*., 2004; Tumwebaze, 2012).

The carbon density in tree biomass depends upon its age, dbh, structure, functional component and the intensity of management (Heriansyah *et al*., 2007). These results are also comparable with the findings of Komiyama *et al.,* (2008) and Chandra *et al*., (2011) who reported that variation in carbon stock may be related to ecology, species composition and location. Yadava (2010) and Juwarkar *et al*., (2011) who reported that trees during initial stages of growth will sequester less carbon and gradually increase its storage with the advancement in age or increase in diameter and height growth. Similar results of increase in carbon stock with increase in tree diameter have been reported by Bhardwaj *et al*., (2001); Albrecht and Kandji (2003); Raizada *et al.,* (2007); Gera *et al*., (2011); Ramachandran *et al.,* (2007); Yadava (2010) and Fonseca *et al*., (2012) for various species under a range of climate and edaphic factors.

Prasad *et al*., (2010) concluded from their study that there is a notable variation among different tree species regarding the allocation of carbon content across various plant parts. It can also be inferred that this significant variation in carbon content among the selected species may be attributed to their genetic composition, crown structure, and the unique chemical and anatomical characteristics of their wood, as suggested by Lamlom and Savidge (2003).

The diversity in carbon allocation among different tree components may be the result of complex interactions occurring between carbon source organs (such as leaves) and carbon sinks, including stems, branches, roots, and others, within a tree, as indicated by Genard *et al.,* (2008). The variations in carbon stock are influenced by several factors, including the type of agroforestry system, site quality, and the land use history. Similar findings regarding carbon stock have been documented by Kumar *et al.*, (2012) and Roshanzada *et al.*, (2018).

These results also aligned with the findings of Post and Kwon (2000), who stated that the average rate of soil carbon sequestration falls within the range of 0 to 3 Mg C ha^{-1} yr^{-1}, with an average value of 0.3 Mg C ha^{-1} yr^{-1}, across various climatic zones. The differences in

the rate of carbon dioxide (CO_2) mitigation potential in plantations can be attributed to their varying rates of photosynthesis, as indicated by Devi *et al.,* (2013).

Loranger *et al.,* (2016) quantitatively highlighted the interplay between regional and local environmental gradients in driving community assembly. Depending on the climatic conditions, taxonomic and functional community composition can be opposite to expected productivity- diversity and disturbance- diversity relationships.

The study reveals that *Alnus nitida*, a moisture loving tree grows gregarious in whole of the riparian corridor along the elevational gradient. Besides *Alnus nitida, Robinia pseudoacacia* and *Populus ciliata* have successfully acclimatized themselves over the slopes as artificially raised plantations (Sharma and Sharma, 2018).

Alder was evaluated by different scientist regarding carbon accumulation. Frouz *et al.,* (2009) in Dakota (USA) designed an experiment with three stand design based on supply, demand and anthropogenic activities indicated that Alder was one among the trees to accommodate 1735.69 million kg carbon. According to Uri *et al.,* (2014) the carbon accumulation capacity of Alder ranges from 0.60 +- 0.09 to 2.31 +-0.23 t $ha^{-1}year^{-1}$. The biomass of a tree is usually linked to the amount of carbon absorbed from the environment (Zhao and Sander, 2015). The young and old trees of Alder have the same potential to accumulate carbon.

4.8 LEAF LITTER DYNAMICS

4.8.1 Leaf Litter Content in Different Tree Plantation Ecosystem under Different Management Regimes

A perusal of the data in table 4.14 revealed that plantation tree species exerted significant difference in litter content. During all the three seasons i.e. winter, summer and rainy, *Alnus nitida* was found with the maximum total litter content of 2.03 (kg m^{-2}). Institutional forest was recorded with higher total litter content of 1.68 (kg m^{-2})**.** It was found that *Populus deltoides* and *Eucalyptus tereticornis* was found to be statistically at par with each other, whereas, *Robinia pseudoacacia* displayed minimum value of 1.16 (kg m^{-2}).

Table 4.14: Effect of seasons (winter, summer and rainy) on leaf –litter production (kg m^{-2}) under different plantation tree species in different management regimes

Management Regimes / Treatments	Winter			Summer			Rainy			Total		
	M_1	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**	**M_1**	**M_2**	**Mean**
T_1* (*R. pseudoacacia)	0.59	0.53	0.56	0.37	0.33	0.35	0.29	0.22	0.26	1.25	1.08	1.16
T_2 (P. deltoides)	0.68	0.65	0.66	0.48	0.45	0.46	0.38	0.29	0.34	1.54	1.38	1.46
T_3 (S. tetrasperma)	0.77	0.71	0.74	0.59	0.55	0.57	0.54	0.44	0.49	1.90	1.70	1.80
T_4 (E. tereticornis)	0.65	0.59	0.62	0.48	0.40	0.44	0.44	0.38	0.41	1.57	1.37	1.47
T_5 (A. nitida)	0.84	0.78	0.81	0.67	0.60	0.63	0.62	0.55	0.59	2.13	1.93	2.03
Mean	0.71	0.65		0.52	0.47		0.46	0.38		1.68	1.49	
$C.D._{0.05}$												
Management Regimes (M)	: 0.02			0.02			0.02			0.03		
Tree Species (T)	: 0.03			0.03			0.03			0.04		
M×T	: 0.15			0.15			0.15			0.25		

In different seasons leaf litter content was in order: winter (0.56-0.81 kg m^{-2}) > summer (0.35-0.63 kg m^{-2}) > rainy season (0.26-0.59 kg m^{-2}). *Alnus nitida* was found with the maximum litter content of 0.81, 0.63 and 0.59 kg m^{-2}, respectively for all the three seasons.

The present study showed that the season wise litter production in different tree plantation indicated that the peak accumulation is found in winter season as compared to summer and rainy season. These results are in accordance and or contrary with following findings: litterfall in the deciduous forest had a bimodal distribution, reaching a maximum in autumn and winter and a second peak in midsummer. The autumn/winter maximum was due primarily to leaf litter abscission (Abelho and Graca, 1996). This finding is found in contrary with the finding of Sharma *et al*., 2020 who found that the seasonal pattern of forest floor data exhibited by most of the forest type was: Rainy > summer > winter. Most of the forest types were observed with maximum litterfall during summer season.

Comparing different species under different seasons are in line with Pande and Sharma (1986) who found that later half of winter to earlier half of summer (Febrauary-March to April – May) was the peak fall period. General trend of inverse relationship among the rainfall and litter falls in study also get support from Martius *et al*., (2004). Higher rate of leaf litter content in winters are confirmed by Lodhiyal *et al*., 2002 that in different seasons *i.e.* winter, summer and rainy, highest litter content was found in order: winter (5.70-8.74 t ha^{-1})> summer (3.91-6.05 t ha^{-1}) > rainy season (0.72-1.51 t ha^{-1}).

4.9 PLANT NUTRIENT ESTIMATION

The nutrient contents: N, P, K, Ca and Mg as observed in *Robinia pseudoacacia, Populus deltoides, Salix tetrasperma, Eucalyptus tereticornis* and *Alnus nitida* under different management regime have been depicted from tables 4.15 - 4.19, respectively.

4.9.1 Nutrient distribution in different components of plantation tree species under different management regimes

Upon reviewing the data, it becomes evident that among the plantation tree species, namely *Robinia pseudoacacia, Populus deltoides, Salix tetrasperma, Eucalyptus tereticornis*, and *Alnus nitida*, the distribution of nitrogen levels exhibited distinct patterns under the institutional forest and community forest settings. Specifically, in the institutional forest, the nitrogen levels ranked in the order of root > leaf > branch > stem for the mentioned species, whereas in the community forest, the sequence was leaf > root > branch > stem.

The concentration of phosphorus varied significantly across different plantation tree species within the institutional forest, displaying a pattern of shoot > leaf > root > branch. In contrast, the trend observed in the community forest was leaf > shoot > root > branch.

Regarding nutrients such as potassium (K), calcium (Ca) and magnesium (Mg), the trends displayed noteworthy variations across different tree components, including leaf, stem, branch, and root. However, these variations followed consistent patterns under both management regimes. Specifically, for potassium, the trend was leaf > root > stem > branch in both the regimes. Calcium exhibited a sequence of stem > leaf > branch > root, while magnesium showcased a pattern of stem > root > branch > leaf, maintaining consistency under both institutional and community forest management.

Across all tree species, the relative abundance of nutrients followed the sequence: N > Ca > K > Mg > P.

Table 4.15: Comparative analysis of different plantation species for nitrogen content in tree components under different management regimes

Treaments / Management Regimes	Nitrogen (Mg ha^{-1})					
	LEAF					
	T_1	**T_2**	**T_3**	**T_4**	**T_5**	**Mean**
Institutional forest	21.19	12.95	26.71	15.46	25.81	20.43
Community forest	8.57	8.11	14.29	9.51	15.44	11.19
Mean	14.88	10.53	20.50	12.48	20.63	
$CD_{0.05}$	M: 2.01		T: 3.18	M×T: 4.49		
	STEM					
Institutional forest	12.76	10.49	13.84	9.03	25.22	14.27
Community forest	4.63	4.19	4.79	3.79	6.80	4.84
Mean	8.70	7.34	9.32	6.41	16.01	
$CD_{0.05}$	M: 0.78		T: 1.26	M×T: 1.79		
	BRANCHES					
Institutional forest	13.22	15.13	17.82	11.02	27.46	16.93
Community forest	6.27	6.55	5.83	5.35	9.55	6.71
Mean	9.74	10.84	11.82	8.18	18.51	
$CD_{0.05}$	M: 0.99		T: 1.57	M×T: 2.21		
	ROOTS					
Institutional forest	7.69	16.15	18.90	18.38	52.45	22.72
Community forest	3.48	7.84	7.38	8.56	20.95	9.64
Mean	5.59	12.00	13.14	13.47	36.70	
$CD_{0.05}$	M: 0.66		T: 1.04	M×T: 1.47		

Table 4.16: Comparative analysis of different plantation species for phosphorus content in tree components under different management regimes

Treaments / Management Regimes	Phosphorus (Mg ha^{-1})					
	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	2.53	2.18	3.78	3.55	4.15	3.24
Community forest	0.90	0.91	1.66	1.29	1.83	1.32
Mean	1.72	1.55	2.72	2.42	2.99	
$CD_{0.05}$	M: 0.32		T: 0.50	M×T: NS		
	STEM					
Institutional forest	2.78	1.30	3.99	2.00	7.12	3.44
Community forest	0.85	0.88	0.40	0.38	0.58	0.62
Mean	1.82	1.09	2.20	1.19	3.85	
$CD_{0.05}$	M: 0.59		T: 0.93	M×T: 1.31		
	BRANCHES					
Institutional forest	0.77	1.10	1.61	0.95	3.77	1.64
Community forest	0.19	0.43	0.27	0.29	0.48	0.34
Mean	0.48	0.77	0.94	0.62	2.13	
$CD_{0.05}$	M: 0.37		T: 0.58	M×T: 0.82		
	ROOTS					
Institutional forest	1.69	1.28	2.39	2.84	5.57	2.75
Community forest	0.58	0.60	0.85	1.06	0.96	0.81
Mean	1.14	0.94	1.62	1.95	3.26	
$CD_{0.05}$	M: 0.43		T: 0.68	M×T: 0.96		

Table 4.17: Comparative analysis of different plantation species for potassium content in tree components under different management regimes

Treaments / Management Regimes	Potassium (Mg ha^{-1})					
	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	20.67	17.48	23.15	11.87	12.98	17.23
Community forest	6.46	10.63	13.16	7.35	7.94	9.11
Mean	13.56	14.06	18.16	9.61	10.46	
$CD_{0.05}$	M: 2.23		T: 3.52	M×T: NS		
	STEM					
Institutional forest	2.75	4.66	6.21	6.36	11.81	6.36
Community forest	1.34	1.36	1.75	2.07	3.66	2.04
Mean	2.05	3.01	3.98	4.21	7.74	
$CD_{0.05}$	M: 0.75		T: 1.19	M×T: 1.68		
	BRANCHES					
Institutional forest	3.25	4.24	5.46	2.83	8.22	4.80
Community forest	1.37	1.72	1.70	1.18	2.70	1.73
Mean	2.31	2.98	3.58	2.01	5.46	
$CD_{0.05}$	M: 0.48		T: 0.75	M×T: 1.06		
	ROOTS					
Institutional forest	3.90	7.88	9.57	9.03	15.23	9.12
Community forest	1.39	3.38	2.63	3.44	5.37	3.24
Mean	2.65	5.63	6.10	6.23	10.30	
$CD_{0.05}$	M: 0.59		T: 0.93	M×T: 1.32		

Table 4.18: Comparative analysis of different plantation tree species for calcium content in tree components under different management regimes

Treaments / Management Regimes	Calcium (Mg ha^{-1})					
	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	13.46	13.63	20.68	19.74	20.01	17.50
Community forest	6.18	8.84	11.46	11.09	11.72	9.86
Mean	9.82	11.23	16.07	15.41	15.87	
$CD_{0.05}$	M: 1.76		T: 2.79	M×T: NS		
	STEM					
Institutional forest	27.99	29.98	29.72	35.69	49.03	34.48
Community forest	11.24	13.68	10.51	15.05	17.46	13.59
Mean	19.61	21.83	20.12	25.37	33.25	
$CD_{0.05}$	M: 0.79		T: 1.25	M×T: 1.76		
	BRANCHES					
Institutional forest	12.28	16.16	14.74	11.43	23.59	15.64
Community forest	5.80	6.95	4.80	5.64	8.13	6.26
Mean	9.04	11.55	9.77	8.54	15.86	
$CD_{0.05}$	M: 0.87		T: 1.37	M×T: 1.94		
	ROOTS					
Institutional forest	3.28	3.39	4.26	3.60	8.34	4.57
Community forest	0.71	0.93	1.22	1.23	1.80	1.18
Mean	1.99	2.16	2.74	2.41	5.07	
$CD_{0.05}$	M: 0.42		T: 0.67	M×T: 0.95		

Table 4.19: Comparative analysis of different plantation tree species for magnesium content in tree components under different management regimes

Treaments / Management Regimes	Magnesium (Mg ha^{-1})					
	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	1.12	0.79	1.27	0.42	0.81	0.88
Community forest	0.16	0.37	0.21	0.18	0.23	0.23
Mean	0.64	0.58	0.74	0.30	0.52	
$CD_{0.05}$	M: 0.21		T: NS	M×T: NS		
	STEM					
Institutional forest	5.06	9.16	13.83	12.03	16.26	11.27
Community forest	1.64	3.79	4.52	4.97	5.49	4.08
Mean	3.35	6.48	9.17	8.50	10.88	
$CD_{0.05}$	M: 0.67		T: 1.06	M×T: 1.51		
	BRANCHES					
Institutional forest	0.95	1.57	2.85	0.78	4.36	2.10
Community forest	0.39	0.56	0.77	0.41	1.05	0.63
Mean	0.67	1.06	1.81	0.59	2.70	
$CD_{0.05}$	M: 0.31		T: 0.49	M×T: 0.69		
	ROOTS					
Institutional forest	1.78	2.74	3.12	1.76	4.68	2.82
Community forest	0.41	0.70	0.92	0.82	1.73	0.92
Mean	1.10	1.72	2.02	1.29	3.21	
$CD_{0.05}$	M: 0.51		T: 0.81	M×T: NS		

4.10. NUTRIENT DYNAMICS

4.10.1 Total Nutrients Uptake (kg ha^{-1}) and Return through Leaf Litter (kg ha^{-1}) in Different Plantation Tree Species under Different Management Regimes

The data presented in table 4.20 illustrates the nutrient uptake variations among different tree species in management regimes. The trends are evident for both management approaches. Specifically, the nitrogen (N) levels ranked in the following sequence: *Alnus nitida* (T_5) > *Salix tetrasperma* (T_3) > *Populus deltoides* (T_2) > *Robinia pseudoacacia* (T_1) > *Eucalyptus tereticornis* (T_4). Similar order was observed for the uptake of phosphorus (P), calcium (Ca), and magnesium (Mg), showing maximum values. Notably, *Salix tetrasperma* (T_3) demonstrated the highest potassium (K) value (143.11 kg ha^{-1}), while *Robinia pseudoacacia* had the lowest values for all nutrients except N (161.21 kg ha^{-1}) and P (20.83 kg ha^{-1}) in institutional forest. The same ranking order was maintained for different tree species under the community forest management regime, as observed in the institutional forest.

Furthermore, the data in table 4.20 highlights a substantial impact on nutrient return through leaf litter across various tree species in both management regimes. The sequence of nutrient uptake remains consistent among different tree species.

4.10.2 Nutrient Cycling (viz., nutrient uptake, return and retention) in Different Plantation Tree Species under Different Management Regimes

4.10.2.1 N uptake, return and retention

The data presented in table 4.21 illustrates how various tree species, under different management regimes, influenced changes in nitrogen uptake, return, and retention. In terms of different species, the most significant increase in N uptake (330.42 kg ha^{-1}) was observed in *Alnus nitida* (T_5), while the lowest (161.21 kg ha^{-1}) was noted in *Eucalyptus tereticornis* (T_4). Notably, the N uptake in *Eucalyptus tereticornis* (T_4) was notably lower than all other treatments, following this sequence: $T_5 > T_3 > T_2 > T_1 > T_4$. The analysis of various components revealed that the highest N uptake change occurred in leaves, followed by branches, stems, and roots in institutional forest. Same trend for N uptake was observed by plantation tree species in community forest.

Regarding nitrogen returns through leaf litter, variations were evident among different tree species in institutional forest. *Alnus nitida* (T_5) exhibited the highest nitrogen return via leaf litter (96.62 kg ha^{-1}), while the lowest (32.22 kg ha^{-1}) was associated with *Populus deltoides* (T_2).

Table 4.20: Comparative analysis of different plantation tree species for total nutrient uptake and return through leaf litter under different management regimes

Plant Nutrient Uptake	Institute forest (M_1)								Community forest (M_2)					
	T_1	T_2	T_3	T_4	T_5	Mean	$CD_{0.05}$	T_1	T_2	T_3	T_4	T_5	Mean	$CD_{0.05}$
N	171.02	175.24	251.10	161.21	330.42	217.80	8.50	154.12	155.43	226.31	151.94	284.78	194.52	6.09
P	24.34	20.83	38.74	28.22	56.38	33.70	8.45	17.95	17.60	19.67	15.93	22.76	18.78	NS
K	90.07	126.02	143.11	91.51	132.53	116.65	11.53	69.27	105.43	123.10	78.61	115.55	98.39	18.54
Ca	203.31	234.57	255.67	247.87	313.26	250.94	6.14	198.45	222.54	236.86	226.16	285.44	233.89	9.48
Mg	29.95	45.56	72.36	46.12	69.49	52.70	9.42	22.29	37.60	59.65	42.88	58.77	44.24	11.50
	Leaf litter nutrient status (kg ha^{-1})													
N	39.91	32.22	80.45	35.73	96.62	56.99	3.59	35.30	33.70	56.64	26.06	71.35	44.61	2.92
P	3.19	3.88	7.37	7.28	15.26	7.40	1.62	2.40	3.44	5.47	3.78	7.69	4.56	1.27
K	31.75	42.17	81.68	25.89	34.79	43.26	5.09	22.94	40.58	57.55	25.33	30.97	35.48	4.23
Ca	22.70	28.77	80.08	52.11	76.74	52.08	2.14	24.02	42.11	53.72	45.20	59.71	44.95	1.96
Mg	0.52	1.06	0.81	0.85	1.39	0.93	NS	0.60	0.64	0.64	0.80	1.10	0.76	NS

Whereas, in community forest it was noticed that *Alnus nitida* (T_5) exhibited the highest nitrogen return via leaf litter (71.35 kg ha^{-1}), while the lowest (26.06 kg ha^{-1}) was associated with *Eucalyptus tereticornis* (T_4).

In terms of nitrogen retention, *Alnus nitida* (T_5) again stood out with the highest value (233.80 kg ha^{-1}), while *Eucalyptus tereticornis* (T_4) had the lowest retention (125.48 kg ha^{-1}). Notably, the nitrogen retention in *Eucalyptus tereticornis* (T_4) was lower than all other treatments, and the trend followed the order as: $T_5 > T_3 > T_2 > T_1 > T_4$ for institutional forest. The trend followed for nitrogen retention in community forest was noticed in the order given as: $T_5 > T_3 > T_4 > T_2 > T_1$.

4.10.2.2 P uptake, return and retention

The data in table 4.22 reveal that phosphorus uptake, returns and retention were influenced by different plantation tree species. Maximum change in P uptake (56.38 kg ha^{-1}) was recorded under *Alnus nitida* (T_5), which was higher than all other treatments and followed the trend: $T_5 > T_3 > T_4 > T_1 > T_2$. Among different components, the maximum (20.85 kg ha^{-1}) P uptake was recorded in stem followed by leaf > branch > root in institutional forest. For P uptake in community forest, the treatments followed the trend as: $T_5 > T_3 > T_1 > T_2 > T_4$.

