NET ECOSYSTEM PRODUCTION AND CARBON FLUX IN TROPICAL MOIST DECIDUOUS FORESTS OF ODISHA

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NET ECOSYSTEM PRODUCTION AND CARBON FLUX IN TROPICAL MOIST DECIDUOUS FORESTS OF ODISHA

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CERTIFICATE

This is to certify that the thesis entitled "Net Ecosystem Production and Carbon Flux in Tropical Moist Deciduous Forest of Odisha" submitted by Mr. Madhab Chandra Behera to the Department of Forestry, Mizoram University, Aizwal for the award of the degree of Doctor of Philosophy in Forestry embodies the record of original investigation carried out by him under my supervision. I further certify that Mr. Madhab Chandra Behera has fulfilled all the criteria prescribed by UGC and the conditions laid down in the Ph.D. regulations of the Mizoram University. The thesis as whole nor any part of it has not been submitted earlier to any university or institute for the award of any degree and the thesis present is worthy of being considered for the award of the Ph. D. Degree.

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DECLARATION

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April 2025

I Madhab Chandra Behera, hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of thesis did not form basis of the award of any previous degree to me, or to do the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/Institute.

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Place: **Madhab Chandra Behera**

Date:

CONTENTS

		Page No.
Title page and Inner page of thesis		I
Supervisor's certificate		III
Candidate's declaration		IV
Acknowledgements		V
Table of contents		VII
List of tables		VIII
List of figures		XI
List of plates		XIII
List of abbreviations used		XIV
Chapter-1	General Introduction	01-06
Chapter-2	Review of Literatures	07-27
Chapter-3	Materials and Methods	28-36
Chapter-4	Soil and Anthropogenic disturbances	37-50
Chapter-5	Phytosociological inventory and vegetation analysis	51-77
Chapter-6	Inventories on biomass and carbon stock and carbon sequestration potential of forest types	78-109
Chapter-7	Litterfall and its dynamism	110-136
Chapter-8	Soil respiration dynamism in three forest types	137-150
Chapter-9	Net primary production, net ecosystem production and carbon flux in three forest types	151-168
Chapter-10	General discussion	169-176
Chapter-11	Summary and Conclusion	177-184
Appendices		185-201
References		202-231

LIST OF TABLES

Table	Title	Page
3.1	Location and geocoordinates of the study sites	30
4.1	Soil physical properties in PSF, SDMDF and MDFWS	42
4.2	Soil chemical properties in PSF, SDMDF and MDFWS	43
4.3	Pearson correlation coefficient between soil physiochemical properties	46
4.4	Sources of anthropogenic disturbances in the studied forest sites	47
5.1	Distribution of plant species in sampled sites	59
5.2	Variations in density, basal area and floristic diversity indices	62
5.3	Density based rarity classification of tree species in three forest types	67
5.4	Distribution pattern of plants in PSF, SDMDF and MDFWS	68
5.5	Regeneration status of trees in three forest types	69
5.6	Density of tree, sapling and seedlings in PSF, SDMDF and MDFWS	70
5.7	Density of saplings and seedlings of major tree species	77
6.1	Non-destructive approaches used for estimation of biomass estimation	85
6.2	Volume equation and wood density of tree species	85
6.3	Allometric equations for biomass estimation of branch and foliage of trees	88
6.4	Biomass stock variations in PSF, SDMDF and MDFWS	91
6.5	Biomass stocks in various vegetation components	93

Table	Title	Page
6.6	Biomass stocks across various ecosystem components of three forest types	94
6.7	Carbon stock (Mg C ha^{-1}) variations in three forest types	95
6.8	Carbon stocks (Mg C ha^{-1}) in various vegetation components of three forest types	97
6.9	Carbon stocks in various ecosystem components of three forest types	98
6.10	Contribution of major tree species to the above-ground biomass and carbon stock of three forest types	101
6.11	Net annual biomass increment of different vegetation components in PSF, SDMDF and MDFWS	102
6.12	Annual carbon sequestration of different vegetation components in PSF, SDMDF and MDFWS	104
6.13	Carbon sequestration potential of different ecosystem components in three forest types	106
7.1	Seasonal variation in litter fall in three forest types	119
7.2	Pearson's correlation coefficient between vegetation attributes and total annual litter fall in three forest types	120
7.3	Initial concentrations of nutrients and secondary compounds in leaf, small branch and root litter of three forest types	121
7.4	Decomposition parameters and time required for various level of decay of different categories of litter in three forest types	124
7.5	Relationship of mass loss with locality factors and litter quality	125
7.6	Nutrient return to the soil after 270 day of in-situ litter incubation in three forest types	127
7.7	Decay parameters: residual stock remaining, annual decay kinetics and time required for 50% release for carbon, Nitrogen, Phosphorus, Potassium from different types of litter in three forest types	130
8.1	Monthly variations in soil temperature, moisture and respiration in three forest types	144

Table	Title	Page
8.2	Variations in soil temperature, moisture, respiration rate, root respiration and microbial respiration across three forest types	146
8.3	Relationship between soil respiration with soil temperature and soil moisture	148
9.1	Net primary production during the period 2021-22 in different vegetation components	157
9.2	Variations in total litter production, decay rate, quantity decayed and amount remain un-decomposed in three forest types	159
9.3	Total biomass stock, total C stock, net primary production (NPP), heterotrophic respiration (Rh) and net ecosystem production (NEP) in three forest types	162
10.1	Comparison of above ground biomass of trees in different sal forests Odisha	