Phosphorus returns through leaf-litter varied among different plantation tree species. Maximum P release through leaf –litter (15.26 kg ha^{-1}) was recorded under *Alnus nitida* (T_5) and minimum under *Robinia pseudoacacia* (T_1; 3.19 kg ha^{-1}) for institutional forest. The trend followed for community forest was: $T_5 > T_3 > T_4 > T_2 > T_1$.

Under institutional forest, *Alnus nitida* (T_5) recorded maximum P retention (41.12 kg ha^{-1}), which was found to be higher than all other treatments and followed the trend: $T_5 > T_3 > T_1 > T_4 > T_2$. Slight variations were noticed for the treatments under community forest and the trend followed was: $T_1 > T_5 > T_3 > T_2 > T_4$.

4.10.2.3 K uptake, return and retention

The data appended in table 4.23 showed that uptake, returns and retention of K varied significantly under different plantation tree species and management regimes. Maximum K uptake (143.11 kg ha^{-1}) for institutional forest was recorded for *Salix tetrasperma* (T_3) which was higher than all other treatments and followed the trend: $T_3 > T_5 > T_2 > T_4 > T_1$. In different components, maximum (86.05 kg ha^{-1}) K uptake was recorded in leaf followed by stem > branches > root. For community forest, same trend was followed by all the treatments as for institutional forest.

Table 4.21: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of nitrogen under different management regimes

NITROGEN (kg ha^{-1})						
Treatments / Management Regimes	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	64.83	63.55	101.28	60.98	114.48	81.02
Community forest	55.52	57.51	83.54	57.47	97.49	70.31
Mean	60.18	60.53	92.41	59.28	105.99	
$CD_{0.05}$	M: 1.55 T: 2.45 M×T: 3.47					
	STEM					
Institutional forest	54.66	41.11	54.11	28.01	76.86	50.95
Community forest	50.94	34.23	51.48	28.53	56.02	44.24
Mean	52.80	37.67	52.80	28.27	66.44	
$CD_{0.05}$	M:2.15 T: 3.39 M×T:4.80					
	BRANCHES					
Institutional forest	41.65	51.86	73.40	48.95	85.85	60.34
Community forest	38.68	49.29	70.09	44.62	80.84	56.70
Mean	40.17	50.58	71.74	46.79	83.35	
$CD_{0.05}$	M: 1.14 T: 1.81 M×T: NS					
	ROOTS					
Institutional forest	9.89	18.72	22.32	23.27	53.22	25.48
Community forest	8.98	14.40	21.19	21.32	50.43	23.27
Mean	9.44	16.56	21.76	22.29	51.83	
$CD_{0.05}$	M:0.61 T:0.94 M×T: 1.36					
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	171.02	175.24	251.10	161.21	330.42	217.80
Community forest	154.12	155.43	226.31	151.94	284.78	194.52
Mean	162.57	165.34	238.70	156.58	307.60	
$CD_{0.05}$	M: 3.02 T: 4.77 M×T: 6.75					
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	39.91	32.22	80.45	35.73	96.62	56.99
Community forest	35.30	33.70	56.64	26.06	71.35	44.61
Mean	37.61	32.96	68.55	30.90	83.99	
$CD_{0.05}$	M: 1.29 T: 2.05 M×T: 2.89					
	RETAINED (kg ha^{-1})					
Institutional forest	131.11	143.02	170.65	125.48	233.80	160.81
Community forest	118.81	121.73	169.67	125.88	213.43	149.91
Mean	124.96	132.37	170.16	125.68	223.62	
$CD_{0.05}$	M: 3.55 T: 5.61 M×T: 7.94					

Table 4.22: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of phosphorus under different management regimes

PHOSPHORUS (kg ha^{-1})						
Treatments / Management Regimes	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	7.75	10.89	14.32	14.04	18.35	13.07
Community forest	5.91	6.39	9.66	7.87	11.56	8.28
Mean	6.83	8.64	11.99	10.95	14.96	
$CD_{0.05}$	M: 0.79 T: 1.24 M×T: 1.75					
	STEM					
Institutional forest	12.05	4.74	15.23	6.46	20.85	11.87
Community forest	9.26	6.85	4.20	2.69	4.77	5.55
Mean	10.66	5.79	9.72	4.58	12.81	
$CD_{0.05}$	M: 2.45 T: 3.88 M×T : 5.48					
	BRANCH					
Institutional forest	2.38	3.74	6.32	4.10	11.59	5.63
Community forest	1.19	3.27	3.31	2.73	4.07	2.92
Mean	1.79	3.50	4.81	3.42	7.83	
$CD_{0.05}$	M: 1.29 T: 2.04 M×T: 2.89					
	ROOTS					
Institutional forest	2.16	1.46	2.87	3.63	5.59	3.14
Community forest	1.59	1.10	2.49	2.65	2.35	2.04
Mean	1.88	1.28	2.68	3.14	3.97	
$CD_{0.05}$	M: 0.57 T: 0.91 M×T : 1.28					
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	24.34	20.83	38.74	28.22	56.38	33.70
Community forest	17.95	17.60	19.67	15.93	22.76	18.78
Mean	21.15	19.22	29.20	22.08	39.57	
$CD_{0.05}$	M: 2.93 T: 4.63 M×T : 6.54					
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	3.19	3.88	7.37	7.28	15.26	7.40
Community forest	2.40	3.44	5.47	3.78	7.69	4.56
Mean	2.79	3.66	6.42	5.53	11.47	
$CD_{0.05}$	M: 0.58 T: 0.92 M×T: 1.30					
	RETAINED (kg ha^{-1})					
Institutional forest	21.15	16.95	31.37	20.94	41.12	26.31
Community forest	15.55	14.17	14.19	12.15	15.06	14.23
Mean	18.35	15.56	22.78	16.55	28.09	
$CD_{0.05}$	M: 2.81 T: 4.45 M×T: 6.29					

Table 4.23: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of potassium under different management regimes

POTASSIUM (kg ha^{-1})						
Treatments / Management Regimes	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	63.18	85.68	86.05	46.95	57.30	67.83
Community forest	42.64	75.85	77.18	44.89	50.39	58.19
Mean	52.91	80.77	81.61	45.92	53.85	
$CD_{0.05}$	M: 4.53		T: 7.16	M×T: NS		
	STEM					
Institutional forest	11.58	16.87	23.64	20.47	34.56	21.42
Community forest	14.35	10.53	17.86	15.07	29.20	17.41
Mean	12.97	13.70	20.75	17.77	31.88	
$CD_{0.05}$	M: 3.40		T: 5.38	M×T: NS		
	BRANCHES					
Institutional forest	10.32	14.49	21.96	12.52	25.38	16.93
Community forest	8.53	12.85	20.46	10.02	22.87	14.95
Mean	9.42	13.67	21.21	11.27	24.13	
$CD_{0.05}$	M: 1.92		T: 3.04	M×T: NS		
	ROOTS					
Institutional forest	5.00	9.00	11.47	11.56	15.29	10.47
Community forest	3.75	6.20	7.60	8.64	13.08	7.86
Mean	4.38	7.60	9.54	10.10	14.19	
$CD_{0.05}$	M: 0.80		T: 1.26	M×T: NS		
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	90.07	126.02	143.11	91.51	132.53	116.65
Community forest	69.27	105.43	123.10	78.61	115.55	98.39
Mean	79.67	115.73	133.11	85.06	124.04	
$CD_{0.05}$	M: 6.07		T: 9.60	M×T: NS		
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	31.75	42.17	81.68	25.89	34.79	43.26
Community forest	22.94	40.58	57.55	25.33	30.97	35.48
Mean	27.35	41.38	69.62	25.61	32.88	
$CD_{0.05}$	M: 1.81		T: 2.86	M×T: 4.04		
	RETAINED (kg ha^{-1})					
Institutional forest	58.32	83.85	61.43	65.61	97.74	73.39
Community forest	46.33	64.85	65.55	53.29	84.59	62.92
Mean	52.33	74.35	63.49	59.45	91.17	
$CD_{0.05}$	M: 6.09		T: 9.62	M×T: NS		

Return of K through leaf litter varied among plantation tree species. Among different species, the maximum change in K release through leaf litter (81.68 Kg ha^{-1}) was recorded under *Salix tetrasperma* (T_3) and lowest (25.89 Kg ha^{-1}) under *Eucalyptus tereticornis* (T_4) for institutional forest. Same trend was followed by community forest for the return of nutrient through leaf litter.

The data pertaining to K retention under institutional forest varied among different plantation tree species.

The maximum K retention (97.74 Kg ha^{-1}) was observed by *Alnus nitida* (T_5), which was higher than all other treatments and followed the trend: $T_5 > T_2 > T_4 > T_3 > T_1$. Community forest was recorded with the same trend but with slight variation in the order for T_2 and T_3 and the trend followed: $T_5 > T_3 > T_2 > T_4 > T_1$.

4.10.2.4 Ca uptake, return and retention

The data depicted in table 4.24 showed variation in Mg uptake, returns and retention under different plantation tree species and management regimes. Maximum Ca uptake (313 Kg ha^{-1}) was recorded under *Alnus nitida* (T_5), whereas, minimum (203.31 Kg ha^{-1}) under *Robinia pseudoacacia* (T_1) which was lower than all other treatments and followed the trend: $T_5 > T_3 > T_4 > T_2 > T_1$. Among different components, the maximum (143.59 Kg ha^{-1}) Ca uptake was recorded in stem followed by leaf > branch > root for institutional forest. Same trend was followed in community forest for different treatments and components.

Among different species, the maximum Ca return through leaf litter (80.08 Kg ha^{-1}) was recorded under *Salix tetrasperma* (T_3) and minimum (22.70 Kg ha^{-1}) under *Robinia pseudoacacia* (T_1).

Ca retention varies among different plantation tree species. The maximum (236.51 Kg ha^{-1}) Ca retention was recorded under *Alnus nitida* (T_5), whereas minimum (175.58 Kg ha^{-1}) under *Salix tetrasperma* (T_3) which was found to be lower than all other treatments and followed the trends: $T_5 > T_2 > T_4 > T_1 > T_3$ for institutional forest. Trend for Ca retention among different tree species for community forest was observed as: $T_5 > T_3 > T_4 > T_3 > T_1$**.**

4.10.2.5 Mg uptake, return and retention

The scrutiny of data in table 4.25 showed significant variation in Mg uptake, return and retention under different plantation tree species and for management regimes. Maximum

Figure 4.1: Comparative analysis of different plantation species for nutrient cycling (through nutrient uptake, return and retention) of nitrogen under different management regimes

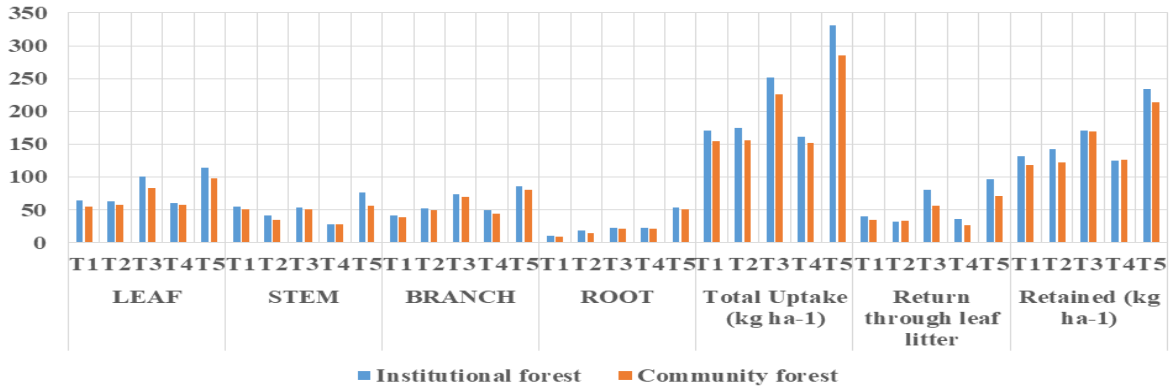


Figure 4.2: Comparative analysis of different plantation species for nutrient cycling (through nutrient uptake, return and retention) of phosphorus under different management regimes

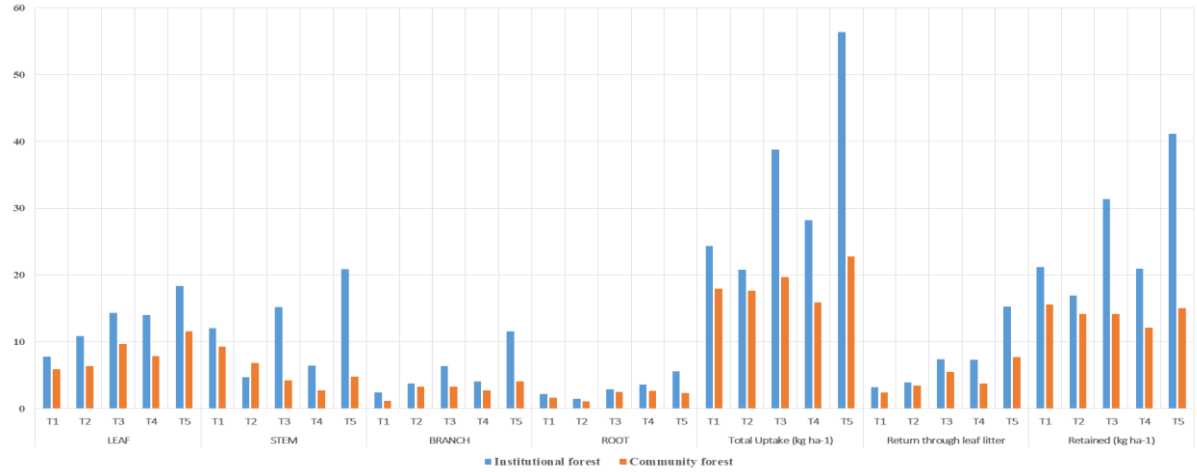


Figure 4.3: Comparative analysis of different plantation species for nutrient cycling (through nutrient uptake, return and retention) of potassium under different management regimes

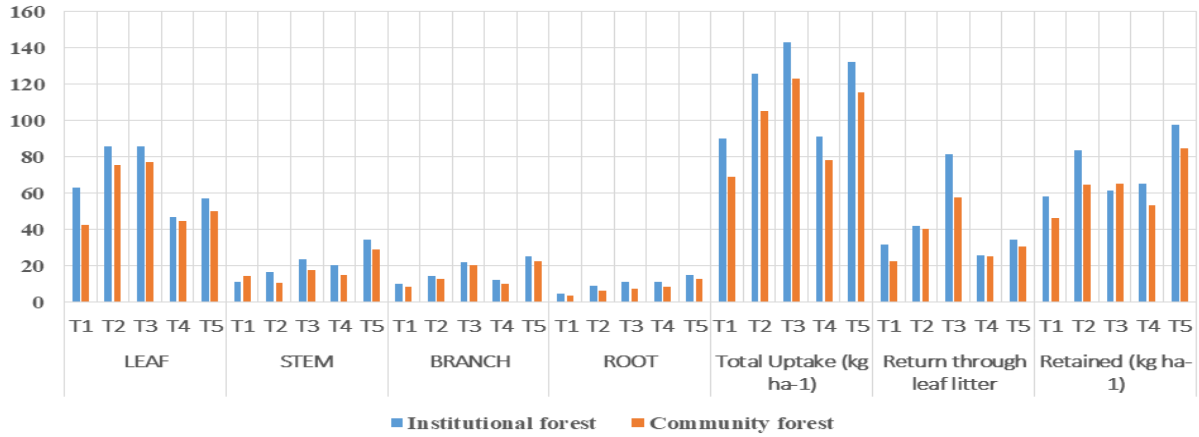


Table 4.24: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of calcium under different management regimes.

CALCIUM (kg ha^{-1})						
Treatments / Management Regimes	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	41.18	66.98	77.75	77.68	88.60	70.44
Community forest	40.21	62.36	66.95	67.03	73.26	61.97
Mean	40.70	64.67	72.35	72.36	80.93	
CD$_{0.05}$	M: 1.88		T: 2.96	M×T :4.21		
	STEM					
Institutional forest	119.05	108.57	112.95	115.27	143.59	119.89
Community forest	120.41	106.39	109.27	108.71	139.47	116.85
Mean	119.73	107.48	111.11	111.99	141.53	
CD$_{0.05}$	M:2.51		T: 3.97	M×T :NS		
	BRANCHES					
Institutional forest	38.88	55.13	59.86	50.32	72.69	55.38
Community forest	35.90	52.09	57.15	47.36	68.31	52.16
Mean	37.39	53.61	58.51	48.84	70.50	
CD$_{0.05}$	M: 1.30		T: 2.06	M×T : NS		
	ROOTS					
Institutional forest	4.21	3.89	5.11	4.60	8.38	5.24
Community forest	1.93	1.70	3.49	3.07	4.41	2.92
Mean	3.07	2.80	4.30	3.83	6.40	
CD$_{0.05}$	M: 0.59		T: 0.94	M×T : NS		
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	203.31	234.57	255.67	247.87	313.26	250.94
Community forest	198.45	222.54	236.86	226.16	285.44	233.89
Mean	200.88	228.56	246.27	237.02	299.35	
CD$_{0.05}$	M: 3.23		T: 5.10	M×T: 7.22		
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	22.70	28.77	80.08	52.11	76.74	52.08
Community forest	24.02	42.11	53.72	45.20	59.71	44.95
Mean	23.36	35.44	66.90	48.66	68.23	
CD$_{0.05}$	M: 0.82		T: 1.30	M×T: 1.83		
	RETAINED (kg ha^{-1})					
Institutional forest	180.62	205.80	175.58	195.76	236.51	198.86
Community forest	174.43	180.43	183.15	180.97	225.73	188.94
Mean	177.53	193.12	179.37	188.36	231.12	
CD	M: 3.41		T: 5.38	M×T: 7.61		

Table 4.25: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of Magnesium under different management regimes

MAGNESIUM (kg ha^{-1})						
Treatments / Management Regimes	LEAF					
	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	3.39	3.83	4.66	1.70	3.65	3.45
Community forest	1.17	2.61	1.25	1.09	1.64	1.55
Mean	2.28	3.22	2.95	1.39	2.64	
$CD_{0.05}$	M: 0.68 T: 1.0 M×T : NS					
	STEM					
Institutional forest	21.31	33.21	52.54	38.78	47.66	38.70
Community forest	17.60	29.49	46.75	36.06	44.10	34.80
Mean	19.45	31.35	49.65	37.42	45.88	
$CD_{0.05}$	M: 2.99 T: 4.73 M×T : NS					
	BRANCHES					
Institutional forest	2.98	5.37	11.43	3.42	13.47	7.34
Community forest	2.38	4.20	9.02	3.64	8.77	5.61
Mean	2.68	4.79	10.23	3.53	11.12	
$CD_{0.05}$	M: 1.36 T: 2.13 M×T : NS					
	ROOTS					
Institutional forest	2.27	3.16	3.74	2.23	4.71	3.22
Community forest	1.14	1.30	2.62	2.09	4.26	2.28
Mean	1.71	2.23	3.18	2.16	4.49	
$CD_{0.05}$	M: 0.67 T: 1.06 M×T : NS					
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	29.95	45.56	72.36	46.12	69.49	52.70
Community forest	22.29	37.60	59.65	42.88	58.77	44.24
Mean	26.12	41.58	66.01	44.50	64.13	
$CD_{0.05}$	M: 4.43 T: 6.99 M×T : NS					
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	0.52	1.06	0.81	0.85	1.39	0.93
Community forest	0.60	0.64	0.64	0.80	1.10	0.76
Mean	0.56	0.85	0.72	0.83	1.25	
$CD_{0.05}$	M: NS T: 0.40 M×T: NS					
	RETAINED (kg ha^{-1})					
Institutional forest	29.43	44.50	71.55	45.27	68.10	51.77
Community forest	21.69	36.96	59.01	42.08	57.67	43.48
Mean	25.56	40.73	65.28	43.67	62.89	
$CD_{0.05}$	M: 4.28 T: 6.77 M×T: NS					

Figure 4.4: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of calcium under different management regimes.

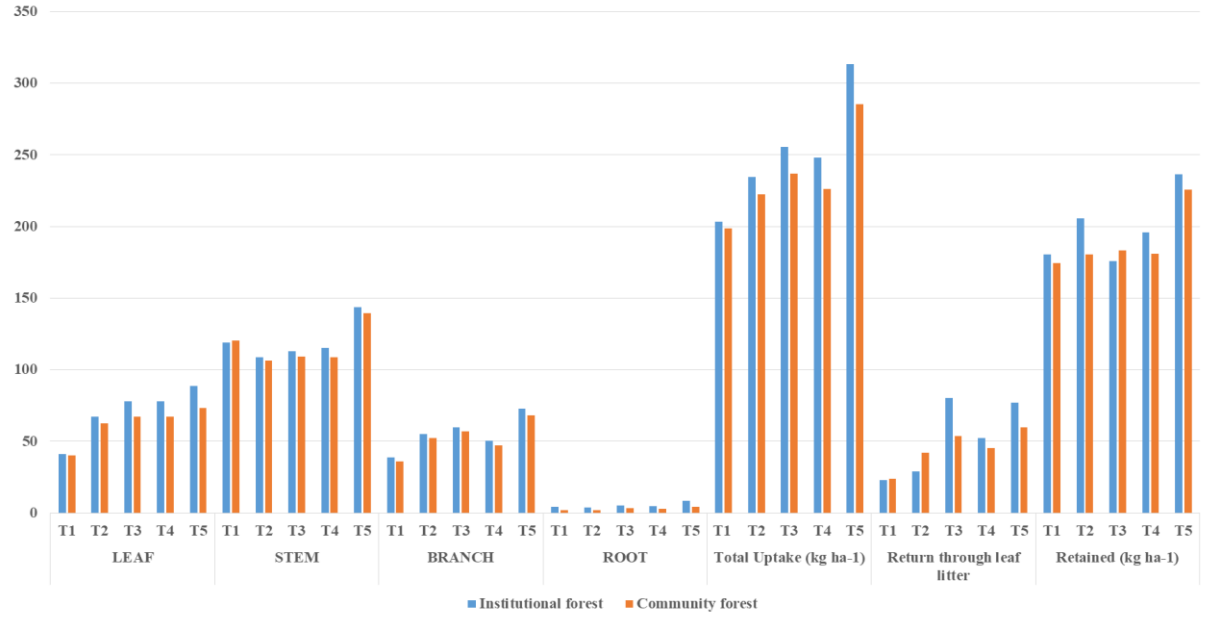
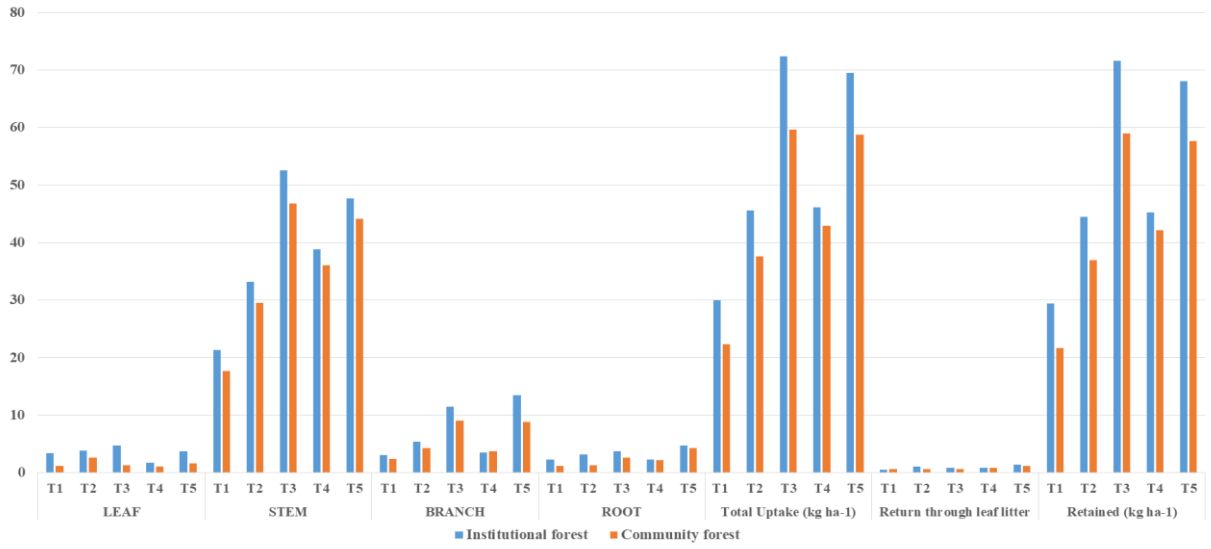


Figure 4.5: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of Magnesium under different management regimes



Mg uptake (72.36 Kg ha^{-1}) was recorded under *Salix tetrasperma* (T_3) followed by *Alnus nitida* (T_5), *Eucalyptus tereticornis* (T_4), *Populus deltoides* (T_2) and minimum Mg uptake (29.95 Kg ha^{-1}) was recorded for *Robinia pseudoacacia*. Among different components, the maximum (52.54 Kg ha^{-1}) Mg uptake was recorded in stem followed by branch > leaf > root for institutional forest.

Among different plantation tree species, maximum Mg return through leaf litter (1.39 Kg ha^{-1}) was observed under *Alnus nitida* (T_5) and minimum (0.52 Kg ha^{-1}) under *Robinia pseudoacacia* (T_1) for institutional forest.

Retention of magnesium (Mg) varies across distinct plantation species. The highest Mg retention (71.55 kg ha^{-1}) occurred with *Salix tetrasperma* (T_3), whereas the lowest (29.43 kg ha^{-1}) was found in the case of *Robinia pseudoacacia* (T_1). This minimum value was lower than all other treatments, following the pattern: $T_3 > T_5 > T_4 > T_2 > T_1$ for institutional forest. This consistent trend was similarly observed within community forest.

The primary productivity within an ecosystem is governed by multiple factors, notably the presence of nutrients and water. Nutrients are absorbed by plants and then transported to various growth regions where they are utilized in the synthesis of organic compounds, subsequently becoming integrated into the biomass (Kramer and Kozlowski, 1960). During the initial stages of stand development, there is a rapid increase in the average rates of nutrient accumulation; however, as the stand matures, changes in nutrient content become less noticeable (Kadeba, 1991). This phenomenon aligns with findings observed in *Eucalyptus* hybrid by Singh (1984) and in *Quercus leucotrichophora* by Lata and Bisht (1993), where a consistent reduction in the levels of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) is documented throughout the growth phases.

In the current investigation, across diverse plantation tree species, the distribution of nutrient concentrations in different components—namely, leaf, stem, and branch—followed distinct trends: N > K > Ca > P > Mg, N > Ca > Mg > K > P, and N > Ca > K > Mg > P, respectively. However, when examining nutrients below ground, the root's nutrient distribution adhered to the sequence of N > K > Ca > Mg > P. These trends align with the typical nutrient concentration patterns observed in the leaves of five canopy tree species within a subtropical forest in southern Brazil (Bundchen *et al*., 2013).

Another study highlighted that the growth of *Robinia pseudoacacia* and *Salix matsudana* was largely constrained by phosphorus (P) nutrients, with *Robinia pseudoacacia* exhibiting higher nitrogen resorption efficiency (NRE) compared to *Salix matsudana* and *Ailanthus altissima* (Wu *et al*., 2020). Furthermore, research focused on subtropical evergreen broad-leaved forests demonstrated variations in the release dynamics of calcium (Ca), magnesium (Mg), and manganese (Mn) during the decomposition of foliar litter among

different tree species. This variance included some species displaying direct nutrient release, while others exhibited initial accumulation followed by subsequent release (Ma *et al*., 2015).

In the current study, among the various cations, the highest nitrogen concentration was recorded in the stem and branch components. In a similar context, research on *Pinus taeda* revealed that nutrient contents in branch components displayed a distinct pattern for nitrogen, phosphorus, potassium, and magnesium. This pattern suggested a phenomenon of nutrient retranslocation and storage in branches before foliage development and after foliage senescence, particularly in the case of *Pinus taeda* (Tetraspermaugh *et al*., 2012).

Disparities in the nutritional requirements of forest species can provide insights for selecting species with a higher capacity for nutrient absorption and efficient nutrient use efficiency (BUE). Such species can be particularly advantageous in regions with soils characterized by low inherent fertility, as commonly found in tropical forests (Silva *et al*., 2018). The same sequence of nutrient stem flow was also observed in various tree species, including *Cinnamomum camphora, Pinus taeda, Quercus aliena,* and *Michelia macclurei* (Kooch *et al.*, 2017).

The nutrient content observed in litter components was comparatively lower than that found in the living biomass. This difference could be attributed in part to the translocation and significant withdrawal of nitrogen (N) before the shedding of leaves or other components (Grubb and Edwards, 1982; Kramer and Kozlowski, 1960). Additionally, certain elements might undergo leaching before the litter's descent.

Climatic variables, chemical composition of the litter and its palatability to soil fauna are most important determinants in the decomposition process of leaves (Van Cleve, 1974).

The process of elements being returned to the soil through litter fall exhibited an augmentation in relation to the age of the ecosystem. This phenomenon is a result of the linear increase in litter fall that corresponds with ecosystem age (Toky and Ramakrishnan, 1983). The investigation revealed that among the diverse nutrients, the highest percentage of returns through leaf litter was consistently observed in nitrogen (N) across all studied plantation tree species. This pattern was subsequently followed by calcium (Ca), potassium (K), phosphorus (P), and magnesium (Mg). These findings align with previous research

conducted on Eucalyptus globulus (Venkataramanan *et al.*, 1983) as well as *Eucalyptus hybrid* and *Eucalyptus globulus* (George and Varghese, 1990).

When considering the nutrient quantities on a per unit area basis, the stem component exhibited the highest accumulation of all nutrients, followed by branches, leaves, and roots. Consequently, the most substantial depletion was observed for calcium (Ca), succeeded by nitrogen (N), potassium (K), magnesium (Mg), and phosphorus (P). This trend aligns with the annual nutrient content typically accompanying biomass expansion, reflecting an average annual production pattern. This content tends to increase linearly during the phase of rapid growth and subsequently declines as the ecosystem matures (Pritckett, 1979).

Generally, plants of high nutrient status have a larger percentage N and P in soluble and inorganic form and retranslocate a larger proportion of their leaf N and P than plants with low nutrient status (Chapin FS, 1980).

In contrast, nutrient uptake from sub-soil horizons is more important in highly weathered warm temperate soils where nutrient depletion takes place deeper in the soil. Nutrient cycling is one of the most significant supporting service for forest ecosystem. There have been limited evidences of any studies and set methodology for estimation of it in India (Mehta and Jain, 2021).

4.11. SOIL PHYSICO-CHEMICAL PROPERTIES

The physico-chemical characteristics of soil in 0-20 and 20-40 cm layers have been found to vary under different management regimes for various plantation species. These variations have been depicted in table 4.26- 4.35.

4.11.1. EC (dSm^{-1}), pH (1:2) and Bulk Density ($g\ cm^{-3}$)

It is evident from the data presented in table 4.26 that EC for plantation tree species (T), management regimes (M) and soil depths(D) exerted significant influence whereas; interactions between these factors exert non-significant influence on EC of the soil. Though *Alnus nitida* displayed significantly higher value of EC than other species of study under different regimes and soil depths. It was depicted that institutional forest ecosystem and soil depth of 0-20 cm had higher value for EC.

Data for pH presented in table 4.27 showed that maximum value (7.58) was recorded for *Robinia pseudoacacia* followed by *Eucalyptus tereticornis* (7.40) and *Populus deltoides* (7.17).

Minimum value was found for *Alnus nitida* (6.35). Both the management regimes where found to be statistically equal. Interaction between tree species and management regimes showed that maximum value (7.69) was found for *Robinia pseudoacacia* under institutional forest. *Populus deltoides* **(**7.12) was found to be statistically at par with *Eucalyptus tereticornis* (7.37) whereas *Salix tetrasperma* (6.54) was found to be statistically at par with *Alnus nitida* (6.30) under institutional forest. For community forest *Robinia pseudoacacia* (7.64) and *Populus deltoides* (7.11) remained statistically equal to each other and were statistically at par with *Eucalyptus tereticornis* (7.48). However, interaction effect for tree species (T), management regimes (M) and soil depth (D) viz: T×D, M×D and T×M×D were found to be non-significant.

Table 4.28 for bulk density showed that tree species (T) were statistically at par with each other. Management regime (M) and soil depth (D) exerts significant influence on BD of soil. Whereas; interactions between these factors exerted statistically non-significant influence on BD of the soil.

4.11.2 Organic Carbon (g kg^{-1})

The data on soil organic carbon as influenced by different tree species (T), management regimes (M), soil depths (D) and interaction between tree species is presented in table 4.29. Soil under *Salix tetrasperma* was measured with higher organic carbon (12.00g kg^{-1}), which was found to be significantly different from all other treatments and followed the trend: $T_3>T_5>T_2>T_4>T_1$ and was found to be statistically at par with *Alnus nitida*. In the average effect of soil depth, higher organic carbon (11.17g kg^{-1}) was observed under upper layer (D_1) of soil (0-20 cm) as compared to sub-layer (D_2) (20-40 cm) i.e. 10.33 g kg^{-1}. Organic carbon was significantly higher (11.68 g kg^{-1}) under institutional forest (M_1) than community forest (M_2); 11.17g kg^{-1}.

4.11.3 SOC stock (Mg ha^{-1})

It is evident from table 4.30 that SOC stock of soil was significantly influenced by tree species (T), management regimes (M) and soil depth (D). Highest stock (26.40 Mg ha^{-1}) was observed under *Salix tetrasperma* which was found to be statistically at par with *Alnus nitida*. Whereas, lowest SOC stock (21.61 Mg ha^{-1}) was reported in *Robinia pseudoacacia*. SOC stock was found significantly higher (26.91 Mg ha^{-1}) for institutional forest (M_1) than for community forest (M_2). In the average effect of soil depth, upper soil layer (0-20 cm) had higher value of SOC stock (25.23 Mg ha^{-1}) than the sub-layer (20-40 cm). Interaction effect of tree species

Table 4.26: Effect of tree species, management regimes, soil depths and their interaction effect on soil EC (dSm^{-1})

EC (dSm^{-1})									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	0.31	0.27	0.29	0.28	0.24	0.26	0.30	0.26	0.28
T_2 (*P. deltoides*)	0.21	0.19	0.20	0.19	0.17	0.18	0.19	0.18	0.18
T_3 (*S. tetrasperma)*	0.24	0.22	0.23	0.21	0.20	0.21	0.23	0.21	0.22
T_4 (*E. tereticornis)*	0.29	0.28	0.29	0.25	0.24	0.25	0.27	0.26	0.27
T_5 (*A. nitida*)	0.42	0.39	0.41	0.37	0.36	0.37	0.40	0.38	0.39
MEAN	0.29	0.27	0.28	0.26	0.24	0.25	0.27	0.26	
$CD_{0.05}$									
M: Management Regimes			0.01				T×M		NS
T: Tree Species			0.01				T×D		NS
D: Soil Depth			0.01				M×D		NS
							T×M×D		NS

Table 4.27: Effect of tree species, management regimes, soil depths and their interaction effect on soil pH (1:2)

pH(1:2)									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	7.69	7.64	7.67	7.57	7.43	7.50	7.63	7.54	7.58
T_2 (*P. deltoides*)	7.12	7.11	7.12	7.19	7.24	7.22	7.16	7.18	7.17
T_3 (*S. tetrasperma)*	6.54	6.42	6.48	6.59	6.48	6.54	6.57	6.45	6.51
T_4 (*E. tereticornis)*	7.37	7.48	7.43	7.35	7.39	7.37	7.36	7.44	7.40
T_5 (*A. nitida*)	6.30	6.37	6.34	6.35	6.38	6.37	6.33	6.38	6.35
MEAN	7.00	7.00	7.00	7.01	6.98	7.00	7.01	6.99	
$CD_{0.05}$									
M: Management Regimes			0.08				T×M		0.12
T: Tree Species			0.53				T×D		NS
D: Soil Depth			0.53				M×D		NS
							T×M×D		NS

Table 4.28: Effect of tree species, management regimes, soil depths and their interaction effect on soil Bulk Density

Bulk Density (g cm^{-3})									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	1.14	1.17	1.16	1.12	1.15	1.14	1.13	1.16	1.15
T_2 (*P. deltoides*)	1.15	1.18	1.17	1.13	1.17	1.15	1.14	1.18	1.16
T_3 (*S. tetrasperma)*	1.13	1.16	1.15	1.10	1.14	1.12	1.12	1.15	1.14
T_4 (*E. tereticornis)*	1.16	1.20	1.18	1.14	1.16	1.15	1.15	1.18	1.15
T_5 (*A. nitida*)	1.11	1.14	1.13	1.11	1.13	1.12	1.11	1.14	1.13
MEAN	1.14	1.17	1.16	1.12	1.15	1.14	1.13	1.16	
$CD_{0.05}$									
M: Management Regimes			0.02				T×M		NS
T: Tree Species			0.01				T×D		NS
D: Soil Depth			0.01				M×D		NS
							T×M×D		NS

Table 4.29: Effect of tree species, management regimes, soil depths and their interaction effect on soil organic carbon (g kg^{-1}).

OC (g kg^{-1})									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	11.03	10.10	10.57	9.13	7.70	8.42	10.08	8.9	9.50
T_2 (*P. deltoides*)	11.90	11.57	11.74	9.83	9.33	9.58	10.87	10.7	10.79
T_3 (*S. tetrasperma)*	13.77	11.63	12.7	11.30	9.93	10.62	12.54	11.47	12.00
T_4 (*E. tereticornis)*	12.30	10.07	11.18	8.77	7.43	8.1	10.54	9.42	9.98
T_5 (*A. nitida*)	12.83	11.57	12.2	10.77	10.20	10.49	11.8	11.17	11.49
MEAN	12.36	10.99	11.68	9.96	8.92	9.44	11.17	10.33	
$CD_{0.05}$									
M: Management Regimes			0.57				T×M		NS
T: Tree Species			0.36				T×D		NS
D: Soil Depth			0.36				M×D		NS
							T×M×D		NS

Table 4.30: Effect of tree species, management regimes, soil depths and their interaction effect on Soil organic carbon stock (Mg ha^{-1})

SOC stock (Mg ha^{-1})									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	25.16	23.62	24.39	20.48	17.76	19.12	22.82	20.39	21.61
T_2 (*P. deltoides*)	27.37	27.29	27.33	22.22	21.83	22.02	24.80	24.56	24.68
T_3 (*S. tetrasperma)*	31.09	26.98	29.04	24.83	22.65	23.74	27.99	24.81	26.40
T_4 (*E. tereticornis)*	28.53	23.97	26.25	19.99	17.25	18.62	24.26	20.61	22.44
T_5 (*A. nitida*)	28.65	26.42	27.53	23.89	23.05	23.47	26.27	24.74	25.51
MEAN	28.16	25.66	26.91	22.28	20.51	21.35	25.23	23.02	
$CD_{0.05}$									
M: Management Regimes			1.18				T×M		NS
T: Tree Species			0.75				T×D		1.67
D: Soil Depth			0.75				M×D		NS
							T×M×D		NS

(T) and soil depth (D) were found statistically at par in case of *Robinia pseudoacacia* (22.82 Mg ha^{-1}) and *Populus deltoides* (24.80 Mg ha^{-1}) with *Eucalyptus tereticornis* (24.26 Mg ha^{-1}) whereas; *Alnus nitida* (26.27 Mg ha^{-1}) was found statistically at par with *Populus deltoides* (24.80 Mg ha^{-1}) under the depth 0-20 cm. *Robinia pseudoacacia* (20.39 Mg ha^{-1}) was found statistically at par with *Eucalyptus tereticornis* (20.61 Mg ha^{-1}) whereas *Salix tetrasperma* (24.81 Mg ha^{-1}) was found statistically at par with *Populus deltoides* (24.56 Mg ha^{-1}) and *Alnus nitida* (24.74 Mg ha^{-1}) under the depth 20-40 cm. However, the interaction effect of tree species (T), management regimes (M) and soil depth (D) *viz*: T×M, M×D and T×M×D were found to be non-significant.

4.11.4 Available Nitrogen (kg ha^{-1})

The data on available nitrogen was significantly influenced by different tree species (T), management regimes (M), soil depth (D) and interaction between tree species (T) and management regimes (M) was enumerated in table 4.31. Under management regimes, higher available N (161.15 Kg ha^{-1}) was reported for institutional forest (M_1) in comparison with (134.54 Kg ha^{-1}) community forest (M_2).

Interaction effect for all tree species displayed significantly higher value of available N under institutional forest (M_1) than community forest (M_2).

4.11.5 Available Phosphorus (Kg ha^{-1})

The available phosphorus content significantly influenced by various factors, including tree species (T), management regime (M), soil depth (D), and the interaction between tree species (T) and soil depth (D), as detailed in table 4.32. Among the different tree species, the highest recorded available phosphorus content was observed under *Alnus nitida* reaching 122.07 kg ha^{-1}. This was followed by *Populus deltoides, Salix tetrasperma, Eucalyptus tereticornis* and *Robinia pseudoacacia* in descending order. In terms of the management regime, institutional forest (M_1) had significantly higher available phosphorus content at 103.02 kg ha^{-1} compared to community forest (100.5 kg ha^{-1}). Regarding soil depth, sub-surface layer (D_2) showed a significantly higher (119.11 kg ha^{-1}) available phosphorus content than the surface layer (D_1). However, a consistent trend was not observed. Regarding the interaction between tree species (T) and soil depth (D), *Salix tetrasperma(*123.22 kg ha^{-1}) was found statistically at par with *Alnus nitida* (122.42 kg ha^{-1}) at soil depth D_2 (20-40 cm). Notably, D_2 consistently displayed significantly higher available phosphorus level compared to D_1 across all tree species.