LIST OF FIGURES

Figure	Title	Page
3.1	Location map of sampling sites	31
3.2	Ombrothermic diagram of the study site	32
4.1	Variations in soil physic-chemical properties of three forest types	44
5.1	Layout of sampling plots and their respective size for tree, shrub and herbs	55
5.2	Diversity of tree, shrub, herb and liana species	60
5.3	Rank-abundance curves for tree species	64
5.4	Bray Curtis cluster dendrogram for trees	64
5.5	Relative density and basal area distribution among various diameter classes	66
5.6	Percentage rarity distributions of tree species	67
5.7	Percentage of population distribution pattern plants	68
5.8	Regeneration statuses of trees in three forest types	70
6.1	Layout of sampling plots and their respective size	81
6.2	Carbon stock variations in three forest types	96
6.3	Share of different components to total C stock	99
6.4	Annual carbon sequestrations potential in different vegetation components	105
6.5	Percentage shares of different ecosystem components to total ecosystem C sequestration.	107
7.1	Litter collection and in-situ incubation in surface soil	116

Figure	Title	Page
7.2	Seasonal variations in litter fall in three forest types	118
7.3	Constituents of litter pool in three forest types	118
7.4	Mass remaining at different days of litter incubation in soil	123
7.5	Temporal changes in carbon (A), nitrogen (B), phosphorus (C) and potassium (D) stock in different litter types during decay study	129
7.6	Change in carbon: nitrogen ratio (A) and Lignin to nitrogen ratio (B) in different litter types of three forest types	134
8.1	In situ total soil respiration (SR_T) absorption by soda lime in closed chamber	141
8.2	Seasonal variations in soil temperature	143
8.3	Pearson's correlation coefficient between soil respiration rate, soil moisture and temperature	147
9.1	Monthly variations in total litter production, decay and net change	160
9.2	Net primary production (NPP), heterotrophic respiration (Rh) and net ecosystem production (NEP) in three forest types.	162
9.3	Share of various vegetation components to net ecosystem production (NEP) in three forest types.	163
9.4	Annual carbon budget and pathways of carbon production in pure sal forest (PSF).	164
9.5	Annual carbon budget and pathways of carbon production in sal dominated moist deciduous forest (SDMDF).	165
9.6	Annual carbon budget and pathways of carbon production in moist deciduous forest without sal (MDFWS).	166

LIST OF PLATES

Plate	Title	Page
Plate-1	Forests types	35
Plate-2	Phytosociological survey	36

LIST OF ABBREVIATIONS

Abbreviations	Descriptions	Abbreviations	Descriptions
%	Percent	YR	Yellow-red
<	Less than	N_{Av}	Available nitrogen
=	Equal to	P_{Av}	Available phosphorus
>	More than	K_{Av}	Available potash
^0C	Degree centigrade	SOC	Soil Organic Carbon
C	Carbon	SMC	Soil moisture content
CO_2	Carbon dioxide	A	Abundance
ha^{-1}	Per hectare	A/F ratio	Abundance/Frequency
cm	Centimetre	TBA	Total Basal Area
m	Meter	C.B.H	Circumference at Breast Height
km	Kilo meter	Cd	Concentration of dominance
m^2	Meter square	D	Density
$m^2 h^{-1}$	Meter square per	RD	Relative Density
g	Grams	*et al.*	And others / co-workers
g cm^{-3}	Gram per cubic	Fig.	Figure
kg ha^{-1}	Kilogram per hectare	H'	Shannon index
Mg ha^{-1}	Megagrams per hectare	IVI	Importance Value Index
Mg C ha^{-1}	Megagrams carbon per hectare	Mg C ha^{-1} yr^{-1}	Megagrams carbon per hectare per year
N	Nitrogen	K	Potassium
amsl	Above mean sea level	P	Phosphorous
SE	Standard error	CCS	Carbon capture and storage
RH	Relative humidity	viz.	Namely
LSD	Least significant difference	NPP	Net Primary Production
dbh	Diameter at breast height	NEP	Net Ecosystem Production
GHG	Greenhouse gases	CF	Carbon flux

CHAPTER-1

GENERAL INTRODUCTION

Forests play a vital role in regulating the global carbon (C) budget by acting as both carbon sinks and sources. They store vast quantities of carbon in biomass, soil and dead organic matter, influencing atmospheric CO_2 levels and climate change. The global forest ecosystem is estimated to contain ~ 861 Pg C of carbon, of which 44% stored in biomass, 45% in soil layer (1 m deep) and the rest in dead-wood and litter (Pan *et al.,* 2011). Through photosynthesis, forests absorb atmospheric CO_2 and convert it into organic carbon, thus mitigating the effects of anthropogenic emissions. On the other hand, deforestation, forest degradation and wildfires release significant amounts of stored carbon back into the atmosphere contributing to global warming (Harris *et al.,* 2021).

The exchange of carbon between the atmosphere, vegetation and soil known as carbon flux, is fundamental to understanding ecosystem carbon storage and emissions (Schlesinger and Bernhardt, 2013). The net carbon flux between the atmosphere and a forest landscape determines whether a forest functions as a net carbon source or sink. Forests act as a dynamic system for regulating atmospheric CO_2, making it essential to evaluate their functionality not only in terms of net primary production (NPP) but also through net ecosystem production (NEP). NPP is the carbon balance of an ecosystem, calculated as gross primary production (GPP) minus total respiration. An ecosystem having positive NEP indicates carbon sequestration, while negative NEP signifies a carbon source (Lovett *et al.,* 2006).

Among various forest ecosystem types of the world, tropical forests contribute significantly to global carbon sequestration, storing approximately 55% of the global forest carbon stock (Bonan, 2008). However, unlike boreal and temperate forests, which store the majority of their carbon in the soil, tropical forests store about 56% of their carbon stock in biomass (Pan *et al.,* 2011). They sequester ~0.5 Mg C ha^{-1} yr^{-1}, playing a vital role in offsetting human-induced emissions (Murphy, 2024). Despite this, deforestation, fire and land-use changes continue to diminish their

capacity, with tropical forest loss contributing substantially to global carbon emissions (Baccini *et al.,* 2017).

Forests store carbon in two main pools: vegetation and soil, linked by the flow of carbon and organic matter. Vegetation includes trees and understory plants, while soil contains easily decomposed organic matter and stable humus. Organic matter accumulates within these components through various interconnected pathways, including phytomass production, annual litter deposition, breaking down of dead organic materials, leaching of water-soluble decaying products, decomposition and conversion of plant residues into humus, followed by its subsequent mineralization (Schlesinger and Bernhardt, 2013). Different pools of forest ecosystem where photosynthetic assimilated carbon get stored include above ground biomass (AGB), below ground biomass (BGB), dead wood (DW), litter (L) and soil organic carbon (SOC) pools.

However, the residence time of carbon within each pool is regulated by multiple interacting factors, including climatic conditions, soil properties, microbial activity, vegetation type, decomposition rates and disturbance events (Bonan, 2008). Temperature and precipitation influence microbial activity and organic matter decomposition, with warm-moist conditions generally accelerating carbon turnover rate (Davidson and Janssens, 2006). Soil properties such as texture and mineral composition affect carbon stabilization, with clay-rich soils enhancing carbon retention by retarding microbial decaying of organic matter (Schmidt *et al.,* 2011). Vegetation type also plays a crucial role, as different plant species contribute varying amounts and qualities of litter, impacting decomposition rates and carbon storage (Cornwell *et al.,* 2008). Additionally, disturbance events such as wildfires, deforestation and land-use changes significantly alter carbon stocks by releasing stored carbon into the atmosphere (Liu *et al.,* 2015). NPP (C input) and heterotrophic respiration (C output) are key to the terrestrial carbon cycle. Their ratio indicates carbon balance, productivity, sequestration potential and ecosystem response to climate change (Vedrova *et al.,* 2006; Luyssaert *et al.,* 2008).

Within tropical forest ecosystems, tropical moist deciduous forests play an important role in carbon storage and ecosystem stability. These forests are primarily found in regions with annual rainfall ranging from 1000 to 2000 mm, where distinct wet and dry seasons shape their structural and functional dynamics. They exhibit a unique blend of deciduous and evergreen tree species, with dominance of species like *Shorea robusta*, *Tectona grandis*, *Madhuca longifolia, Dalbergia latifolia, Lagerstroemia parviflora, Diospyrous melonxylon, Terminalia tomentosa* and *Terminalia chebula etc.* which collectively influence forest productivity and carbon storage capacity (Champion and Seth, 1968). The seasonal variability in these forests drives key ecological processes. During the wet season, rapid vegetation growth enhances carbon assimilation through photosynthesis, leading to significant carbon uptake and biomass accumulation. Conversely, in the dry season, many tree species shed their leaves as a drought adaptation strategy to reduce water loss through transpiration, which in turn affects nutrient cycling, litter decomposition and soil organic carbon dynamics. This cyclical pattern of growth and dormancy is integral to carbon fluxes within the ecosystem and contributes to its resilience against climate variability. Beyond carbon sequestration, tropical moist deciduous forests provide wide range of ecosystem services, including biodiversity conservation, soil stabilization, hydrological regulation and climate moderation (Malhi *et al.*, 1999). However, due to increasing pressures from deforestation, logging and agricultural expansion tropical moist deciduous forests are highly vulnerable to degradation emphasizing the need for conservation strategies to preserve their ecological and climate-regulating functions (Murphy & Lugo, 1986).

Several carbon budgeting models of variable complexity have been developed and used to estimate forest carbon dynamics. The methodologies applied in the models are either top down or bottom up in nature. Top-down methods, such as remote sensing, eddy covariance and inverse modeling infer carbon fluxes from atmospheric CO_2 concentrations (Upton *et al.,* 2024). In contrast, bottom-up approaches directly measure carbon stocks and fluxes at the ecosystem level, providing more detailed, site-specific estimates. Bottom-up methods include forest inventories, biometric measurements, and process-based modelling, which integrate

data on forest cover, biomass turnover and soil carbon storage (Kohl *et al.,* 2015). Forest inventories use ground-based measurements, such as tree diameter and wood density, to estimate biomass and carbon storage, while biometric models apply regression equations to quantify carbon fluxes (Peltoniemi *et al.,* 2004). Process-based models, such as dynamic vegetation models, simulate carbon dynamics by incorporating physiological processes like photosynthesis and respiration (Friend *et al.,* 2014). The accuracy of these methods depends on data quality, biomass conversion factors and modelling assumptions, influencing the reliability of carbon budget estimates. Bottom-up approaches are essential for national and global carbon accounting, supporting climate policies, $REDD^{++}$ initiatives and carbon offset programs (Grassi *et al.,* 2017). By complementing top-down methods, they enhance our understanding of forest carbon sequestration and improve climate change mitigation strategies.