Table 4.31: Effect of tree species, management regimes, soil depths and their interaction effect on soil available N (kg ha^{-1})

Available N (kg ha^{-1})									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	109.76	101.92	105.84	105.28	100.80	103.04	107.52	101.14	104.33
T_2 (*P. deltoides*)	143.36	134.40	138.89	120.96	114.49	117.73	132.16	124.45	128.31
T_3 (*S. tetrasperma)*	202.27	196.45	199.36	133.28	125.44	129.36	167.78	160.95	164.37
T_4 (*E. tereticornis)*	152.09	141.12	146.61	127.68	118.72	123.2	139.88	129.92	134.9
T_5 (*A. nitida*)	217.95	212.13	215.04	206.08	192.64	199.36	212.01	202.38	207.20
MEAN	165.09	157.20	161.15	138.66	130.27	134.54	151.87	143.77	
$CD_{0.05}$									
M: Management Regimes			2.93				T×M		4.15
T: Tree Species			1.85				T×D		NS
D: Soil Depth			1.85				M×D		NS
							T×M×D		NS

Table 4.32: Effect of tree species, management regimes, soil depths and their interaction effect on soil available P ((kg ha^{-1})

Available P ((kg ha^{-1})									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	60.83	99.98	80.40	57.96	99.53	78.74	59.39	99.75	79.57
T_2 (*P. deltoides*)	98.28	119.94	109.11	95.91	118.79	107.35	103.69	119.36	111.52
T_3 (*S. tetrasperma)*	78.06	125.52	101.79	76.95	120.93	98.94	77.50	123.22	100.36
T_4 (*E. tereticornis)*	69.85	133.66	101.75	64.11	127.97	96.04	66.98	130.81	98.89
T_5 (*A. nitida*)	121.38	122.79	122.08	120.84	122.06	121.45	121.73	122.42	122.07
MEAN	85.68	120.37	103.02	83.15	117.85	100.5	85.85	119.11	
$CD_{0.05}$									
M: Management Regimes			2.00				T×M		NS
T: Tree Species			1.26				T×D		2.83
D: Soil Depth			1.26				M×D		NS
							T×M×D		NS

Table 4.33: Effect of tree species, management regimes, soil depths and their interaction effect on soil available K ((kg ha^{-1})

Available K ((kg ha^{-1})									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	67.20	52.89	60.04	49.62	43.40	46.51	58.41	48.15	53.28
T_2 (*P. deltoides*)	121.94	117.69	119.81	98.13	79.42	88.77	110.04	98.56	104.3
T_3 (*S. tetrasperma)*	167.27	133.38	150.32	136.03	101.20	118.62	151.65	117.29	134.47
T_4 (*E. tereticornis)*	102.26	92.71	97.48	49.21	43.94	46.58	75.74	68.33	72.04
T_5 (*A. nitida*)	132.56	131.16	131.86	99.60	93.71	96.65	116.08	112.44	114.26
MEAN	118.25	105.57	111.91	86.52	72.33	79.43	102.38	88.95	
$CD_{0.05}$									
M: Management Regimes			4.61				T×M		6.53
T: Tree Species			2.92				T×D		6.53
D: Soil Depth			2.92				M×D		NS
							T×M×D		NS

4.11.6 Available Potassium (kg ha^{-1})

The data presented in table 4.33 demonstrates that several factors significantly affected available potassium. These factors include different tree species (T), management regimes (M), soil depth (D), and the interaction between tree species (T) with management regimes (M), and soil depth (D). *Salix tetrasperma* exhibited the highest available potassium content at 134.47 kg ha^{-1}, while *Robinia pseudoacacia* had the lowest at 53.28 kg ha^{-1}. When considering soil depth, the surface layer (0-20 cm) had higher available potassium content (102.38 kg ha^{-1}) compared to the sub-surface layer (88.95 kg ha^{-1}). Among management regimes, institutional forest (M_1) had higher available potassium (111.91 kg ha^{-1}) compared to community forest (M_2) with 79.43 Kg ha^{-1}. Furthermore, for the interaction between tree species (T) and management regimes (M), M_1 (119.91 kg ha^{-1}) showed significantly higher available potassium values than M_2 (79.43 kg ha^{-1}). In the interaction between tree species (T) and soil depth (D), *Salix tetrasperma* (117.29 kg ha^{-1}) was found statistically at par with *Alnus nitida* (112.44 kg ha^{-1}) under 20-40 cm soil depth.

However, under D_1, all the species had significantly higher available potassium levels compared to D_2. The interaction effect of tree species (T), management regimes (M) and soil depth (D) *viz*: MxD and TxMxD were found to be non-significant.

4.11.7 Exchangeable Ca [c mol (p$^+$)/kg]

Exchangeable calcium were significantly affected by several factors, including tree species (T), management practices (M), and soil depth (D), as shown in table 4.34. Among the tree species, soil under *Salix tetrasperma* had the highest exchangeable calcium content at 17.44 c mol (p+)/kg, while the lowest content was found under *Robinia pseudocacia* at 2.47 c mol (p+)/kg. Regarding soil depth, the surface layer (0-20 cm) had higher exchangeable calcium levels at 14.11 c mol (p+)/kg compared to the sub-surface layer at 12.74 c mol (p+)/kg. Institutional forest (M_1) resulted in higher exchangeable calcium levels at 13.70 c mol (p+)/kg compared to community forest (M_2). The interaction between tree species (T) and management regimes (M) showed that under institutional forest (M_1), *Populus deltoides* (16.66 c mol (p$^+$)/kg) was significantly at par with *Alnus nitida* (16.49 c mol (p$^+$)/kg), respectively. Under community forest management (M_2), *Populus deltoides* (14.60 c mol (p+)/kg) remained statistically at par with *Eucalyptus tereticornis* (14.83 c mol (p+)/kg). Different interactions viz., T×D, M×D and T×D×M were found to be statistically non-significant.

Table 4.34: Effect of tree species, management regimes, soil depths and their interaction effect on soil exchangeable Ca (c mol (p+)/kg)

Exchangeable Ca (c mol (p+)/kg)									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	3.58	2.64	3.11	2.02	1.61	1.82	2.8	2.13	2.47
T_2 (*P. deltoides*)	17.37	15.95	16.66	14.96	14.23	14.60	16.17	15.09	15.63
T_3 (*S. tetrasperma)*	19.75	17.15	18.45	16.97	15.83	16.4	18.36	16.49	17.44
T_4 (*E. tereticornis)*	14.39	13.17	13.78	16.04	13.62	14.83	15.21	13.40	14.31
T_5 (*A. nitida*)	17.17	15.81	16.49	18.81	17.38	18.10	17.99	16.60	17.30
MEAN	14.45	12.94	13.70	13.76	12.53	13.15	14.11	12.74	

$CD_{0.05}$			
M: Management Regimes	0.56	T×M	0.79
T: Tree Species	0.35	T×D	NS
D: Soil Depth	0.35	M×D	NS
		T×M×D	NS

Table 4.35: Effect of tree species, management regimes, soil depths and their interaction effect on soil soil exchangeable Mg (cmol (p+)/kg)

Exchangeable Mg (c mol (p+)/kg)									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	1.77	1.70	1.74	1.71	1.42	1.57	1.74	1.56	1.65
T_2 (*P. deltoides*)	1.97	1.71	1.84	1.81	1.50	1.65	1.89	1.61	1.75
T_3 (*S. tetrasperma)*	2.33	2.31	2.32	1.98	1.94	1.96	2.16	2.13	2.15
T_4 (*E. tereticornis)*	2.48	2.26	2.37	1.87	1.57	1.72	2.18	1.92	2.05
T_5 (*A. nitida*)	1.44	1.36	1.4	1.25	1.18	1.21	1.35	1.27	1.31
MEAN	1.99	1.87	1.93	1.72	1.52	1.62	1.86	1.73	
$CD_{0.05}$									
M: Management Regimes			0.07				T×M		0.10
T: Tree Species			0.04				T×D		0.10
D: Soil Depth			0.04				M×D		NS
							T×M×D		NS

4.11.8 Exchangeable Mg [c mol (p^+)/kg]

The data presented in table 4.35 demonstrated significant variations in exchangeable Mg influenced by different factors including tree species (T), management regimes (M), and soil depth (D). Notably, soil under *Salix tetrasperma* showed the maximum (2.15 c mol (p+)/kg) exchangeable Mg concentration while the lowest was observed for *Alnus nitida* (1.31 c mol (p+)/kg). The treatments followed this trend: $T_5 < T_1 < T_2 < T_4 < T_3$. On average, surface soil layer (0-20 cm) exhibited higher exchangeable Mg (1.86 c mol (p+)/kg) compared to sub-surface layer (20-40 cm). The interaction effect between tree species (T) and management regimes (M) (TxM), it was noted that *Salix tetrasperma* (2.32 c mol (p+)/kg) and *Eucalyptus tereticornis* (2.37 c mol (p+)/kg) were found statistically at par with each other under institutional forest. Likewise, *Populus deltoides* (1.65 c mol (p+)/kg) and *Eucalyptus tereticornis* (1.72 c mol (p+)/kg) were found statistically at par with each other in community forest. Furthermore, when considering the interaction between tree species (T) and soil depth (D), *Salix tetrasperma* (2.16 c mol (p+)/kg) was comparable to *Eucalyptus tereticornis* (2.18 c mol (p+)/kg) in the 0-20 cm depth range.

Institutional forest reported higher exchangeable Mg levels at 1.93 c mol (p+)/kg compared to community forest at 1.62 c mol (p+)/kg. Interactions between tree species (T), management regimes (M), and soil depth (D) such as M×D and T×D×M were found to be statistically non-significant.

The physico-chemical analysis of the soil revealed elevated levels of available nitrogen and organic carbon, along with reduced bulk density, pH and electrical conductivity (EC). The outcomes were consistent with the findings of Kumar *et al*., in 1998. He proposed that the variations in soil enrichment patterns could be attributed to the diverse interactions between species and their respective environments, varying amounts of litter produced differences in decomposition and mineralization rates, as well as distinct nutrient uptake and cycling processes. Soils found in the research area originate from parent materials like quartzite and sandstone (Cotter, 2000). These materials have limited ability to retain nutrients due to their low clay content caused by illuviation (Aweto and Moleele, 2005; del Moral and Muller, 1970; Hazlett *et al.,* 2005). Consequently, the capacity to exchange cations in the root environment of most plants, especially native species, is diminished. This is particularly noticeable when compared to dominant non-native plants such as Acacia species, which often have deeper root systems (Morris *et al.,* 2011). Other researchers such as Prasad *et al.,* (1985), Saralach (1994),

Bhola (1995) and Nayak (1996) have also documented dissimilar changes in soil characteristics in response to tree plantations due to differential nutrient biocycling.

The pH measurements of the soil ranged from 6.34 to 7.67, these pH values fall within the range of pH values (7.63 ± 0.3) reported by Al Sherif *et al.,* in 2009. The recorded pH values are also comparable to the pH range (7.0-6.7) found in rivers of South West Bengal as reported by Pradhan *et al*., in 2005. The current pH values are likewise in agreement with the findings of Chauhan *et al.,* in 2008 in Katarniaghat Wildlife Sanctuary.

The soil bulk density observed in the current study varied from 1.11 to 1.17 g cm^{-3} for the vegetation along the river. These findings align closely with the findings of Bohra *et al.,* (2010), who reported values ranging from 1.14 to 1.99 g cm^{-3} in the Shiwalik region of Nainital. Similarly, the bulk density values obtained in this study are comparable to those documented by Rai *et al*., (2011) in their research conducted in the Dehradun region of the Garhwal Himalayas.

The forest ecosystem plays a significant role in enriching the soil with organic material like leaves, twigs, stems, flowers, and fruits. As these components break down, they give rise to organic carbon and the release of various nutrients. However, the organic matter content tends to be lower near rivers, possibly because the constant water flow gradually washes away essential elements from the top layer of soil, as suggested by Iqbal *et al.,* in 2013.

The SOC stock obtained in the present study was lower than the range of 93.7-220.1 Mg C ha^{-1} reported by Zhang and Wang (2010) in temperate forest and 62.7-88.7 Mg C ha^{-1} reported by Zhu *et al*., (2010) in temperate mixed old growth forests of China. The higher range of SOC value reported in Chinese temperate forests was due to lower altitude (400 m.a.s.l). However, low range of SOC stock recorded in the present study may be due to higher altitude and its related environmental variables. Total SOC stock variation could be attributed to SOC concentration or simply due to the spatial variation of soil bulk density as reported by Li *et al*., (2010).

Nitrogen content availability ranged from 100.80 to 217.95 kg ha^{-1}, with consistently low levels observed across the entire plantation for both management regimes. The surface soils exhibited higher nitrogen content, displaying a linear decline with increasing soil depth.

This trend aligns with findings from previous studies by Najar (2009), Dar (2013), Naidu and Sireesha (2013), and Wani *et al.*, (2017). The results highlight the limited efficiency of nitrogen utilization, primarily attributed to nitrogen loss through various pathways such as NH3 volatilization, denitrification, chemical and microbial nitrogen fixation, as well as leaching and runoff, as noted by Sharma *et al.*, (2005).

The concentration of available potassium (K) exhibited a downward trend as soil depth increased, consistently showing lower levels of K in the surface layer across all seven sampled locations. Deeper soil layers showed a moderate to low availability of K. This declining trend of available potassium content with increasing depth highlights the prevalence of higher K concentrations in the surface soils. These findings align with previous studies conducted by Najar (2009) and Dar (2013).

The decline in soil nutrients such as phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) in plantations compared to natural forests can be attributed to various factors. These include activities like harvesting biomass, burning slash and logging residues as part of site preparation, thinning during silvicultural practices, and the absorption of cations into aboveground biomass through fine roots in plantations. Scientific research by Paul *et al.*, (2002), Jobbágy and Jackson (2003), and Berthrong *et al.*, (2009) have pointed to these potential causes.

This reduction in soil K, Ca, and Mg nutrients can have repercussions, leading to a decrease in the soil's cation exchange capacity (CEC) and the saturation of cations. This, in turn, can impact the overall availability and balance of nutrients in the soil environment.

Within hardwood stands, an interesting observation has been made regarding recycling processes. There appears to be a consistent link between these processes and the loss of Ca^{2+} (calcium ions) at depths beyond 20 cm in the mineral soil (Schroth *et al*., 2007).

Following a significant flood event, the vegetation zones exhibit lower levels of Ca, Mg, K, and Na content. This phenomenon is attributed to leaching and dilution processes, as highlighted by Conklin (2005), Day (1982), and De Datta (1981). The increased solubility of mineral nutrients induced by flooding, as noted by Mitsch (2000), plays a role in this outcome. During intense flooding, there is a heightened likelihood of soil nutrients becoming soluble and subsequently being carried away through leaching as water permeates the soil.

It might be assumed that due to the negative charge of clay particles, cations would bind to the soil, mitigating leaching. However, contrary to this expectation, research by Barber (1995) reveals that the dissociation of NO_3^- from HNO_3 (a product of nitrification) actually accelerates cation leaching. In the zones subjected to prolonged and deep flooding, conditions that encourage greater dissolution of soil nutrients in water, a substantial loss of nutrients through leaching is to be expected.

4.12 SOIL MICROBIOLOGICAL COUNT (cfu g^{-1})

4.12.1 Total culturable microbial count (cfu g^{-1})

The data presented on the actinomycetes counts, bacterial counts and fungi counts have been depicted in the tables 4.36 to 4.38, respectively.

4.12.1.1 Actinomycetes count

The data presented in table 4.36 reveals that microbial population was significantly influenced by different tree species, management regimes and soil depths. The soil under *Alnus nitida* was recorded with maximum actinomyctes count (3.38 x 10^5 $cfug^{-1}$ soil). *Populus deltoides* (2.33 x 10^5 $cfug^{-1}$ soil) was found to be statistically at par with *Eucalyptus tereticornis* (2.41 x 10^5 $cfug^{-1}$ soil). *Robinia pseudoacacia* (1.91 x 10^5 $cfug^{-1}$ soil) was found statistically different from *Alnus nitida* (3.38 x 10^5 $cfug^{-1}$ soil). In terms of soil depth, significantly higher actinomyctes count (3.08 x 10^5 $cfug^{-1}$ soil) were found for surface layer of soil (0-20cm) as compared to sub surface layer (2.12 x 10^5 $cfug^{-1}$ soil). The data on interaction between tree species (T) with management regimes (M) showed that *Populus deltoides* (3.05 x 10^5 cfu g^{-1} soil) was found to be statistically at par with *Eucalyptus tereticornis* (2.96 x 10^5 cfu g^{-1} soil) under institutional forest. *Salix tetrasperma* (1.95 x 10^5 cfu g^{-1} soil) was found to be statistically at par with *Eucalyptus tereticornis* (1.86 x 10^5 cfu g^{-1} soil). Whereas; *Robinia pseudoacacia* (1.58 x 10^5 cfu g^{-1} soil) remained statistically at par with *Populus deltoides* (1.61 x 10^5 cfu g^{-1} soil) under community forest. Data on interaction between T×M×D was found to be non-significant.

4.12.1.2 Bacterial Count

The study found that various factors significantly affected the bacterial population in the soil, including different tree species, management practices, and soil depths (as shown in table 4.37). The data pertaining to soil bacterial counts reveal that highest bacterial count

(140.30 x 10^5 cfu g^{-1} soil) was observed in soil associated with *Alnus nitida*. On the other hand, the lowest bacterial count (124.81 x 10^5 cfu g^{-1} soil) was recorded for *Robinia pseudoacacia*, which was statistically at par with *Eucalyptus tereticornis* (126.88 x 10^5 cfu g^{-1} soil) and *Populus deltoides* (130.31 x 10^5 cfu g-1 soil). Additionally, *Populus deltoides* (130.31 x 10^5 cfu g^{-1} soil) showed no significant difference in bacterial count compared to *Salix tetrasperma* (134.26 x 10^5 cfu g^{-1} soil). The order of tree species in terms of bacterial count was as follows: $T_1 < T_4 < T_2 < T_3 < T_5$. Furthermore, the analysis of soil depth revealed that the surface layer (0-20 cm) had a higher bacterial count (158.88 x 10^5 cfu g^{-1} soil) compared to the sub-surface layer (103.73 x 10^5 cfu g^{-1} soil). Importantly, there was a significant interaction between management practices (M) and soil depth (D), indicating that these two factors had a combined effect on bacterial populations. However, interactions between tree species (T) with management practices (M) and soil depth (D), as well as the interaction of TxMxD, were not found to be statistically significant.

The bacterial population was significantly influenced by different tree species, management regimes and soil depths (table 4.37). The data pertaining to soil bacterial counts reveals that *Alnus nitida* recorded maximum bacterial counts (140.30 x 10^5 cfu g^{-1} soil). Minimum bacterial count (124.81 x 10^5 $cfug^{-1}$ soil) was reported for *Robinia pseudoacacia* which was found to be statistically at par with *Eucalyptus tereticornis* (126.88 x 10^5 cfu g^{-1} soil) which remains statistically at par with *Populus deltoides* (130.31 x 10^5 cfu g^{-1} soil). Further *Populus deltoides* (130.31 x 10^5 cfu g^{-1} soil) was found to be statistically at par with *Salix tetrasperma* (134.26 x 10^5 cfu g^{-1} soil). Tree species under investigation followed the trend as $T_1 < T_4 < T_2 < T_3 < T_5$. Effect of soil depth depicted that higher bacterial count (158.88 x 10^5 cfu g^{-1} soil) was observed under surface layer (0-20 cm) as compared to sub surface layer (103.73 x 10^5 cfu g^{-1} soil). Interaction between management regimes (M) and soil depth (D) were found to be significantly different. Interaction between tree species (T) with management regimes (M) and soil depth (D) *viz.,* T×M, T×D and interaction of T×M×D were found to be non-significant.