Although tropical forests function as significant carbon sinks, deforestation and land-use changes have transformed many areas into net carbon sources, contributing 10 to 15% of global anthropogenic CO_2 emissions (Baccini *et al.,* 2017). Monitoring carbon fluxes is crucial for tracking emissions from forest loss, degradation and disturbances, enhancing the accuracy of their impact on atmospheric CO_2 levels (Gatti *et al.,* 2021). However, rising temperature and changing rainfall patterns jeopardize forest productivity and carbon storage, potentially altering long-term sequestration capacity (Hubau *et al.,* 2020). Hence, precise C assessments are essential for maintaining global C budgets and achieving Paris Agreement targets (Friedlingstein *et al.,* 2022).

During past two decades, India has been substantially contributing to the global greening mission, but it remains unclear whether this greening has led to increased primary productivity and carbon sequestration, especially during this changing climate arena. Growth and productivity of these forests are always fluctuating because of increasing temperature and draught, soil erosion, frequent fire and increased human pressure (Das *et al.,* 2023). Hence long-term monitoring of carbon fluxes of Indian forests is essential to know whether they are a net contributor to the global emission or sink. This will robust the understanding of regional carbon budget

as well as its link to the global C cycle. Various studies estimate the net carbon flux of Indian forests to range from a source of 0.4 Tg C yr^{-1} to a sink of 5.0 Tg C yr^{-1} (Nayak *et al.,* 2015).

NPP estimation based on Advanced Very High-Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) data provide different findings on the forest productivity. Bala *et al.,* (2013) using AVHRR data set (1982–2006), estimated NPP increase of 3.9% per decade during the period 1982 to 2006. Other workers also estimated the NPP of Indian forests using alternate methods (model-based approach using different parameters as controlling factor) and found similar increasing trend for the growth period 1980s to 2010. The findings revealed an increase in NPP over the period ranging 0.005 Pg C yr^{-1} to 1.70 Pg C yr^{-1} (Gahlot *et al.,* 2017; Nayak *et al.,* 2013; Nayak *et al.,* 2016; Valsala *et al.,* 2013). However, Das *et al.,* (2023) while estimating the NPP using MODIS quality-controlled satellite data of LAI, GPP, NPP, and Net Photosynthesis for the period of 2001–2019 found 6.19% reduction in NPP despite 6.75% increased leaf area index due to increased forest area. The reduction in NPP was attributable to reduced photosynthetic rate and stable respiration rate at an elevated temperature regime because of climate change. They have also highlighted that, forest areas around North-eastern region, Peninsular India and the Western Ghats are more sensitive to the climate change having a declining NPP graph. This suggests that while India's forests have historically functioned as carbon sinks, their future sequestration capacity may be compromised by climate change.

It is estimated that, carbon stock of India's forests is 7285.53 Mt of which 41% is present as soil organic matter, 42% as living biomass (above and below ground), 6% in deadwood and 11% in litter. The share of Odisha's Forest resources to the national carbon budget is 6.23% (453.68 Mt) (Indian State of Forest Report, Forest Survey of India, 2023). Odisha, in eastern India, hosts extensive tropical moist and dry deciduous forests in regions like Simlipal, Satkosia and many hill ranges within the Eastern Ghats, playing a crucial role in carbon sequestration. However, deforestation, agricultural expansion, industrialization and climate change are altering carbon fluxes, potentially affecting the state's net ecosystem production.

Despite their ecological importance, research on NEP and carbon dynamics in Odisha's forests remains limited. This study hypothesizes that Odisha's tropical moist deciduous forests function as significant carbon sinks, but their sequestration capacity is being impacted by anthropogenic and climatic factors. By analyzing carbon flux and NEP, this research aims to enhance scientific understanding and inform regional climate mitigation strategies. Amongst thirty districts of Odisha, Kandhamal have a sizable area (65.01% of geographical area) under forest cover. Being a part of the undulating Eastern Ghats landscape, forests are diverse, biologically rich and virgin in nature. The continued dependence of people on forests for their livelihood is threatening the pristine nature of these ecosystems. Deforestation, agricultural expansion, stone quarrying and climate change are altering carbon fluxes, potentially affecting the NEP of these forests. Hence the objectives of the present research work are to

a) Assess the vegetation composition of tropical moist deciduous forests in Odisha
b) Quantify biomass production, litter production, decomposition rates and net primary productivity in the forest ecosystem
c) Investigate net ecosystem production and carbon fluxes across various pools within the forest ecosystem.

CHAPTER-2

REVIEW OF LITRATURE

The relevant literature relating to the present research work titled "Net ecosystem production and carbon flux in tropical moist deciduous forest of Odisha" is reviewed under following heads.