4.12.1.3 Fungi Count

An examination of the data presented in table 4.38 indicated that the fungal population in the soil was significantly affected by various factors such as tree species, management regimes and soil depths. Specifically, soil associated with *Alnus nitida* had the

Table 4.36: Effect of tree species, management regimes, soil depths and their interaction effect on microbial count (Actinomycetes) of soil

Microbial count (10^5 cfu g^{-1}) (Actinomycetes)									
Management Regimes / Treatments	**M_1 (Institutional forest)**			**M_2 (Community forest)**			**D_1 (0-20 cm)**	**D_2 (20-40 cm)**	**MEAN**
	D_1 (0-20 cm)	**D_2 (20 40 cm)**	**MEAN**	**D_1 (0-20 cm)**	**D_2 (20-40 cm)**	**MEAN**			
T_1 (*R. pseudoacacia)*	3.07	1.43	2.25	1.84	1.31	1.58	2.45	1.37	1.91
T_2 (*P. deltoides*)	3.87	2.22	3.05	1.97	1.25	1.61	2.92	1.73	2.33
T_3 (*S. tetrasperma)*	4.34	3.55	3.94	2.08	1.82	1.95	3.21	2.69	2.95
T_4 (*E. tereticornis)*	3.52	2.40	2.96	1.98	1.73	1.86	2.75	2.07	2.41
T_5 (*A. nitida*)	5.23	3.48	4.36	2.88	1.95	2.42	4.05	2.72	3.38
MEAN	4.01	2.62	3.31	2.15	1.61	1.88	3.08	2.12	
$CD_{0.05}$									
M: Management Regimes			0.14				T×M		0.20
T: Tree Species			0.09				T×D		0.20
D: Soil Depth			0.09				M×D		0.13
							T×M×D		NS

Table 4.37: Effect of tree species, management regimes, soil depths and their interaction effect on microbial count (Bacteria) of soil

Microbial count (10^5 cfu g^{-1}) (Bacteria)									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	209.06	107.33	158.20	98.28	84.54	91.41	153.67	95.94	124.81
T_2 (*P. deltoides*)	215.57	113.10	164.34	104.13	88.43	96.28	159.85	100.76	130.31
T_3 (*S. tetrasperma)*	213.21	118.10	165.66	106.43	99.30	102.87	159.82	108.7	134.26
T_4 (*E. tereticornis)*	208.33	106.23	157.28	100.16	92.76	96.46	154.25	99.50	126.88
T_5 (*A. nitida*)	220.88	122.96	171.92	112.75	104.57	108.66	166.82	113.77	140.30
MEAN	213.41	113.54	166.75	104.35	93.92	99.14	158.88	103.73	

$CD_{0.05}$			
M: Management Regimes	5.35	T×M	NS
T: Tree Species	3.38	T×D	NS
D: Soil Depth	3.38	M×D	4.78
		T×M×D	NS

Table 4.38: Effect of tree species, management regimes, soil depths and their interaction effect on microbial count (Fungi) of soil

Microbial count (10^5 cfu g^{-1}) (Fungi)									
Management Regimes / Treatments	M_1 (Institutional forest)			M_2 (Community forest)			D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN
	D_1 (0-20 cm)	D_2 (20 40 cm)	MEAN	D_1 (0-20 cm)	D_2 (20-40 cm)	MEAN			
T_1 (*R. pseudoacacia)*	1.17	0.88	1.03	0.82	0.79	0.81	0.99	0.84	0.92
T_2 (*P. deltoides*)	1.27	1.21	1.24	1.03	0.91	0.97	1.15	1.06	1.11
T_3 (*S. tetrasperma)*	1.34	1.18	1.26	0.96	0.99	0.96	1.15	1.08	1.12
T_4 (*E. tereticornis)*	1.26	1.09	1.18	0.85	0.75	0.32	1.06	0.92	0.99
T_5 (*A. nitida*)	1.96	1.68	1.82	1.31	0.95	1.13	1.64	1.32	1.48
MEAN	1.40	1.21	1.30	0.99	0.88	0.84	1.20	1.04	
$CD_{0.05}$									
M: Management Regimes			0.08				T×M		0.12
T: Tree Species			0.05				T×D		0.12
D: Soil Depth			0.05				M×D		NS
							T×M×D		NS

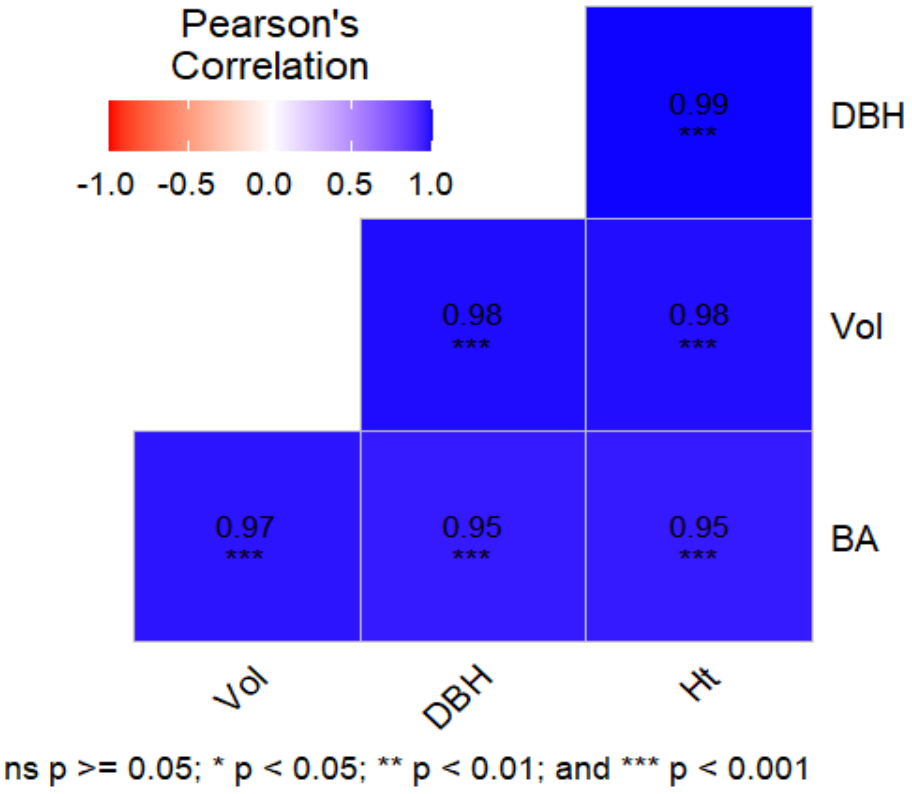
maximum fungal count (1.48 x 10^5 cfu g^{-1} soil), while the minimum fungal count (0.92 x 10^5 cfu g^{-1} soil) was observed in soil under *Robinia pseudoacacia*. In terms of soil depths, there was a noteworthy difference, with significantly higher fungal counts (1.20 x 10^5 cfu g^{-1} soil) in the surface layer (0-20 cm) compared to the sub-surface layer (20-40cm, 1.04 x 10^5 cfu g^{-1} soil). The interactions between tree species (T) and management practices (M), as well as tree species and soil depth (D), namely T×M and T×D, revealed that under institutional forest, *Populus deltoides* (1.24 x 10^5 cfu g^{-1} soil) was found to be statistically at par with *Eucalyptus tereticornis* (1.18 x 105 cfu g^{-1} soil) and *Salix tetrasperma* (1.26 x 10^5 cfu g^{-1} soil). In the context of community forest, *Robinia pseudoacacia* (0.81 x 10^5 cfu g^{-1} soil) had fungal counts statistically at par with *Populus deltoides* (0.97 x 10^5 cfu g^{-1} soil) and *Salix tetrasperma* (0.96 x 10^5 cfu g^{-1} soil), while *Populus deltoides* (0.97 x 10^5 cfu g^{-1} soil) and *Salix tetrasperma* (0.96 x 10^5 cfu g^{-1} soil) remained statistically at par with each other under community forest. Regarding the effect of soil depth, *Populus deltoides* (1.15 x 10^5 cfu g^{-1}) and *Salix tetrasperma* (1.15 x 10^5 cfu g^{-1} soil) displayed statistically identical fungal counts in the surface layer (0-20 cm) and were statistically at par under sub-surface layer (20-40 cm). Similarly, *Robinia pseudoacacia* (0.99 x 10^5 cfu g^{-1}) and *Eucalyptus tereticornis* (1.06 x 10^5 cfu g^{-1}) were statistically at par with each other in both the surface layer (0-20 cm) and the sub-surface layer (20-40 cm). However, interactions between tree species (T), management regime (M), and soil depth (D), represented by M×D and T×M×D, were not found to be statistically significant.

In the present study, under warm temperate conditions of North Western Himalayas, microbial count was reported to be maximum under *Alnus nitida* and *Salix tetrasperma* and minimum under *Robinia pseudoacacia* respectively, for both the management regimes under different plantations which might be due to higher leaf litter production and organic matter in its rhizosphere which support the microbial population. These results are in conformation with those of Selvi *et al.,* (2004) and Qureshi *et al.,* (2005). Zhang *et al.,* (2006) reported that different environmental parameters, content of soil organic carbon, total nitrogen and altitude could affect the diversity of soil flora, including nitrogen fixing bacteria. The increased microbial population may be due to the fact that organic manure provided necessary food and micro environment for their quicker multiplication and growth (Kumari and Kumari, 2002). The *Robinia pseudoacacia* plantation matures around 30 years old, and then the density and canopy cover declined (Bligh and Dyer, 1959). Vegetation degradation was an important factor for the reduction in microbial biomass in alpine grasslands, due to a decrease in

vegetation cover and biomass by Papaioannou *et al.,* (2016). It was reported that the microbial community structure changed across soil depths in tea plantations, and that these changes were related to substrate availability. Impact of trees on soil communities has shown that the presence of trees do not always lead to an increase in soil diversity, but more frequently result in an increase in microbial biomass (Huang *et al.,* 2013).

4.13 CORRELATION STUDIES

The correlation matrix between tree diameter at breast height (cm), height (m), basal area (m^2 ha^{-1}) and volume (m^3 ha^{-1}) among different plantation tree species managed under different management regimes have been depicted in Figure 4.6 revealed strong positive correlation with each other. Tree volume strongest relationship with diameter at breast height and basal area.

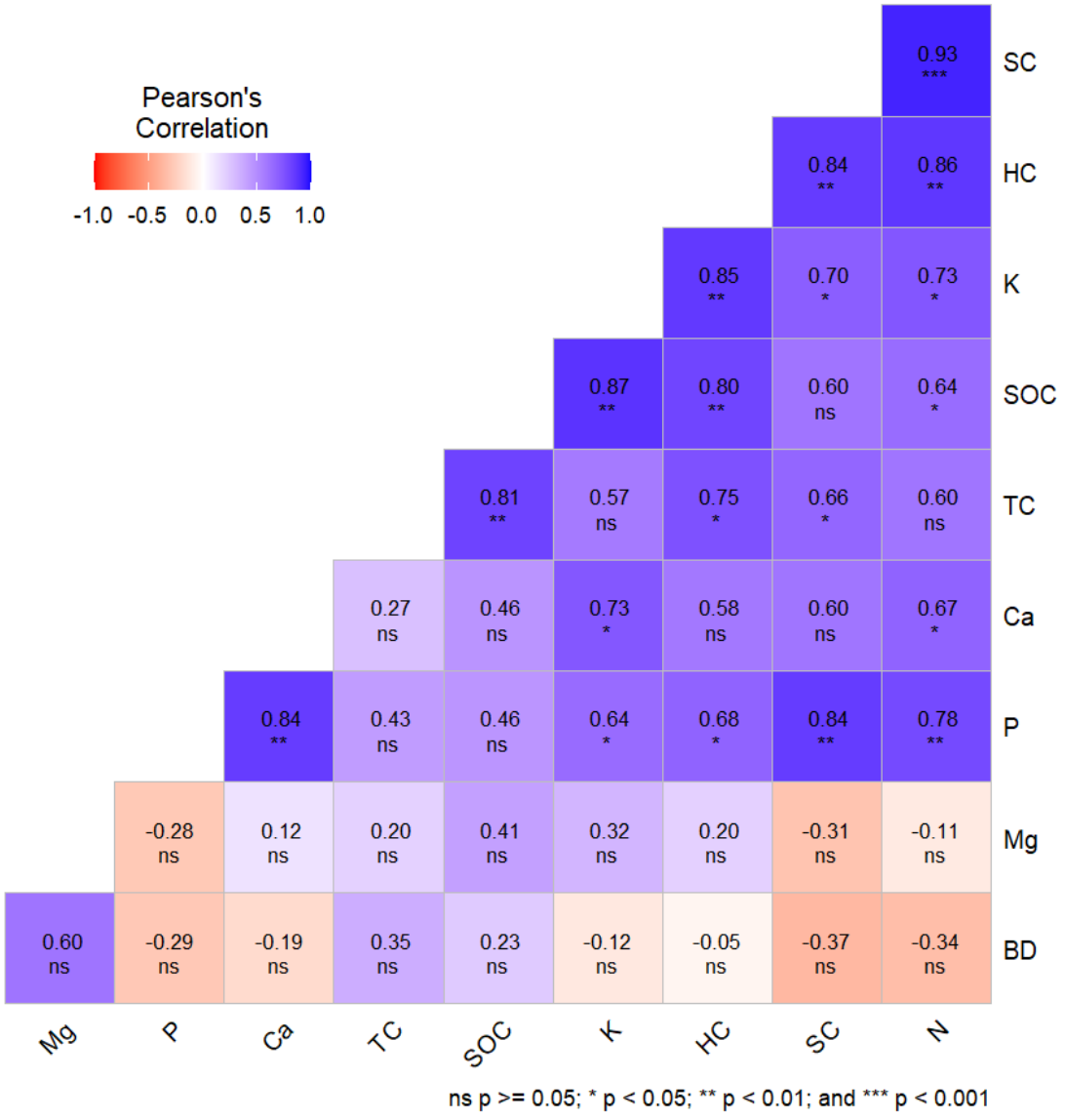


Vol= Volume, DBH = Diameter at breast height, BA= Basal area, Ht= Height

Figure 4.6: Correlation matrix between tree diameter at breast height (cm), height (m), basal area (m^2 ha^{-1}) and volume (m^3 ha^{-1})

The correlation between the tree carbon, shrub carbon, herb carbon with different soil physic-chemical characteristics have been depicted in Figure 4.7.

Tree carbon was associated with a strong positive relationship with SOC and positively correlated with herb and shrub carbon. Whereas, negative association between BD and available nitrogen, shrub carbon, herb carbon, available potassium, available phosphorus and exchangeable calcium was detected. However, HC was associated with a strong positive relationship with N and SC. While, SC showed strongest correlation with N. Furthermore, K was highly positively correlated with HC and had positive association with SC and N. Meanwhile, P was highly positively correlated with N, SC and Ca and had positive association with K and HC. Mg was shown to be negatively associated to N, SC and P.



SC= Shrub carbon, HC= Herb carbon, K= Potassium, SOC= Soil organic carbon, TC= Tree carbon, Ca= Exchangeable Calcium, P= Available phosphorus, Mg= Exchangeable magnesium, BD= Bulk density, N= Nitrogen.

Figure 4.7: Correlation matrix between tree carbon, shrub carbon, herb carbon and soil physico-chemical characteristics

Chapter-5

SUMMARY AND CONCLUSION

The present investigation entitled **"Evaluation of plantation tree species for biomass production and nutrient cycling in warm temperate North Western Himalayas"** was conducted during the year 2021-2023. Field investigation were carried out at the Regional Horticultural Research and Training Station, Bajaura. Two way ANOVA technique was used to analyse various traits viz., tree parameters, biomass production and carbon sequestration, etc. In which each plantation tree species was considered as treatment. Three way ANOVA was used for analysing the soil for various physico-chemical characteristics. A brief summary of the results emerging out from current investigation are being presented here under.

5.1 TREE PARAMETERS

5.2 BIOMASS PRODUCTION

5.3 CARBON STUDIES

5.4 LEAF–LITTER DYNAMICS

5.5 NUTRIENT ESTIMATION IN PLANTS

5.6 NUTRIENT DYNAMICS

5.7 SOIL PHYSICO-CHEMICAL CHARACTERISTICS

5.8 SOIL MICROBIAL PARAMETERS

5.1 TREE PARAMETERS

Observations recorded on tree parameters, viz., diameter at breast height (cm), height (m), basal area (m^2 ha^{-1}) and volume of standing tree (m^3 ha^{-1}) for different plantation tree species established under different management regimes. Statistically significant variations were observed for all the tree parameters under different management regimes.

Table 4.1 showed the effect of different plantation tree species managed under different management regimes on diameter at breast height (cm) and height (m).

- Average diameter at breast height (34.09 cm) and average height (17.84 m) were recorded maximum in *Populus deltoides* as compared to other species.

- Average diameter at breast height (24.64 cm) and average height (13.22 m) were recorded minimum in *Robinia pseudoacacia*.
- Diameter at breast height (34.61 cm) and height (17.89 m) were recorded highest under institutional forest.

Table 4.2 showed the effect of different plantation tree species managed under different management regimes on basal area (m^2 ha^{-1}) and volume (m^3 ha^{-1}).

- The results reflected that average basal area (12.82 m^2 ha^{-1}) and average volume (84.21 m^3 ha^{-1}) were recorded maximum in *Populus deltoides* as compared to other species.
- Average basal area (6.70 m^2 ha^{-1}) and average volume (32.18 m^3 ha^{-1}) were recorded minimum in *Robinia pseudoacacia*.
- Average basal area (12.39 m^2 ha^{-1}) and average volume (84.20 m^3 ha^{-1}) were observed highest under institutional forest.

5.2 BIOMASS PRODUCTION

Different biomass parameters *i.e.* above ground biomass (AGB), below ground biomass (BGB) and total biomass (TB) of different plantation tree species established under different management regimes (Table 4.3) are summarized as below:

- Maximum average above ground biomass (62.53 Mg ha^{-1}), below ground biomass (31.01 Mg ha^{-1}) and total biomass (93.54 Mg ha^{-1}) was displayed by *Alnus nitida* among other plantation tree species.
- Minimum average of above ground biomass (37.04 Mg ha^{-1}), below ground biomass (19.58 Mg ha^{-1}) and total biomass (56.63 Mg ha^{-1}) was displayed by *Robinia pseudoacacia.*
- Highest of above ground biomass (67.00 Mg ha^{-1}), below ground biomass (33.23 Mg ha^{-1}) and total biomass (100.23 Mg ha^{-1}) were displayed by institutional forest.

Table 4.4 displayed the effect of different plantation tree species managed under different management regimes on shrub and herb biomass (Mg ha^{-1}).

- Average shrub biomass (0.65 Mg ha^{-1}) and herb biomass (5.89 Mg ha^{-1}) (above + below) (Mg ha^{-1}) were recorded maximum under *Alnus nitida.*

- Average shrub biomass (0.29 Mg ha^{-1}) and herb biomass (3.67 Mg ha^{-1}) (above + below) (Mg ha^{-1}) were recorded minimum under *Robinia pseudoacacia.*

Table 4.8 showed detritus biomass (Mg ha^{-1}) of different plantation tree species under different management regimes**.**

- Leaf litter biomass (2.66 Mg ha^{-1}), dead twigs and branches (0.83 Mg ha^{-1}), dead tree biomass (0.50 Mg ha^{-1}) and total detritus biomass presented maximum value (4.00 Mg ha^{-1}) for *Alnus nitida*.
- Minimum value of leaf litter biomass (1.53 Mg ha^{-1}), dead tree biomass (0.21 Mg ha^{-1}) and total detritus biomass presented maximum value (2.55 Mg ha^{-1}) for *Robinia pseudoacacia.* Dead twigs and branches (0.46 Mg ha^{-1}) was recorded minimum under *Eucalyptus tereticornis.*

5.3 CARBON STUDIES

5.3.1 Carbon Density

- Table 4.6 showed that maximum tree carbon density (44.43 Mg C ha^{-1} yr^{-1}) was found for *Alnus nitida* plantation and minimum (26.90 Mg C ha^{-1} yr^{-1}) was recorded for *Robinia pseudocacacia.*
- Table 4.7 showed maximum shrub carbon density (0.31 Mg C ha^{-1} yr^{-1}), herb carbon density (2.80 Mg C ha^{-1} yr^{-1}) for *Alnus nitida* and mimimum showed similar trend as tree carbon density.
- Table 4.5 showed maximum vegetation carbon density (67.91 Mg C ha^{-1} yr^{-1}) for *Alnus nitida* and minimum (18.73 Mg C ha^{-1} yr^{-1}) for *Robinia pseudocacacia.*
- Table 4.9 showed total detritus carbon density (1.90 Mg C ha^{-1} yr^{-1}) which was found maximum for *Alnus nitida* and mimimum (1.22 Mg C ha^{-1} yr^{-1}) for *Robinia pseudocacacia.*
- Table 4.10 showed maximum (0.65 Mg C ha^{-1} yr^{-1}) humus carbon density for *Alnus nitida* and minimum (1.22 Mg C ha^{-1} yr^{-1}) was shown by *Robinia pseudocacacia* and *Eucalyptus tereticornis*.
- Table 4.10 represented maximum soil carbon density (52.78 Mg C ha^{-1} yr^{-1}) found for *Salix tetrasperma*. Total carbon density [humus + soil (0-40 cm)] showed similar trend as humus carbon density and *Robinia pseudocacacia* recorded minimum value for total carbon density (43.68 Mg C ha^{-1} yr^{-1}).