2.1 Phyto-diversity inventories in tropical forests of the Eastern Ghats

2.2 Biomass and carbon inventories in tropical forests

2.3 Litter production, decomposition and carbon stock in tropical forest ecosystem

2.4 Carbon stock Assessment in forest soil (SOC)

2.5 Net primary production, ecosystem production and ecosystem exchange

2.1 Phyto-diversity inventories in tropical forests of the Eastern Ghats

Tropical forests are biodiversity rich regions of the earth. Apart from habitat provisioning and species preservation, these forests provide many ecosystem services such as soil conservation, climate regulation and livelihood support (Naidu and Kumar, 2016). Anthropogenic pressure and climate change in conjunction with many direct and indirect aversive forces compelling the tropical forests to shrink annually 1.0 to 4.0% of their current coverage (Naidu *et al.,* 2018). This leads to an alarming rate of biodiversity erosion along tropics, needing immediate attention for its conservation and sustained use. For successful implementation a holistic conservation project, biodiversity assessment is the prerequisite and everybody agrees with this. Biodiversity assessment has two aspects; first is inventory and second one is monitoring the temporal changes. Inventorying biodiversity is a static process whilst monitoring is dynamic process, orient towards documenting change in species status over time (Gordon and Newton, 2006).

Premavani *et al.* (2014) inventoried tree species diversity and population structure of four dry deciduous forest types of the north-central Eastern Ghats located in the West Godavari district of Andhra Pradesh. They obtained tree density of 447.25 ha^{-1} encompassing 92 species. The Shannon-Weiner (S-W) index, dominance index, and even-ness index ranged from 3.32 to 3.55, 0.76 to 0.81 and 0.95 to 0.97

respectively. Within Eastern Ghats, the floristic composition of dry deciduous forest of East Godavari district differs greatly from its western counterpart. The tree density in this forest type ranged from 371 to 660 trees ha^{-1} having basal area between 14.54 to 46.51 $m^2 ha^{-1}$. *Protium serratum, Anogeissus latifolia, Dalbergia paniculata* were dominant tree species with *Terminalia alata*, *Xylia xylocarpa* and *S. cumini, Cleistanthus collinus* as major associates (Premavani *et al.,* 2017). Naidu *et al.* (2018) observed the dominance of families Euphorbiaceae, Rubiaceae, Anacardiaceae and Mimosaceae in relatively moist localities within dry tropical forests of north-central part of the Eastern Ghats.

Naidu and Kumar (2016) assessed the tree diversity in Visakhapatnam district of Andhra Pradesh located in the northern part Eastern Ghats and obtained tree diversity in the range of 435 to 767 ha^{-1}. These forests harbour 129 species which belong to 98 genera and 44 families. Rubiaceae, Euphorbiaceae, Combretaceae and Meliaceae were dominant families of the forest.

Reddy and Ugle (2008) compared the tree diversity in three tropical forests *viz*. semi-evergreen (SE), moist deciduous (MD) and savanna (S) forests of Visakhapatnam district located within the Eastern Ghats. They observed high species richness (84 numbers) in semi-evergreen forest and low (18 numbers) in savanna forest with tree basal area in the range of 49.2 (SE) to 7.79 (S) $m^2 ha^{-1}$ respectively. The Shannon-Weiner diversity index was high in MD forest (5.50). Anacardiaceae, Euphorbiaceae, Papilionaceae, Sapindaceae and Caesalpiniaceae were dominant families in SE and MD forests.

Kadavul and Parthasarathy (1999) assessed the tree diversity in tropical semi-evergreen forests of Shervarayan hills of Tamil Nadu, (s-w portion of the Eastern Ghats located in Tamil Nadu) and observed 815 trees ha^{-1} having basal area of 44.30 $m^2 ha^{-1}$. *S. cumini* and *Canthium dicoccum* were dominant species. Among the documented 44 families, Euphorbiaceae, Rubiaceae and Oleaceae were dominant families having high species diversity.

Pragasan and Parthasarathy (2010) made floristic inventory in the major hill complexes of South-Eastern Ghats through line transects (120 numbers) covering 60 ha of forest area. They recorded 272 numbers of tree species (181 genera and 62

family) having density in the range of 290 to 527 stem ha^{-1} and basal area between 5.6 to 24.40 m^2 ha^{-1}. The prominent families reported by them were Euphorbiaceae (25 species) and Mimosaceae (68.77 stems ha^{-1}). *Albizia amara* and *Canthium dicoccum* were dominant tree species in South-Eastern Ghats having IVI value 15.87 and 11.58 respectively.

2.1.1 Phytodiversity inventories in Forests of Odisha

Major hill ranges of Odisha are Mahendragiri, Deomali, Gandhamardan, Niamagiri and Kondakamberu and they are being a part of the Eastern Ghat mountain ranges act as ecological estuaries of plant genetic diversities (Pattanaik *et al*., 2008). Similipal biosphere reserve (SBR) located in the Mayurbhanj district of Odisha is the eastern end of Eastern Ghats Mountain range. The SBR harbours nearly 38% tropical forests of the state and is very rich in floristic diversity. These tropical forests are grouped as moist deciduous forest, semi-evergreen forest, dry deciduous forest, dry sal forest and high level sal forest. Many ecologists explored the diversity of plants in the SBR, notable among them are Saxena *et al.,* (1988), Reddy *et al.,* (2007), Mishra *et al.,* (2012), Saranya *et al.,* (2014), Saranya and Reddy, *(*2016), Mohanta *et al.,* (2021), and Saranya *et al.,* (2023).

Reddy *et al.* (2007) reported presence of 185 tree species from in three forest types (moist deciduous, dry deciduous and semievergreen) in SBR with tree density ranging from 527-665 ha^{-1} and mean basal area of 43.52 m^2 ha^{-1}. Mohanta *et al.* (2021) observed high species richness in dry deciduous forest (DDFT) type as compared to moist deciduous forest (MDFT) type and semi-evergreen forest (SEFT) type. DDF type occupies much area over other two forest types having *S. robusta-X. xylocarpa-T. tomentosa* as the dominant community. In MDFT and SEFT major associates of sal were *Protium serratum, T. tomentosa, Syzygium cumini*. Saranya *et al.* (2023) evaluated the impact of various anthropogenic and natural disturbances on plant diversity of SBR. They observed high degree of disturbance in riparian and low level sal forest.

Mahendragiri hill range lies in the Gajapati district of Odisha. High elevation (1501 amsl) and sub-tropical climate of this hill range favousrs luxuriant growth of many tropical plants and allow ecasis of temperate species. Thus, this tract of Eastern

Ghats possesses unique assemblage south Indian and Himalayan flora. Khadanga *et al.* (2023) recorded presence of 189 species of trees (131genus, 51family) across various elevations of Mahendra hills with tree density varying from 51.15 to 75.25 number ha^{-1} and basal area 14.32 to 27.13 m^2 ha^{-1}. The Shannon diversity index ranged from 1.89 to 2.25 and Simpson's dominance index from 0.74 to 0.84. Taxonomically, Fabaceae (23 species) and Phyllanthaceae (12 species) were dominant families where as from family importance value (FIV) point of view Fabaceae (73.98) and Anacardiaceae (16.70) were significant families. Tree diversity was high in mid-elevation zones with dominance of *S. cumini, Aporosa octandra* and *Anacardium occidentale.*

The tropical dry deciduous forest of Malayagiri hill ranges in Anugul district, Odisha are a part of the Eastern Ghats harbours 57 tree species with density of 443 stems ha^{-1} and basal area 13.74 m^2 ha^{-1}. The diversity index (S-W) and dominance index (Simpson) were 3.38 and 1.0 respectively. *S. robusta* dominated these forests sharing canopy with *T. alata, M. latifolia, A. latifolia* and *D. melanoxylon* (Sahu *et al.,* 2012a).

The tropical moist peninsular sal forests of Niamagiri hills, in the Eastern Ghats shares boundary with Rayagada and Kalahandi district, possess 46 tree species (42genus, 27family) with density in the range of 470 to 490 stems ha^{-1} and basal area in the range of 3.16 to 10.04 m^2 ha^{-1}. The diversity index (S-W) ranged from 2.34 to 4.53 and dominance index (Simpson) from 0.07 to 0.09. Taxonomically, the families Combretaceae (10 species) and Caesalpiniaceae (8 species) were dominant families having high species richness (Sahu *et al.,* 2012b).

Ganghamardan hills spreading over Bolangir and Bargarh district of Odisha is famous for its medicinal plant repository. Nrusinghanath hills situated in the northern aspect and Harishankar in the southern aspects are having distinct edaphic mass and also floral diversity. Sahu *et al.* (2010) compared the tree diversity among these two hills through quadrat sampling spreading over 17.6 ha area. They observed high species diversity in Nrusinghnath hill side (78 species, diversity index-3.92) as compared to the Harishankar hill side (61 species, diversity index-3.31). The density of trees was also high in Nrusinghnath (671 trees ha^{-1}) than Harishankar (565

trees ha^{-1}). On the basis of IVI value *M. latifolia, D. melanoxylon, C. collinus* and *A. latifolia* were dominant in these tracts of Eastern Ghats bearing moist deciduous forests.

Saptasajaya hills, located in the Dhenkanal district of Odisha a part of Eastern Ghats hill range possesses tropical moist deciduous forests with high floral diversity. Sahu *et al*. (2019) inventoried variation in tree diversity along altitudinal gradient in the Saptasajaya hills. This hill range possesses 48 tree species (42genus, 27family) with density variation from 433 to 390 ha^{-1} and basal area of 30.64 m^2 ha^{-1}. The diversity index (S-W) ranged for 2.19 at lower elevation to 1.29 at higher elevations.

Sahoo *et al.* (2017) assessed the tree diversity in Nayagarh forest division possessing sal forest (dry mixed and peninsular), moist mixed deciduous forest and dry deciduous forest. This tract of the Eastern Ghats found possessing 177 tree species (120 genera, 44 families) with density ranging between 355 to 740 ha^{-1}, basal area 7.77 to 31.62 m^2 ha^{-1}. The diversity index (S-W) ranged between 2.07 to 3.79, Simpson's index from 0.03 to 0.88. Dipterocarpaceae, Fabaceae and Anacardiaceae were dominant families with respect to family importance value. *Shorea robust* dominates the forests of this division (IVI-88.62) with major associates *B. lanzan, L. coromandelica* and *T. alata.*

Kuldiha wildlife sanctuary is also another floristic rich area of the state because of its location in the Nato and Sukhupada hills joining to the Similipal biosphere reserve. Many ecologists surveyed the floral status of sanctuary using quadrat sampling procedure (Behera *et al.,* 2021; Saravanan *et al.,* 2018; Rout *et al*., 2018) and remote sensing technique (Pattanaik *et al.,* 2010). The sanctuary possesses 118 tree species (95 genera, 39 families) with high diversity in core zone as compared buffer zone. *T. tomentosa, S. robusta* and *Croton roxburghii* were dominant trees in the sanctuary having IVI of 292.27, 50.89 and 17.11 respectively. Combretaceae, Dipterocarpaceae, and Anacardiaceae were dominant families.