- Table 4.11 reflected maximum ecosystem carbon density for *Alnus nitida* (125.94 Mg C ha^{-1} yr^{-1}) under institutional forest which was reported with higher value (106.51 Mg C ha^{-1} yr^{-1}) for ecosystem carbon density among management regimes and the minimum ecosystem carbon density (58.20 Mg C ha^{-1} yr^{-1}) was recorded for *Robinia pseudocacacia* in community forest.
- For tree carbon density (47.61 Mg C ha^{-1} yr^{-1}), shrub carbon density (0.23 Mg C ha^{-1} yr^{-1}), herb carbon density (2.57 Mg C ha^{-1} yr^{-1}), vegetation carbon density (50.41 Mg C ha^{-1} yr^{-1}), total detritus carbon density (1.80 Mg C ha^{-1} yr^{-1}), total carbon density [humus + soil (0-40 cm)] (54.30 Mg C ha^{-1} yr^{-1}) were recorded higher under institutional forest in comparison with community forest.

5.3.2 Carbon Sequestration

Carbon sequestration rate was estimated for different plantation tree species established under different management regimes and the salient results emerging are summarized as below:

- Table 4.6 Carbon sequestration rate was recorded maximum (1.23 Mg C ha^{-1} yr^{-1}) for *Alnus nitida* under institutional forest which was reported with higher (1.23 Mg C ha^{-1} yr^{-1}) carbon sequestration rate in comparison with community forest.
- Table 4.12 revealed carbon sequestration potential for different plantation tree species managed under different management regimes and found that maximum (66.53 Mg C ha^{-1}) carbon sequestration potential was recorded higher (48.57 Mg C ha^{-1}) under institutional forest for *Alnus nitida* and minimum (17.07 Mg C ha^{-1}) was recorded for *Robinia pseudocacacia* under community forest.
- Carbon sequestration potential for soil was found maximum (57.75 Mg C ha^{-1}) for *Salix tetrasperma* under institutional forest which also recorded with higher carbon sequestration potential and minimum (36.93 Mg C ha^{-1}) was examined for *Robinia pseudocacacia* under community forest.
- Total (plant + soil) Carbon sequestration potential was found maximum (121.60 Mg C ha^{-1}) for *Alnus nitida* and minimum (53.99 Mg C ha^{-1}) was recorded for *Robinia pseudocacacia* under community forest.

5.4 LEAF –LITTER DYNAMICS

Leaf litter dynamics was also recorded in three different seasons (winter, summer and rainy) for different plantation tree species managed under different management regimes and the results are summarized below:

- *Alnus nitida* was found with the maximum total litter content of 2.03 (kg m^{-2}) (table 4.14)
- In different seasons leaf litter content was in order: winter (0.56-0.81 kg m^{-2}) > summer (0.35-0.63 kg m^{-2}) > rainy season (0.26-0.59 kg m^{-2}). *Alnus nitida* was found with the maximum litter content of 0.81, 0.63 and 0.59 kg m^{-2}, respectively for all the three seasons.
- Institutional forest was recorded with higher total litter content of 1.68 (kg m^{-2}).
- Minimum value for leaf litter for different seasons and among plantation tree species were showed by *Robinia pseudoacacia.*

5.5 NUTRIENT ESTIMATION IN PLANTS

- In institutional forest, the nitrogen (N) levels ranked in the order of root > leaf > branch > stem for the mentioned species, whereas in the community forest, the sequence was leaf > root > branch > stem.
- The concentration of phosphorus (P) varied significantly across different plantation tree species within the institutional forest, displaying a pattern of shoot > leaf > root > branch. In contrast, the trend observed in the community forest was leaf > shoot > root > branch.
- For potassium (K), the trend was leaf > root > stem > branch in both the regimes. Calcium (Ca) exhibited a sequence of stem > leaf > branch > root, while magnesium (Mg) showcased a pattern of stem > root > branch > leaf, maintaining consistency under both institutional and community forest management.
- Across all tree species, the relative abundance of nutrients followed the sequence: N > Ca > K > Mg > P.

5.6 NUTRIENT DYNAMICS

- The nitrogen (N) levels ranked in the following sequence: *Alnus nitida* (T_5) > *Salix tetrasperma* (T_3) > *Populus deltoides* (T_2) > *Robinia pseudoacacia* (T_1) > *Eucalyptus tereticornis* (T_4). Similar order was observed for the uptake of phosphorus (P), calcium (Ca), and magnesium (Mg), showing maximum values. Notably, *Salix tetrasperma* (T_3) demonstrated the highest potassium (K) value (143.11 kg ha^{-1}), while *Robinia pseudoacacia* had the lowest values for all nutrients except N (161.21 kg ha^{-1}) and P (20.83 kg ha^{-1}) in institutional forest.

- Under institutional forest, *Alnus nitida* showed better nutrient cycling among different plantation tree species.

5.7 SOIL PHYSICO-CHEMICAL CHARACTERISTICS

In different plantations under different management regimes had non –significant effect on soil EC, pH, bulk density and organic carbon whereas, SOC density (26.40 Mg ha^{-1}) was recorded maximum in *Salix tetrasperma*.

5.7.1 Available N, P, K

- Among plantation tree species, maximum value of available N (215.04 kg ha^{-1}) and P (122.08 kg ha^{-1}) were recorded for *Alnus nitida* and K (150.32 kg ha^{-1}) were recorded for *Salix tetrasperma* under institutional forest.
- Available N and K were more in 0-20 cm soil layer than 20-40 cm but available P was found more in 20-40 cm soil layer.

5.7.2 Available Ca and Mg

- Available calcium (17.44 c mol (p+)/kg) and magnesium (2.15 c mol (p+)/kg) were recorded more for *Salix tetrasperma*.
- Both Ca and Mg were recorded maximum in 0-20 cm soil layer.

5.8 SOIL MICROBIAL PARAMETERS

Soil biological property, *viz.*, microbial count for different plantation tree species managed under different management regimes were recorded and summarized below:

- The maximum microbial count (10^5 cfu g^{-1}) *viz.*, actinomycetes (3.38), bacterial (140.30) and fungal (1.48) were observed for *Alnus nitida* under institutional forest. In the effect of soil depth, surface layer was observed with higher microbial count as compared to sub-surface layer.

CONCLUSIONS

- In different plantation forest ecosystems, the biomass production was found maximum in *Alnus nitida* plantation (93.54 Mg ha^{-1}) and followed the trend: *Alnus nitida* > *Eucalyptus tereticornis* > *Populus deltoides* > *Salix tetrasperma* > *Robinia*

pseudoacacia. Among different management regimes, highest biomass (135.47 Mg ha^{-1}) was recorded for institutional forest.

- Maximum carbon storage (125.94 Mg C ha^{-1}) in different plantation forest ecosystems was displayed by *Alnus nitida* followed by *Salix tetrasperma, Populus deltoides, Eucalyptus tereticornis* and *Robinia pseudoacacia,* respectively. Among management regimes highest carbon storage (106.51 Mg C ha^{-1}) was revealed by institutional forest.
- Rate of carbon sequestration (soil + vegetation pool) found maximum (3.38 Mg C ha^{-1} yr^{-1}) for *Alnus nitida* followed by *Salix tetrasperma, Populus deltoides, Eucalyptus tereticornis* and *Robinia pseudoacacia* in descending order. Among management regimes highest rate of carbon sequestration (2.83 Mg C ha^{-1}) was displayed by institutional forest.
- *Alnus nitida* showed better nutrient cycling in different plantation forest ecosystems and among different management regimes. Different species followed the order: *Alnus nitida* > *Salix tetrasperma* > *Eucalyptus tereticornis* > *Populus deltoides* > *Robinia pseudoacacia*.
- The physical and chemical properties of soil like EC, organic carbon, available N, P and K were found maximum under *Alnus nitida* in the soil depth 0-20 cm for institutional forest.
- Soil microbial count (actinomycetes, bacteria and fungi) was recorded maximum in *Alnus nitida* plantation at 0-20 cm soil depth for institutional management regime.

Thus, it can be concluded from the results of the study that under institutional management regime *Alnus nitida* displayed maximum biomass production, carbon sequestration potential and better nutrient stock and is found to be better species for afforestation of riverine sites with harsh edapho-climatic conditions followed by *Salix tetrasperma, Populus deltoides, Eucalyptus tereticornis* and *Robinia pseudoacacia*. Community forest is subjected to biotic interference by way of tree felling for timber, firewood collection, lopping, and grazing and therefore has resulted in poor biomass production and finally the poor nutrient stock. Human disturbance had a strong influence on the species richness and stand characteristics that in turn influence the biomass and C stock in the community forests.

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APPENDIX – I

Table 1: Specific gravity, biomass expansion factor and root: shoot ratio of different forest tree species (FSI, 1996)

S. No	Species Name	Specific gravity	References	BEF	Root: Shoot Ratio
1.	*Alnus nitida*	0.68	Hidayat and Simpson, 1994	1.50	BEF=EXP(1.05+0.884*LN(AGB)+0.284)
2.	*Eucalyptus tereticornis*	0.70	Singh, 1994	1.31	BEF=EXP(1.05+0.884*LN(AGB)+0.284)
3.	*Populus deltoides*	0.38	Sachil, 2000	1.41	BEF=EXP(1.05+0.884*LN(AGB)+0.284)
4.	*Robinia pseudoacacia*	0.71	Wani *et al.*, 2014	1.47	BEF=EXP(1.05+0.884*LN(AGB)+0.284)
5.	*Salix tetrasperma*	0.42	Wani *et al.*, 2014	1.50	BEF=EXP(1.05+0.884*LN(AGB)+0.284)

Table 2: List of shrubs and herbs found under different plantation tree species in two different management regimes

S.No	Name of shrubs	Name of herbs
1.	*Asparagus adscendens*	*Achyranthus aspera*
2.	*Berberis aristata*	*Cannabis sativa*
3.	*Carissa carandas*	*Datura stramonium*
4.	*Lantana camara*	*Oenothera biennis*
5.	*Solanum khasianum*	*Parthenuim hysterophorus*
6.	*Murraya koenigii*	*Rubia cordifolia*
7.	*Opuntia* spp	*Urtica dioica*
8.	*Prinsepia utilis*	Local grasses (Chij, Baru and ghumbar grass)
9.	*Rosa moschatta*	
10.	*Zanthoxylum alatum*	
	Ziziphus mauritiana	

APPENDIX – II

ANALYSIS OF VARIANCE FOR TREE PARAMETERS, BIOMASS AND CARBON

ANOVA 1: Tree diameter at breast height

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	10.874		
Management Regimes	1	636.555	636.555	1,430.23
Tree species	4	294.575	73.644	165.465
Interaction A X B	4	13.138	3.285	7.38
Error	18	8.011	0.445	

ANOVA 2: Tree Height

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	2.382		
Management Regimes	1	143.751	143.751	345.730
Tree species	4	72.692	18.173	43.707
Interaction A X B	4	2.044	0.511	1.229
Error	18	7.484	0.416	

ANOVA 3: Tree basal area

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	6.656		
Management Regimes	1	211.578	211.578	70.784
Tree species	4	150.718	37.68	12.606
Interaction A X B	4	34.429	8.607	2.88
Error	18	53.803	2.989	

ANOVA 4: Tree volume

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	5.727		
Management Regimes	1	18,505.31	18,505.31	2,410.87
Tree species	4	8,895.79	2,223.95	289.735
Interaction A X B	4	1,410.76	352.69	45.948
Error	18	138.164	7.676	

ANOVA 5: Above ground biomass (AGB)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	5.164		
Management Regimes	1	11,512.65	11,512.65	3,168.69
Tree species	4	2,166.56	541.639	149.078
Interaction A X B	4	747.312	186.828	51.422
Error	18	65.399	3.633	

ANOVA 6: Below ground biomass (BGB)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	1.102		
Management Regimes	1	2,418.85	2,418.85	3,420.71
Tree species	4	436.9	109.225	154.465
Interaction A X B	4	133.233	33.308	47.104
Error	18	12.728	0.707	

ANOVA 7: Total biomass (TB)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	11.056		
Management Regimes	1	24,486.22	24,486.22	3,263.83
Tree species	4	4,548.51	1,137.13	151.571
Interaction A X B	4	1,510.61	377.653	50.338
Error	18	135.041	7.502	

ANOVA 8: Total carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	2.494		
Management Regimes	1	5,524.072	5,524.072	3,260.023
Tree species	4	1,026.626	256.657	151.465
Interaction A X B	4	340.789	85.197	50.279
Error	18	30.501	1.694	

ANOVA 9: Tree carbon sequestered

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.002		
Management Regimes	1	4.256	4.256	3,348.16
Tree species	4	0.792	0.198	155.749
Interaction A X B	4	0.263	0.066	51.779
Error	18	0.023	0.001	
Total	29	5.337		

ANOVA 10: Tree carbon mitigated

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	33.573		
Management Regimes	1	74,407.24	74,407.24	3,261.54
Tree species	4	13,825.61	3,456.40	151.507
Interaction A X B	4	4,591.00	1,147.75	50.31
Error	18	410.644	22.814	
Total	29	93,268.07		

ANOVA 11: Shrub total biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.452		
Management Regimes	1	0.067	0.067	34.319
Tree species	4	0.454	0.114	57.963
Interaction A X B	4	0.039	0.01	5.036
Error	18	0.035	0.002	

ANOVA 12: Herb total biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.223		
Management Regimes	1	10.514	10.514	940.362
Tree species	4	17.255	4.314	385.816
Interaction A X B	4	7.626	1.906	170.514
Error	18	0.201	0.011	

ANOVA 13: Shrub carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.099		
Management Regimes	1	0.015	0.015	32.719
Tree species	4	0.106	0.026	56.136
Interaction A X B	4	0.009	0.002	4.822
Error	18	0.008	0	

ANOVA 14: Herb carbon

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.051		
Management Regimes	1	2.38	2.38	935.922
Tree species	4	3.898	0.975	383.218
Interaction A X B	4	1.72	0.43	169.084
Error	18	0.046	0.003	

ANOVA 15: Vegetation Biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	6.432		
Management Regimes	1	25,594.32	25,594.32	3,492.49
Tree species	4	5,094.81	1,273.70	173.804
Interaction A X B	4	1,639.81	409.953	55.94
Error	18	131.911	7.328	

ANOVA 16: Vegetation carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	1.48		
Management Regimes	1	5,774.10	5,774.10	3,488.17
Tree species	4	1,149.89	287.472	173.664
Interaction A X B	4	369.764	92.441	55.844
Error	18	29.796	1.655	

ANOVA 17: Leaf litter biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.012		
Management Regimes	1	3.612	3.612	589.711
Tree species	4	4.79	1.198	195.505
Interaction A X B	4	1.198	0.3	48.908
Error	18	0.11	0.006	

ANOVA 18: Dead twigs and branches biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.069		
Management Regimes	1	0.492	0.492	68.596
Tree species	4	0.527	0.132	18.393
Interaction A X B	4	0.093	0.023	3.258
Error	18	0.129	0.007	

ANOVA 19: Dead trees biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.131		
Management Regimes	1	0.343	0.343	49.293
Tree species	4	0.337	0.084	12.106
Interaction A X B	4	0.222	0.056	7.979
Error	18	0.125	0.007	

ANOVA 20: Total detritus biomass

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.461		
Management Regimes	1	10.162	10.162	345.966
Tree species	4	9.648	2.412	82.120
Interaction A X B	4	2.678	0.670	22.795
Error	18	0.529	0.029	

ANOVA 21: Leaf litter carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.003		
Management Regimes	1	0.81	0.81	558.057
Tree species	4	1.074	0.268	184.93
Interaction A X B	4	0.267	0.067	46.007
Error	18	0.026	0.001	

ANOVA 22: Dead twigs and branches carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.016		
Management Regimes	1	0.112	0.112	68.456
Tree species	4	0.117	0.029	17.896
Interaction A X B	4	0.021	0.005	3.227
Error	18	0.029	0.002	

ANOVA 23: Dead tree carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.030		
Management Regimes	1	0.076	0.076	49.723
Tree species	4	0.077	0.019	12.637
Interaction A X B	4	0.048	0.012	7.875
Error	18	0.028	0.002	

ANOVA 24: Total detritus carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.103		
Management Regimes	1	2.296	2.296	348.582
Tree species	4	2.186	0.547	82.974
Interaction A X B	4	0.602	0.15	22.841
Error	18	0.119	0.007	

ANOVA 25: Humus carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.002		
Management Regimes	1	0.069	0.069	168.627
Tree species	4	0.796	0.199	485.771
Interaction A X B	4	0.041	0.01	25.074
Error	18	0.007	0	

ANOVA 26: Soil carbon density (0-40 cm)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	329.499		
Management Regimes	1	912.103	912.103	190.656
Tree species	4	379.946	94.987	19.855
Interaction A X B	4	40.38	10.095	2.11
Error	18	86.112	4.784	

ANOVA 27: Total soil carbon density (Humus + Soil)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	327.838		
Management Regimes	1	927.97	927.97	193.247
Tree species	4	410.537	102.634	21.373
Interaction A X B	4	38.287	9.572	1.993
Error	18	86.436	4.802	

ANOVA 28: Total ecosystem carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	373.566		
Management Regimes	1	11,656.94	11,656.94	1,662.06
Tree species	4	2,356.18	589.045	83.987
Interaction A X B	4	289.777	72.444	10.329
Error	18	126.244	7.014	

ANOVA 29: Soil vegetation carbon density

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.234		
Management Regimes	1	5.284	5.284	244.331
Tree species	4	1.481	0.37	17.127
Interaction A X B	4	0.535	0.134	6.184
Error	18	0.389	0.022	

Table 15: Comparative analysis of different plantation tree species for nitrogen content in tree components under different management regimes

	Nitrogen (Mg ha^{-1})					
	LEAF					
Tree species / Management Regimes	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**Mean**
Institutional forest	21.19 (2.23)	12.95 (1.79)	26.71 (2.97)	15.46 (1.68)	25.81 (3.04)	20.43 (2.34)
Community forest	8.57 (1.91)	8.11 (1.62)	14.29 (2.45)	9.51 (1.58)	15.44 (2.58)	11.19 (2.03)
Mean	14.88 (2.07)	10.53 (1.71)	20.50 (2.71)	12.48 (1.63)	20.63 (2.81)	
CD	M: 2.01 (0.05)		T: 3.18 (0.07)		M×T: 4.49 (0.10)	
	STEM					
Institutional forest	12.76 (0.39)	10.49 (0.24)	13.84 (0.33)	9.03 (0.18)	25.22 (0.41)	14.27 (0.31)
Community forest	4.63 (0.36)	4.19 (0.21)	4.79 (0.32)	3.79 (0.17)	6.80 (0.30)	4.84 (0.28)
Mean	8.70 (0.37)	7.34 (0.22)	9.32 (0.33)	6.41 (0.18)	16.01 (0.36)	
CD	M: 0.78 (0.02)		T: 1.26 (0.02)		M×T: 1.79 (0.03)	
	BRANCHES					
Institutional forest	13.22 (0.70)	15.13 (0.74)	17.82 (0.80)	11.02 (0.71)	27.46 (0.90)	16.93 (0.77)
Community forest	6.27 (0.65)	6.55 (0.70)	5.83 (0.77)	5.35 (0.66)	9.55 (0.85)	6.71 (0.73)
Mean	9.74 (0.68)	10.84 (0.72)	11.82 (0.78)	8.18 (0.69)	18.51 (0.88)	
CD	M: 0.99 (0.02)		T: 1.57 (0.02)		M×T: 2.21 (NS)	
	ROOTS					
Institutional forest	7.69 (0.29)	16.15 (0.51)	18.90 (0.61)	18.38 (0.56)	52.45 (1.19)	22.72 (0.63)
Community forest	3.48 (0.28)	7.84 (0.48)	7.38 (0.58)	8.56 (0.52)	20.95 (1.16)	9.64 (0.60)
Mean	5.59 (0.28)	12.00 (0.49)	13.14 (0.59)	13.47 (0.54)	36.70 (1.18)	
CD	M: 0.66 (0.02)		T: 1.04 (0.03)		M×T: 1.47 (NS)	

Figure in parenthesis is percent value (%) of nitrogen

Table 16: Comparative analysis of different plantation tree species for phosphorus content in tree components under different management regimes