Mishra *et al.* (2012) assessed the composition and stand structure of moist deciduous forest in Similipal biosphere reserve and recorded 117 tree species with a density of 793.67 stems ha^{-1} and basal area 71.04 m^2 ha^{-1}. The diversity index (S-W) of trees ranged between 1.8 to 3.11 and dominance index (Simpson's) from 0.07 to

0.32. *S. robusta* was found dominant species with major associates *Terminalia alata, Anogeissus latifolia* and *Dillenia pentagyna* form dense upper story canopy.

Sahoo *et al.* (2018) inventoried the floral diversity in the Chandaka Damapara wildlife sanctuary and recorded 655 species of angiosperms among which 113 were trees (83 genera, 36 families). The density of trees was 222.21 stems ha^{-1} with mean basal area 11.20 m^2 ha^{-1} and diversity index (S-W) of 3.96. The tropical dry deciduous forest (DDF) of sanctuary varied from other DDF of the state because of dominance of *Xylia xylocarca* instead of *Shorea robusta.*

2.2 Biomass and carbon stock inventories in tropical forests

Forests occupy nearly about 31% of the earth's surface area (4.06 billion hectares), act as keystone in maintaining global carbon budget (FAO and UNEP 2020). Plants remove atmospheric CO_2 through photosynthesis but it is the woody perennials particularly trees that store the carbon in its biomass for an extended period until harvested. Thus, forest play a pivotal role in bioenergy production, carbon (C) storage and limiting the effect of global warming. Studies have shown that forests can annually sequester about 12 per cent CO_2 emission from various anthropogenic sources (Hurteau *et al*., 2019). But the increased rates of deforestation, land use change in recent decades have caused more carbon release to atmosphere impending biomass production and C sequestration potential of forests. There are many pathways to capture and store atmospheric C but managing vegetation carbon pool through sustainable forest management practices is somehow easy and cost effective. Among various forest types of the world, tropical forests are very dynamic and rich in biodiversity. Tropical forests though occupy only ~15% of earth surface, harbour $2/3^{rd}$ of the terrestrial plant biomass and $1/3^{rd}$ of soil organic carbon (Gandhi and Sundarpandian, 2017). About $1/3^{rd}$ of the gross primary production of terrestrial ecosystems is contributed by tropical forest and much exploited for food, fodder, fiber and energy. Hence the C flux rate is high in tropical forests than any other biomes of the world (Beer *et al*., 2010). These forests may play as carbon source or sink depending on the biomass production rate and the level of exploitation or deforestation. Hence it is impediment to assess these resources for

biomass stock and as well as C sink potential at regular intervals. Vegetation biomass and carbon stock is estimated through direct and indirect methods. In the direct method destructive sampling is done for biomass estimation and then carbon fraction is multiplied to estimate biomass carbon stock. Sample trees from a representative area is harvested and dry weight of various parts such as bole, branch, leaf, root and reproductive parts were estimated (Hossain *et al*., 2016). Though this method provides an accurate estimation of biomass, it is applicable only for estimating biomass in a small patch of forest. The destructive harvesting of plants, expensiveness and labor intensiveness limits its application for biomass estimation on broad scale (country or landscape level) (Sileshi, 2014). Hence mathematical models (indirect method) using measurable variables such as tree height, girth or diameter of tree at breast height and wood density is quite often used to estimate vegetation biomass without felling the trees (Chave *et al.*, 2005). Biomass estimation using growing stock volume, wood density and biomass expansion factor gives relatively close estimation of biomass with respect to direct method (Vashum and Jayakumar, 2012). The common non-destructive approach often adopted is use of species specific or multi species regression equations involving one or more measurable tree parameters such as DBH/GBH, height and wood density (Kaul *et al.,* 2011). Many researchers have also developed common biomass estimation allometric equations for various forest types on a global or regional level (Brown *et al*., 1999; Chave *et al.,* 2005; Chaturvedi *et al.,* 2011).

Another method of biomass estimation is using remote sensing and GIS (geographical information system) technology. This method is very effective for estimating biomass on a broad scale level where field associability is limited or economically not feasible. In this method information on vegetation attributes is obtained using optical, SAR or LiDAR data sets. Satellite derived parameters in conjunction with field inventory data are used to develop spectral models and after authenticating the best fit model, biomass estimation is carried out (Vashum and Jayakumar, 2012; Kumar and Mutanga, 2017).

Fang *et al.* (2019) estimated the forest biomass carbon stock in five major east Asian countries (China, Japan, North Korea, South Korea and Mongolia)

adopting allometric equations and field inventory data of FAO during the period 1970s to 2000s. Average carbon sequestration rate of forest in these regions was 66.90 Tg C yr^{-1}. Forests in China, Japan and S Korea were major contributor to the forest C sink of the region.

2.2.1 Biomass and carbon inventories in tropical forests of India

Biomass estimation is prerequisite for understanding ecological processes happening in a forest ecosystem and various ecosystem services harnessed from it (Palma *et al.*, 2021). Accurate assessments of biomass, carbon stock and flux are essential for predicting forests' capacity to mitigate climate change in the current global climate change scenario (Hu *et al.,* 2022). Many vegetation dependance factors (forest type, composition and structure), environmental variables (temperature, precipitation, geographic position), perturbations and silvicultural treatments influence carbon stock of a forest at a specific period of time (Gogoi *et al*., 2022). Although there have been notable advancements in vegetation sampling and biomass determination procedures, precise estimation of biomass stocks for diversified forest types of India is very challenging because of the absence of generalized allometric equations (Brahma *et al.,* 2021).