	Phosphorus (Mg ha^{-1})					
	LEAF					
Tree species / Management Regimes	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**Mean**
Institutional forest	2.53 (0.27)	2.18 (0.31)	3.78 (0.42)	3.55 (0.39)	4.15 (0.49)	3.24 (0.37)
Community forest	0.90 (0.20)	0.91 (0.18)	1.66 (0.28)	1.29 (0.22)	1.83 (0.31)	1.32 (0.24)
Mean	1.72 (0.24)	1.55 (0.24)	2.72 (0.35)	2.42 (0.30)	2.99 (0.40)	
CD	M: 0.32 (0.02)		T: 0.50 (0.04)		M×T: NS (0.05)	
	STEM					
Institutional forest	2.78 (0.09)	1.30 (0.03)	3.99 (0.10)	2.00 (0.04)	7.12 (0.11)	3.44 (0.07)
Community forest	0.85 (0.07)	0.88 (0.04)	0.40 (0.03)	0.38 (0.02)	0.58 (0.03)	0.62 (0.04)
Mean	1.82 (0.08)	1.09 (0.04)	2.20 (0.06)	1.19 (0.03)	3.85 (0.07)	
CD	M: 0.59 (0.02)		T: 0.93 (0.03)		M×T: 1.31 (0.04)	
	BRANCHES					
Institutional forest	0.77 (0.04)	1.10 (0.05)	1.61 (0.07)	0.95 (0.06)	3.77 (0.12)	1.64 (0.07)
Community forest	0.19 (0.02)	0.43 (0.05)	0.27 (0.04)	0.29 (0.04)	0.48 (0.04)	0.34 (0.04)
Mean	0.48 (0.03)	0.77 (0.05)	0.94 (0.05)	0.62 (0.05)	2.13 (0.08)	
CD	M: 0.37 (0.02)		T: 0.58 (0.03)		M×T: 0.82 (NS)	
	ROOTS					
Institutional forest	1.69 (0.06)	1.28 (0.04)	2.39 (0.08)	2.84 (0.09)	5.57 (0.13)	2.75 (0.08)
Community forest	0.58 (0.05)	0.60 (0.04)	0.85 (0.07)	1.06 (0.06)	0.96 (0.05)	0.81 (0.05)
Mean	1.14 (0.06)	0.94 (0.04)	1.62 (0.07)	1.95 (0.08)	3.26 (0.09)	
CD	M: 0.43 (0.02)		T: 0.68 (0.02)		M×T: 0.96 (0.03)	

Figure in parenthesis is percent value (%) of phosphorus

Table 17: Comparative analysis of different plantation tree species for potassium content in tree components under different management regimes

	Potassium (Mg ha $^{-1}$)					
	LEAF					
Management Regimes/ Tree species	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**Mean**
Institutional forest	20.67 (2.17)	17.48 (2.41)	23.15 (2.52)	11.87(1.29)	12.98 (1.52)	17.23 (1.99)
Community forest	6.46 (1.47)	10.63 (2.14)	13.16 (2.26)	7.35 (1.24)	7.94 (1.34)	9.11 (1.69)
Mean	13.56 (1.82)	14.06 (2.28)	18.16 (2.39)	9.61 (1.27)	10.46 (1.43)	
CD	M: 2.23 (0.13) T: 3.52 (0.21) M×T: NS (0.30)					
	STEM					
Institutional forest	2.75 (0.08)	4.66 (0.11)	6.21 (0.15)	6.36 (0.13)	11.81(0.19)	6.36 (0.13)
Community forest	1.34 (0.10)	1.36 (0.07)	1.75 (0.11)	2.07 (0.09)	3.66 (0.16)	2.04 (0.11)
Mean	2.05 (0.09)	3.01 (0.09)	3.98 (0.13)	4.21 (0.11)	7.74 (0.18)	
CD	M: 0.75 T: 1.19 M×T: 1.68					
	BRANCHES					
Institutional forest	3.25 (0.17)	4.24 (0.21)	5.46 (0.24)	2.83 (0.18)	8.22 (0.27)	4.80 (0.22)
Community forest	1.37 (0.14)	1.72 (0.18)	1.70 (0.23)	1.18 (0.15)	2.70 (0.24)	1.73 (0.19)
Mean	2.31 (0.16)	2.98 (0.20)	3.58 (0.24)	2.01 (0.17)	5.46 (0.26)	
CD	M: 0.48 (0.02) T: 0.75 (0.04) M×T: 1.06 (NS)					
	ROOTS					
Institutional forest	3.90 (0.15)	7.88 (0.25)	9.57 (0.31)	9.03 (0.28)	15.23 (0.35)	9.12 (0.27)
Community forest	1.39 (0.11)	3.38 (0.21)	2.63 (0.21)	3.44 (0.21)	5.37 (0.30)	3.24 (0.21)
Mean	2.65 (0.13)	5.63 (0.23)	6.10 (0.26)	6.23 (0.24)	10.30 (0.32)	
CD	M: 0.59 (0.02) T: 0.93 (0.03) M×T: 1.32 (NS)					

Figure in parenthesis is percent value (%) of potassium

Table 18: Comparative analysis of different plantation tree species for calcium content in tree components under different management regimes

	Calcium (Mg ha $^{-1}$)					
	LEAF					
Tree species Management Regimes	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**Mean**
Institutional forest	13.46(1.42)	13.63(1.89)	20.68(2.28)	19.74(2.14)	20.01(2.35)	17.50 (2.02)
Community forest	6.18 (1.38)	8.84 (1.76)	11.46(1.96)	11.09(1.85)	11.72(1.94)	9.86 (1.78)
Mean	9.82 (1.40)	11.23(1.82)	16.07(2.12)	15.41(1.85)	15.87(2.15)	
CD	M: 1.76 (0.05) T: 2.79 (0.08) M×T: NS (0.12)					
	STEM					
Institutional forest	27.99 (0.86)	29.98(0.69)	29.72 (0.72)	35.69(0.71)	49.03(0.80)	34.48(0.76)
Community forest	11.24 (0.87)	13.68(0.67)	10.51 (0.67)	15.05(0.67)	17.46(0.78)	13.59(0.74)
Mean	19.61 (0.86)	21.83(0.68)	20.12 (0.71)	25.37(0.69)	33.25(0.79)	
CD	M: 0.79 (0.02) T: 1.25 (0.03) M×T: 1.76 (NS)					
	BRANCHES					
Institutional forest	12.28 (0.65)	16.16(0.79)	14.74(0.66)	11.43 (0.74)	23.59(0.77)	15.64(0.72)
Community forest	5.80 (0.60)	6.95 (0.74)	4.80 (0.63)	5.64 (0.69)	8.13 (0.73)	6.26 (0.68)
Mean	9.04 (0.63)	11.55(0.77)	9.77 (0.65)	8.54 (0.72)	15.86(0.73)	
CD	M: 0.87 (0.02) T: 1.37 (0.03) M×T: 1.94 (NS)					
	ROOTS					
Institutional forest	3.28 (0.12)	3.39 (0.11)	4.26 (0.14)	3.60 (0.11)	8.34 (0.19)	4.57 (0.13)
Community forest	0.71 (0.06)	0.93 (0.06)	1.22 (0.09)	1.23 (0.07)	1.80 (0.10)	1.18 (0.08)
Mean	1.99 (0.09)	2.16 (0.08)	2.74 (0.12)	2.41 (0.09)	5.07 (0.15)	
CD	M: 0.42 (0.02) T: 0.67 (0.02) M×T: 0.95 (NS)					

Figure in parenthesis is percent value (%) of calcium

Table 19: Comparative analysis of different plantation tree species for magnesium content in tree components under different management regimes

	Magnesium (Mg ha $^{-1}$)					
	LEAF					
Tree species / Management Regimes	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**Mean**
Institutional forest	1.12 (0.12)	0.79 (0.11)	1.27 (0.14)	0.42 (0.05)	0.81 (0.10)	0.88 (0.10)
Community forest	0.16 (0.04)	0.37 (0.07)	0.21 (0.04)	0.18 (0.03)	0.23 (0.04)	0.23 (0.05)
Mean	0.64 (0.08)	0.58 (0.09)	0.74 (0.09)	0.30 (0.04)	0.52 (0.07)	
CD	M: 0.21 (0.02) T: NS (0.03) M×T: NS (NS)					
	STEM					
Institutional forest	5.06 (0.15)	9.16 (0.21)	13.83 (0.33)	12.03 (0.24)	16.26 (0.27)	11.27 (0.24)
Community forest	1.64 (0.13)	3.79 (0.19)	4.52 (0.30)	4.97 (0.22)	5.49 (0.25)	4.08 (0.22)
Mean	3.35 (0.14)	6.48 (0.20)	9.17 (0.32)	8.50 (0.23)	10.88 (0.26)	
CD	M: 0.67 (0.02) T: 1.06 (0.03) M×T: 1.51 (NS)					
	BRANCHES					
Institutional forest	0.95 (0.05)	1.57 (0.08)	2.85 (0.13)	0.78 (0.05)	4.36 (0.14)	2.10 (0.09)
Community forest	0.39 (0.04)	0.56 (0.06)	0.77 (0.10)	0.41 (0.05)	1.05 (0.09)	0.63 (0.07)
Mean	0.67 (0.05)	1.06 (0.07)	1.81 (0.11)	0.59 (0.05)	2.70 (0.012)	
CD	M: 0.31 (0.02) T: 0.49 (0.03) M×T: 0.69 (NS)					
	ROOTS					
Institutional forest	1.78 (0.07)	2.74 (0.09)	3.12 (0.10)	1.76 (0.05)	4.68 (0.11)	2.82 (0.08)
Community forest	0.41 (0.03)	0.70 (0.04)	0.92 (0.07)	0.82 (0.05)	1.73 (0.10)	0.92 (0.06)
Mean	1.10 (0.05)	1.72 (0.07)	2.02 (0.09)	1.29 (0.05)	3.21 (0.10)	
CD	M: 0.51 (0.02) T: 0.81 (0.03) M×T: NS (NS)					

Figure in parenthesis is percent value (%) of magnesium

Table 20: Comparative analysis of different plantation tree species for total nutrient uptake and return through leaf litter under different management regimes

Plant Nutrient Uptake	Institutional forest (M_1)							Community forest (M_2)						
	T_1	T_2	T_3	T_4	T_5	Mean	CD	T_1	T_2	T_3	T_4	T_5	Mean	CD
N	171.02	175.24	251.10	161.21	330.42	217.80	8.50	154.12	155.43	226.31	151.94	284.78	194.52	6.09
P	24.34	20.83	38.74	28.22	56.38	33.70	8.45	17.95	17.60	19.67	15.93	22.76	18.78	NS
K	90.07	126.02	143.11	91.51	132.53	116.65	11.53	69.27	105.43	123.10	78.61	115.55	98.39	18.54
Ca	203.31	234.57	255.67	247.87	313.26	250.94	6.14	198.45	222.54	236.86	226.16	285.44	233.89	9.48
Mg	29.95	45.56	72.36	46.12	69.49	52.70	9.42	22.29	37.60	59.65	42.88	58.77	44.24	11.50
	Leaf litter nutrient return (kg ha^{-1})													
N	39.91 (2.09)	32.22 (1.52)	80.45 (2.18)	35.73 (1.44)	96.62 (2.79)	56.99 (2.00)	3.59	35.30 (1.96)	33.70 (1.47)	56.64 (2.07)	26.06 (1.08)	71.35 (2.35)	44.61 (1.79)	2.92
P	3.19 (0.17)	3.88 (0.18)	7.37 (0.20)	7.28 (0.29)	15.26 (0.44)	7.40 (0.26)	1.62	2.40 (0.13)	3.44 (0.15)	5.47 (0.20)	3.78 (0.16)	7.69 (0.25)	4.56 (0.18)	1.27
K	31.75 (1.66)	42.17 (1.99)	81.68 (2.22)	25.89 (1.04)	34.79 (1.00)	43.26 (1.58)	5.09	22.94 (1.27)	40.58 (1.77)	57.55 (2.10)	25.33 (1.05)	30.97 (1.02)	35.48 (1.44)	4.23
Ca	22.70 (1.19)	28.77 (1.36)	80.08 (2.17)	52.11 (2.10)	76.74 (2.21)	52.08 (1.81)	2.14	24.02 (1.33)	42.11 (1.84)	53.72 (1.96)	45.20 (1.87)	59.71 (1.97)	44.95 (1.80)	1.96
Mg	0.52 (0.03)	1.06 (0.05)	0.81 (0.02)	0.85 (0.03)	1.39 (0.04)	0.93 (0.04)	NS	0.60 (0.03)	0.64 (0.03)	0.64 (0.02)	0.80 (0.03)	1.10 (0.04)	0.76 (0.03)	NS

Figure in parenthesis is percent value (%) of leaf litter nutrient content

Table 21: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of nitrogen under different management regimes

Nitrogen (kg ha^{-1})						
	LEAF					
Tree species / Management Regimes	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**Mean**
Institutional forest	64.83 (2.23)	63.55 (1.79)	101.28 (2.97)	60.98 (1.68)	114.48 (3.04)	81.02(2.34)
Community forest	55.52 (1.91)	57.51 (1.62)	83.54 (2.45)	57.47 (1.58)	97.49 (2.59)	70.31(2.03)
Mean	60.18 (2.07)	60.53 (1.71)	92.41 (2.71)	59.28 (1.63)	105.99 (2.81)	
CD	M: 1.55(0.05)		T: 2.45 (0.07)		M×T: 3.47(0.10)	
	STEM					
Institutional forest	54.66 (0.39)	41.11 (0.24)	54.11 (0.33)	28.01 (0.18)	76.86 (0.41)	50.95 (0.31)
Community forest	50.94 (0.36)	34.23 (0.21)	51.48 (0.32)	28.53 (0.17)	56.02 (0.30)	44.24 (0.27)
Mean	52.80 (0.37)	37.67 (0.22)	52.80 (0.33)	28.27 (0.18)	66.44 (0.36)	
CD	M:2.15 (0.02)		T: 3.39 (0.02)		M×T:4.80 (0.03)	
	BRANCHES					
Institutional forest	41.65 (0.70)	51.86 (0.74)	73.40 (0.80)	48.95 (0.71)	85.85 (0.90)	60.34 (0.77)
Community forest	38.68 (0.65)	49.29 (0.70)	70.09 (0.77)	44.62 (0.66)	80.84 (0.85)	56.70 (0.73)
Mean	40.17 (0.68)	50.58 (0.72)	71.74 (0.78)	46.79 (0.69)	83.35 (0.88)	
CD	M: 1.14 (0.02)		T: 1.81(0.02)		M×T: NS (NS)	
	ROOTS					
Institutional forest	9.89 (0.29)	18.72 (0.51)	22.32 (0.61)	23.27 (0.56)	53.22 (1.19)	25.48 (0.63)
Community forest	8.98 (0.28)	14.40 (0.48)	21.19 (0.58)	21.32 (0.52)	50.43 (1.16)	23.27 (0.60)
Mean	9.44 (0.28)	16.56 (0.49)	21.76 (0.59)	22.29 (0.54)	51.83 (1.18)	
CD	M:0.61 (0.02)		T:0.94 (0.03)		M×T: 1.36 (NS)	
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	171.02	175.24	251.10	161.21	330.42	217.80
Community forest	154.12	155.43	226.31	151.94	284.78	194.52
Mean	162.57	165.34	238.70	156.58	307.60	
CD	M: 3.02		T: 4.77		M×T: 6.75	
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	39.91 (2.09)	32.22(1.52)	80.45(2.18)	35.73(1.44)	96.62 (2.79)	56.99 (2.00)
Community forest	35.30 (1.96)	33.70(1.47)	56.64(2.07)	26.06(1.08)	71.35 (2.35)	44.61 (1.79)
Mean	37.61 (2.02)	32.96(1.50)	68.55(2.13)	30.90(1.26)	83.99 (2.57)	
CD	M: 1.29 (0.04)		T: 2.05 (0.07)		M×T: 2.89 (0.10)	
	RETAINED (kg ha^{-1})					
Institutional forest	131.11	143.02	170.65	125.48	233.80	160.81
Community forest	118.81	121.73	169.67	125.88	213.43	149.91
Mean	124.96	132.37	170.16	125.68	223.62	
CD	M: 3.55		T: 5.61		M×T: 7.94	

Figure in parenthesis is percent value (%) of nitrogen

Table 22: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of phosphorus under different management regimes

Phosphorus (kg ha^{-1})						
	LEAF					
Tree species / Management Regimes	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	7.75 (0.27)	10.89 (0.31)	14.32 (0.42)	14.04 (0.39)	18.35 (0.49)	13.07 (0.37)
Community forest	5.91 (0.20)	6.39 (0.18)	9.66 (0.28)	7.87 (0.22)	11.56 (0.31)	8.28 (0.24)
Mean	6.83 (0.24)	8.64 (0.24)	11.99 (0.35)	10.95 (0.30)	14.96 (0.40)	
CD	M: 0.79 (0.02)		T: 1.24 (0.04)		M×T: 1.75 (0.05)	
	STEM					
Institutional forest	12.05 (0.09)	4.74 (0.03)	15.23 (0.10)	6.46 (0.04)	20.85 (0.12)	11.87 (0.07)
Community forest	9.26 (0.07)	6.85 (0.04)	4.20 (0.03)	2.69 (0.02)	4.77 (0.03)	5.55 (0.04)
Mean	10.66 (0.08)	5.79 (0.04)	9.72 (0.06)	4.58 (0.03)	12.81 (0.07)	
CD	M: 2.45 (0.02)		T: 3.88 (0.03)		M×T: 5.48 (0.04)	
	BRANCHES					
Institutional forest	2.38 (0.04)	3.74 (0.05)	6.32 (0.07)	4.10 (0.06)	11.59 (0.12)	5.63 (0.07)
Community forest	1.19 (0.02)	3.27 (0.05)	3.31 (0.04)	2.73 (0.04)	4.07 (0.04)	2.92 (0.04)
Mean	1.79 (0.03)	3.50 (0.05)	4.81 (0.05)	3.42 (0.05)	7.83 (0.08)	
CD	M: 1.29 (0.02)		T: 2.04 (0.03)		M×T: 2.89 (NS)	
	ROOTS					
Institutional forest	2.16 (0.06)	1.46 (0.04)	2.87 (0.08)	3.63 (0.09)	5.59 (0.13)	3.14 (0.08)
Community forest	1.59 (0.05)	1.10 (0.04)	2.49 (0.07)	2.65 (0.06)	2.35 (0.05)	2.04 (0.05)
Mean	1.88 (0.06)	1.28 (0.04)	2.68 (0.07)	3.14 (0.08)	3.97 (0.09)	
CD	M: 0.57 (0.02)		T: 0.91 (0.02)		M×T : 1.28 (0.03)	
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	24.34	20.83	38.74	28.22	56.38	33.70
Community forest	17.95	17.60	19.67	15.93	22.76	18.78
Mean	21.15	19.22	29.20	22.08	39.57	
CD	M: 2.93		T: 4.63		M×T: 6.54	
	RETURN THROUGH LEAF LITTER (Kg ha^{-1})					
Institutional forest	3.19 (0.17)	3.88 (0.18)	7.37 (0.20)	7.28 (0.29)	15.26 (0.44)	7.40 (0.26)
Community forest	2.40 (0.13)	3.44 (0.15)	5.47 (0.20)	3.78 (0.16)	7.69 (0.25)	4.56 (0.18)
Mean	2.79 (0.15)	3.66 (0.17)	6.42 (0.20)	5.53 (0.23)	11.47 (0.35)	
CD	M: 0.58 (0.02)		T: 0.92 (0.03)		M×T: 1.30 (0.05)	
	RETAINED (kg ha^{-1})					
Institutional forest	21.15	16.95	31.37	20.94	41.12	26.31
Community forest	15.55	14.17	14.19	12.15	15.06	14.23
Mean	18.35	15.56	22.78	16.55	28.09	
CD	M: 2.81		T: 4.45		M×T: 6.29	

Figure in parenthesis is percent value (%) of phosphorus

Table 23: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of potassium under different management regimes

Potassium (kg ha^{-1})						
	LEAF					
Tree species Management Regimes	**T_1**	**T_2**	**T_3**	**T_4**	**T_5**	**Mean**
Institutional forest	63.18 (2.17)	85.68(2.41)	86.05 (2.52)	46.95 (1.29)	57.30 (1.52)	67.83 (1.99)
Community forest	42.64 (1.47)	75.85 (2.14)	77.18 (2.26)	44.89 (1.24)	50.39 (1.34)	58.19 (1.69)
Mean	52.91 (1.82)	80.77 (2.28)	81.61(2.39)	45.92 (1.27)	53.85 (1.43)	
CD	M: 4.53 (0.13)		T: 7.16 (0.21)		M×T: NS (0.30)	
	STEM					
Institutional forest	11.58 (0.08)	16.87 (0.11)	23.64 (0.15)	20.47 (0.13)	34.56 (0.19)	21.42 (0.13)
Community forest	14.35 (0.10)	10.53 (0.07)	17.86 (0.11)	15.07 (0.09)	29.20 (0.16)	17.41 (0.11)
Mean	12.97 (0.09)	13.70 (0.09)	20.75 (0.13)	17.77 (0.11)	31.88 (0.18)	
CD	M: 3.40 (0.02)		T: 5.38 (0.03)		M×T: NS (NS)	
	BRANCHES					
Institutional forest	10.32 (0.17)	14.49 (0.21)	21.96 (0.24)	12.52 (0.18)	25.38 (0.27)	16.93 (0.22)
Community forest	8.53 (0.14)	12.85 (0.18)	20.46 (0.23)	10.02 (0.15)	22.87 (0.24)	14.95 (0.19)
Mean	9.42 (0.16)	13.67 (0.20)	21.21 (0.24)	11.27 (0.17)	24.13 (0.26)	
CD	M: 1.92 (0.02)		T: 3.04 (0.04)		M×T: NS (NS)	
	ROOTS					
Institutional forest	5.00 (0.15)	9.00 (0.25)	11.47 (0.31)	11.56 (0.28)	15.29 (0.35)	10.47 (0.27)
Community forest	3.75 (0.11)	6.20 (0.21)	7.60 (0.20)	8.64 (0.21)	13.08 (0.30)	7.86 (0.21)
Mean	4.38 (0.13)	7.60 (0.23)	9.54 (0.26)	10.10 (0.24)	14.19 (0.32)	
CD	M: 0.80 (0.02)		T: 1.26 (0.03)		M×T: NS (NS)	
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	90.07	126.02	143.11	91.51	132.53	116.65
Community forest	69.27	105.43	123.10	78.61	115.55	98.39
Mean	79.67	115.73	133.11	85.06	124.04	
CD	M: 6.07		T: 9.60		M×T: NS	
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	31.75(1.66)	42.17 (1.99)	81.68 (2.22)	25.89 (1.04)	34.79 (1.00)	43.26 (1.58)
Community forest	22.94(1.27)	40.58 (1.77)	57.55 (2.10)	25.33 (1.05)	30.97 (1.02)	35.48 (1.44)
Mean	27.35(1.47)	41.38 (1.88)	69.62 (2.16)	25.61 (1.05)	32.88 (1.01)	
CD	M: 1.81 (0.07)		T: 2.86 (0.11)		M×T: 4.04 (0.15)	
	RETAINED (kg ha^{-1})					
Institutional forest	58.32	83.85	61.43	65.61	97.74	73.39
Community forest	46.33	64.85	65.55	53.29	84.59	62.92
Mean	52.33	74.35	63.49	59.45	91.17	
CD	M: 6.09		T: 9.62		M×T: NS	

Figure in parenthesis is percentage value (%) of potassium

Table 24: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of calcium under different management regimes

Calcium (kg ha^{-1})						
	LEAF					
Tree species / Management Regimes	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	41.18 (1.42)	66.98 (1.89)	77.75 (2.28)	77.68 (2.14)	88.60 (2.35)	70.44 (2.02)
Community forest	40.21 (1.38)	62.36 (1.76)	66.95 (1.96)	67.03 (1.85)	73.26 (1.94)	61.97 (1.78)
Mean	40.70 (1.40)	64.67 (1.82)	72.35 (2.12)	72.36 (1.99)	80.93 (2.15)	
CD	M: 1.88 (0.05)		T: 2.96 (0.08)		M×T :4.21 (0.12)	
	STEM					
Institutional forest	119.05(0.86)	108.57(0.69)	112.95(0.72)	115.27(0.71)	143.59(0.80)	119.89(0.76)
Community forest	120.41(0.87)	106.39(0.67)	109.27(0.69)	108.71(0.67)	139.47(0.78)	116.85(0.74)
Mean	119.73(0.86)	107.48(0.68)	111.11(0.71)	111.99(0.69)	141.53(0.79)	
CD	M:2.51 (0.02)		T: 3.97 (0.03)		M×T :NS (NS)	
	BRANCHES					
Institutional forest	38.88 (0.65)	55.13 (0.79)	59.86(0.66)	50.32 (0.74)	72.69 (0.77)	55.38 (0.72)
Community forest	35.90 (0.60)	52.09 (0.74)	57.15(0.63)	47.36 (0.69)	68.31 (0.73)	52.16 (0.68)
Mean	37.39 (0.63)	53.61 (0.76)	58.51 (0.65)	48.84 (0.72)	70.50 (0.75)	
CD	M: 1.30 (0.02)		T: 2.06 (0.03)		M×T : NS (NS)	
	ROOTS					
Institutional forest	4.21(0.12)	3.89 (0.11)	5.11 (0.14)	4.60 (0.11)	8.38 (0.19)	5.24 (0.13)
Community forest	1.93(0.06)	1.70 (0.06)	3.49 (0.09)	3.07 (0.07)	4.41 (0.10)	2.92 (0.08)
Mean	3.07(0.09)	2.80 (0.08)	4.30 (0.12)	3.83 (0.09)	6.40 (0.15)	
CD	M: 0.59 (0.02)		T: 0.94 (0.02)		M×T : NS (NS)	
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	203.31	234.57	255.67	247.87	313.26	250.94
Community forest	198.45	222.54	236.86	226.16	285.44	233.89
Mean	200.88	228.56	246.27	237.02	299.35	
CD	M: 3.23		T: 5.10		M×T: 7.22	
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	22.70 (1.19)	28.77 (1.36)	80.08(2.17)	52.11 (2.10)	76.74 (2.21)	52.08 (1.81)
Community forest	24.02 (1.33)	42.11 (1.84)	53.72(1.96)	45.20 (1.87)	59.71 (1.97)	44.95 (1.80)
Mean	23.36 (1.26)	35.44 (1.60)	66.90(2.07)	48.66 (1.99)	68.23 (2.09)	
CD	M: 0.82 (NS)		T: 1.30 (0.05)		M×T: 1.83 (0.06)	
	RETAINED (kg ha^{-1})					
Institutional forest	180.62	205.80	175.58	195.76	236.51	198.86
Community forest	174.43	180.43	183.15	180.97	225.73	188.94
Mean	177.53	193.12	179.37	188.36	231.12	
CD	M: 3.41		T: 5.38		M×T: 7.61	

Figure in parenthesis is percentage value (%) of calcium

Table 25: Comparative analysis of different plantation tree species for nutrient cycling (through nutrient uptake, return and retention) of Magnesium under different management regimes

Magnesium (kg ha^{-1})						
	LEAF					
Tree species / Management Regime	T_1	T_2	T_3	T_4	T_5	Mean
Institutional forest	3.39 (0.12)	3.83 (0.11)	4.66 (0.14)	1.70 (0.05)	3.65 (0.10)	3.45 (0.10)
Community forest	1.17 (0.04)	2.61 (0.07)	1.25 (0.04)	1.09 (0.03)	1.64 (0.04)	1.55 (0.05)
Mean	2.28 (0.08)	3.22 (0.09)	2.95 (0.09)	1.39 (0.04)	2.64 (0.07)	
CD	M: 0.68 (0.02)		T: 1.08 (0.03)		M×T : NS (NS)	
	STEM					
Institutional forest	21.31 (0.15)	33.21 (0.21)	52.54 (0.33)	38.78 (0.24)	47.66 (0.27)	38.70 (0.24)
Community forest	17.60 (0.13)	29.49 (0.19)	46.75 (0.30)	36.06 (0.22)	44.10 (0.25)	34.80 (0.22)
Mean	19.45 (0.14)	31.35 (0.20)	49.65 (0.32)	37.42 (0.23)	45.88 (0.26)	
CD	M: 2.99 (0.02)		T: 4.73 (0.03)		M×T : NS (NS)	
	BRANCHES					
Institutional forest	2.98 (0.05)	5.37 (0.08)	11.43 (0.13)	3.42 (0.05)	13.47 (0.14)	7.34 (0.09)
Community forest	2.38 (0.04)	4.20 (0.06)	9.02 (0.10)	3.64 (0.05)	8.77 (0.09)	5.61 (0.07)
Mean	2.68 (0.05)	4.79 (0.07)	10.23 (0.11)	3.53 (0.05)	11.12 (0.12)	
CD	M: 1.36 (0.02)		T: 2.13 (0.03)		M×T : NS (NS)	
	ROOTS					
Institutional forest	2.27 (0.07)	3.16(0.09)	3.74 (0.10)	2.23 (0.05)	4.71 (0.11)	3.22 (0.08)
Community forest	1.14 (0.03)	1.30(0.04)	2.62 (0.07)	2.09 (0.05)	4.26 (0.10)	2.28 (0.06)
Mean	1.71 (0.05)	2.23(0.07)	3.18 (0.09)	2.16 (0.05)	4.49 (0.10)	
CD	M: 0.67 (0.02)		T: 1.06 (0.03)		M×T : NS (NS)	
	TOTAL UPTAKE (kg ha^{-1})					
Institutional forest	29.95	45.56	72.36	46.12	69.49	52.70
Community forest	22.29	37.60	59.65	42.88	58.77	44.24
Mean	26.12	41.58	66.01	44.50	64.13	
CD	M: 4.43		T: 6.99		M×T : NS	
	RETURN THROUGH LEAF LITTER (kg ha^{-1})					
Institutional forest	0.52 (0.03)	1.06 (0.05)	0.81 (0.02)	0.85 (0.03)	1.39 (0.04)	0.93 (0.04)
Community forest	0.60 (0.03)	0.64 (0.03)	0.64 (0.02)	0.80 (0.03)	1.10 (0.04)	0.76 (0.03)
Mean	0.56 (0.03)	0.85 (0.04)	0.72 (0.02)	0.83 (0.03)	1.25 (0.04)	
CD	M: NS (NS)		T: 0.40 (NS)		M×T: NS (NS)	
	RETAINED (kg ha^{-1})					
Institutional forest	29.43	44.50	71.55	45.27	68.10	51.77
Community forest	21.69	36.96	59.01	42.08	57.67	43.48
Mean	25.56	40.73	65.28	43.67	62.89	
CD	M: 4.28		T: 6.77		M×T: NS	

Figure in parenthesis is percent value (%) of magnesium

APPENDIX – III

ANALYSIS OF VARIANCE FOR LEAF LITTER DYNAMICS

ANOVA 1: Leaf litter content in winter

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.006		
Management Regimes	1	0.021	0.021	48.05
Tree species	4	0.299	0.075	168.403
Interaction A X B	4	0.003	0.001	1.651
Error	18	0.008	0	

ANOVA 2: Leaf litter content in summer

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.006		
Management Regimes	1	0.05	0.05	110.777
Tree species	4	0.406	0.101	226.6
Interaction A X B	4	0.002	0	0.924
Error	18	0.008	0	

ANOVA 3: Leaf litter content in rainy

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.002		
Management Regimes	1	0.021	0.021	31.499
Tree species	4	0.237	0.059	89.616
Interaction A X B	4	0.001	0	0.283
Error	18	0.012	0.001	

ANOVA 4: Total leaf litter content

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	2	0.034		
Management Regimes	1	0.263	0.263	228.585
Tree species	4	2.716	0.679	589.709
Interaction A X B	4	0.003	0.001	0.642
Error	18	0.021	0.001	

APPENDIX – IV

ANALYSIS OF VARIANCE FOR NUTRIENT ESTIMATION IN DIFFERENT PLANT COMPONENTS

ANOVA 1: N, P, K, Ca and Mg content in Leaf

Leaf Nutrient Content						
Source of Variation	DF	Mean Sum of Sqaure				
		Total N (Mg /ha)	Total P (Mg /ha)	Total K (Mg /ha)	Total Ca (Mg /ha)	Total Mg (Mg /ha)
Replication	2					
Management Regimes	1	640.424	27.59	494.425	438.232	3.188
Tree species	4	127.552	2.359	68.713	51.606	0.164
Interaction A X B	4	19.867	0.309	24.294	4.555	0.183
Error	18	6.756	0.167	8.299	5.201	0.075

ANOVA 2: N, P, K, Ca and Mg content in Stem

Stem Nutrient Content						
Source of Variation	DF	Mean Sum of Sqaure				
		Total N (Mg /ha)	Total P (Mg /ha)	Total K (Mg /ha)	Total Ca (Mg /ha)	Total Mg (Mg /ha)
Replication	2					
Management Regimes	1	666.56	59.671	140.054	3,273.78	387.146
Tree species	4	85.908	7.466	27.895	189.59	49.949
Interaction A X B	4	41.225	8.388	9.089	58.156	13.075
Error	18	1.066	0.575	0.945	1.039	0.758

ANOVA 3: N, P, K, Ca and Mg content in Branch

Branch Nutrient Content						
Source of Variation	DF	Mean Sum of Sqaure				
		Total N (Mg /ha)	Total P (Mg /ha)	Total K (Mg /ha)	Total Ca (Mg /ha)	Total Mg (Mg /ha)
Replication	2					
Management Regimes	1	783.671	12.779	70.441	659.415	16.163
Tree species	4	94.815	2.606	11.247	53.028	4.739
Interaction A X B	4	36.167	1.981	3.833	21.958	2.257
Error	18	1.64	0.225	0.379	1.262	0.159

ANOVA 4: N, P, K, Ca and Mg content in Root

Root Nutrient Content						
Source of Variation	DF	Mean Sum of Sqaure				
		Total N (Mg /ha)	Total P (Mg /ha)	Total K (Mg /ha)	Total Ca (Mg /ha)	Total Mg (Mg /ha)
Replication	2					
Management Regimes	1	1,281.97	28.324	259.367	86.428	26.999
Tree species	4	850.931	5.055	44.655	9.511	4.144
Interaction A X B	4	170.194	3.593	11.382	4.719	0.904
Error	18	0.724	0.306	0.58	0.301	0.438

APPENDIX – V

ANALYSIS OF VARIANCE FOR NUTRIENT DYNAMICS

ANOVA 1: Plant Nutrient Uptake

Plant Nutrient Uptake						
Source of Variation	**DF**	**Mean Sum of Square**				
		Total N (kg /ha)	**Total P (kg /ha)**	**Total K (kg /ha)**	**Total Ca (kg /ha)**	**Total Mg (kg /ha)**
Replication	2					
Management Regimes	1	4,066.72	1,669.10	2,499.54	2,178.62	536.672
Tree species	4	26,061.34	418.602	3,412.56	7,804.32	1,673.14
Interaction A X B	4	281.65	218.883	16.994	117.803	19.244
Error	18	15.247	14.332	61.61	17.429	32.771

ANOVA 2: Return through leaf-litter

Return through leaf-litter						
Source of Variation	**DF**	**Mean Sum of Square**				
		Total N (kg /ha)	**Total P (kg /ha)**	**Total K (kg /ha)**	**Total Ca (kg /ha)**	**Total Mg (kg /ha)**
Replication	2					
Management Regimes	1	1,149.61	30.744	540.086	13.174	0.86
Tree species	4	3,456.44	17.376	1,086.11	316.142	1.381
Interaction A X B	4	208.841	7.331	840.253	287.565	0.652
Error	18	2.121	0.027	2.276	1.081	0

ANOVA 3: Retention of nutrients

Retention of Nutrients						
Source of Variation	**DF**	**Mean Sum of Square**				
		Total N (kg /ha)	**Total P (kg /ha)**	**Total K (kg /ha)**	**Total Ca (kg /ha)**	**Total Mg (kg /ha)**
Replication	2					
Management Regimes	1	891.988	1,094.44	822.367	737.146	515.608
Tree species	4	10,817.15	160.851	1,373.78	2,844.44	1,641.94
Interaction A X B	4	159.604	135.304	111.998	218.544	18.56
Error	18	21.074	13.241	61.976	19.397	30.634

APPENDIX – VI

ANALYSIS OF VARIANCE FOR SOIL PHYSICO-CHEMICAL PROPERTIES

ANOVA 1: EC, pH and BD

Source of Variation	DF	Mean Sum of Square		
		EC	pH	BD
Replication	2	0.000262	0.01608	0.000563
Treatment	19	0.015551	0.762442	0.001698
A	4	0.068043	3.562279	0.00314
B	1	0.01329	0.000667	0.005629
A*B	4	0.000249	0.032113	0.000104
C	1	0.006884	0.002407	0.01294
A*C	4	0.000374	0.022936	0.000104
B*C	1	0.000105	0.001927	2.2E-08
A*B*C	4	0.00013	0.003022	7.65E-05
ERROR	38	0.000167	0.010564	0.000674

ANOVA 2: Organic carbon and SOC stock

Source of Variation	DF	Mean Sum of Square	
		Organic carbon	SOC stock
Replication	2	14.30	82.34
Treatment	19	7.97	40.23
A	4	11.44	47.50
B	1	75.04	456.02
A*B	4	0.77	5.04
C	1	21.96	68.51
A*C	4	1.00	5.46
B*C	1	0.43	2.00
A*B*C	4	0.30	1.45
ERROR	38	0.48	2.04

ANOVA 3: Available N, P and K

Source of Variation	DF	Mean Sum of Square		
		Available N	Available P	Available K
Replication	2	26.82359	3.76952	40.69337
Treatment	19	4961.449	1913.822	3895.735
A	4	18687.27	2833.235	12843.74
B	1	10619.89	95.65963	15823.7
A*B	4	1956.831	11.39212	531.6087
C	1	974.3695	18061.35	2706.977
A*C	4	8.497765	1703.13	437.8653
B*C	1	0.472033	2.67E-05	8.482179
A*B*C	4	15.60187	3.645881	56.73976
ERROR	38	12.64483	5.878413	31.24245

ANOVA 4: Exchangeable Ca and Mg

Source of Variation	DF	Mean Sum of Square	
		Exchangeable Ca	Exchangeable Mg
Replication	2	1.174832	0.01
Treatment	19	103.0004	0.41
A	4	470.3088	1.32
B	1	4.536125	1.44
A*B	4	9.237314	0.13
C	1	27.95179	0.42
A*C	4	0.766807	0.04
B*C	1	0.299627	0.02
A*B*C	4	0.742068	0.01
ERROR	38	0.459358	0.01
TOTAL	59		

APPENDIX – VII

ANALYSIS OF VARIANCE FOR SOIL MICROBIAL COUNT

ANOVA 1: Actinomycetes, Bacterial and Fungi count

Source of Variation	DF	Mean Sum of Square		
		Actinomycetes Count	Bacterial Count	Fungi Count
Replication	2	0.11	55.94874	0.03
Treatment	19	3.60	7358.373	0.28
A	4	3.96	457.258	0.56
B	1	30.63	62098.19	2.03
A*B	4	0.94	26.8313	0.11
C	1	13.95	45621.91	0.36
A*C	4	0.36	32.25463	0.03
B*C	1	2.73	29994.38	0.02
A*B*C	4	0.03	7.30666	0.02
ERROR	38	0.03	41.98279	0.01

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Title of the Thesis	:	**"Evaluation of plantation tree species for biomass production and nutrient cycling in warm temperate North Western Himalayas"**
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Admission Number	:	F-2019-20-D
Major Advisor	:	Dr. Manoj Kumar Thakur
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ABSTRACT

The present investigation entitled **"Evaluation of plantation tree species for biomass production and nutrient cycling in warm temperate North Western Himalayas"** was conducted during 2021-2023 at the Regional Horticultural Research and Training Station, Bajaura. The study aimed to compare plantations named as *Robinia pseudoacacia, Populus deltoides, Salix tetrasperma, Eucalyptus tereticornis* and *Alnus nitida* managed under two different regimes i.e. institutional forest and community forest for biomass productivity, nutrient cycling and soil microbial status. Biomass allocated by different plantation type of both the management regimes was estimated using non-destructive method of sampling. The results of the experiments in plantation forest ecosystem have revealed that maximum biomass (142.97 Mg ha^{-1}) was recorded in *Alnus nitida* plantation managed under institutional forest. Vegetation carbon density in plantation ecosystems of both the management regimes was again reported maximum for institutional forest and followed the order: *Alnus nitida* (67.91 Mg ha^{-1}) > *Eucalyptus tereticornis* (49.50 Mg ha^{-1}) > *Populus deltoides* (48.22 Mg ha^{-1}) > *Salix tetrasperma* (47.57 Mg ha^{-1}) > *Robinia pseudoacacia* (38.84 Mg ha^{-1}). Similar trends were also seen in respect of biomass carbon stock of different vegetation types managed under two different regimes. Soil carbon (humus + soil 0-40 cm layer) density in plantation ecosystem was recorded maximum (51.67 Mg ha^{-1}) under *Alnus nitida* plantation. Total soil carbon density under plantation ecosystem did not varied significantly for both management regimes. In plantation ecosystem maximum total detritus carbon density was recorded (2.19 Mg ha^{-1}) in *Alnus nitida* plantation for institutional forest. Maximum ecosystem carbon density (125.94 Mg ha^{-1}) was displayed by *Alnus nitida* for institutional forest, which is followed by *Salix tetrasperma, Populus deltoides, Eucalyptus tereticornis* and *Robinia pseudoacacia* respectively in descending order. Among plantation ecosystems, *Alnus nitida* under institutional forest showed better nutrient cycling. In temperate harsh edapho-climatic conditions with riverain site better nutrient status was recorded in soil under *Alnus nitida* plantation for institutional forest. Except available phosphorus, all the soil physico-chemical and microbiological parameters decreased with increase in soil depth. Based on the findings of the study, it can be concluded that in all *Alnus nitida* under institutional forest displayed maximum biomass production, carbon sequestration potential and better nutrient cycling followed by *Salix tetrasperma, Populus deltoides, Eucalyptus tereticornis* and *R. pseudoacacia* respectively in descending order. Tree felling for timber, firewood collection, lopping, and grazing in the community forest resulted in poor biomass production and finally the poor nutrient stock.

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