Indirabai and Nilsson (2024) estimated the above ground biomass stock (AGBS) of Betul forest in central India and Mudumalai forest in South India using Global Ecosystem Dynamics Investigation (L4B) data sets. The AGBS in Betul forest ranged from 42.20 to 238.80 t ha^{-1} and in Mudumalai forest from 75.90 to 353.60 t ha^{-1}.

Gogoi *et al.* (2022) compared the AGBS and C stock in six major forest types (tropical wet evergreen, montane sub-tropical temperate, bamboo, quercus and jhum-land forest) of the Eastern Himalaya. They observed high AGB in tropical wet evergreen forest (322.60 Mg ha^{-1}) and low in jhum-land forest (18.34 Mg ha^{-1}).

Raj and Jhariya (2021) assessed the biomass of mixed sal forest of Chattishgarh in four site qualities (I-IV) and found total biomass variation of 375.84 Mg ha^{-1} in site quality I to 182.27 Mg ha^{-1} in site quality IV. The carbon sequestration of trees varied from 12.21 t ha^{-1} yr^{-1} to 5.41 t ha^{-1} yr^{-1} in site quality IV.

Raha *et al.* (2020) studied the biomass and carbon stock in tree species of three dry deciduous forests (teak forest, mixed forest and Boswellia forest) of Madhya Pradesh through non-destructive method (volume equations of FSI and wood density). The total biomass (above ground and below ground biomass) ranged from 160.70 Mg ha^{-1} in dry teak forest to 223.30 Mg ha^{-1} in boswellia forest. Similarly, the total carbon stock ranged from 75.30 Mg C ha^{-1} (teak forest) to 104.70 Mg C ha^{-1} (boswellia forest).

Srinivas and Sundarapandian (2019) enumerated the above ground biomass (AGB) and above ground biomass carbon (AGBC) in tropical dry forests (TDF) of East-Godavari region adopting allometric equations. The AGB ranged between 58.04 to 368.39 Mg ha^{-1} and the AGBC stock of trees from 44.51 to 218.84 Mg C ha^{-1}. Major tree species contributing to the biomass and carbon stock were *Xylia xylocarpa*, *Terminalia arjuna and Mangifera indica*.

Deb *et al.* (2020) studied the impact of anthropogenic disturbances on biomass and carbon stock of tropical forest in Tripura. The AGBS and AGBC stock ranged from 236.67 to 169.18 Mg ha^{-1} and 118.34 Mg ha^{-1} to 84.59 Mg ha^{-1} in low disturbed site and high disturbed site respectively.

Banik *et al.* (2018) assessed the biomass and carbon allocation pattern in tropical moist sal forest managed under various management regime in Tripura. The total C stock (AGBC + BGBC +SOC) was found higher in sal plantation (219.68 Mg C ha^{-1}) than natural sal forest (167.64 Mg C ha^{-1}).

Padmakumar *et al.* (2018) studied the tree biomass and carbon stock in tropical dry forest of Chinar WL sanctuary using allometric equations (volume equation of FSI and wood density) and recorded the total biomass as 132.72 Mg ha^{-1} and carbon stock as 63.07 Mg C ha^{-1}. *Tamarindus indica* was the major contributor (17.0%) to the biomass and carbon stock of the forest.

Behera *et al.* (2017) assessed the above ground biomass stock (AGBS) and above ground biomass carbon stock (AGBCS) in three plant function groups (mixed forest, sal mixed forest and teak plantation) within the Katerniaghat WL sanctuary using single variable (DBH) allometric equation. The AGB ranged between 290.82 to 455.99 Mg ha^{-1} and the AGBCS ranged between 125.94 to 228.87 Mg C ha^{-1}.

Gandhi and Sundarapandian (2017) assessed the AGB and carbon stock of tropical dry deciduous forest in the Eastern Ghats using allometric equations. The total biomass and carbon stock of woody vegetation (tree + juvenile + liana) varied between 85.02 to 723.50 Mg ha^{-1}. The total carbon stock of the forest ranged from 37.86 to 322.16 Mg C ha^{-1}. They also studied the contribution of each woody components towards the biomass and carbon stock. Higher share towards biomass and carbon among tree species shown by *Chloroxylon swietenia*, in juvenile group by *Albizia amara* and among liana by *Combretum albidum*.

Khaple *et al.* (2015) compared the AGB and AGBC stock between tropical dry deciduous forest and moist deciduous forest (MDF) located in the Dharwad district of Karnataka adopting allometric equations. The AGB and AGBC was found high in moist deciduous forest (95.87 Mg ha^{-1} and 45.06 Mg C ha^{-1}) than dry deciduous forest (43.86 Mg ha^{-1} and 20.61 Mg C ha^{-1}).

Das and Singh (2016) studied the variations in AGB among four tropical forest types *viz*. moist deciduous (MDF), dry deciduous (DDF), semi evergreen (SEF) and evergreen forests (EF) in the western ghats of Maharashtra using remote sensing techniques. The AGB in MDF ranged between 30.20 to 151.10 Mg ha^{-1}, in DDF from 9.20 to 99.10 Mg ha^{-1}, in SEF from 42.10 to 158.60 Mg ha^{-1} and in EF from 160.90 to 271.00 Mg ha^{-1}.

Majumdar *et al.* (2016) compared the AGB and AGBC stock among four forest types (moist bamboo brakes, moist deciduous sal, moist mixed deciduous and semi evergreen dipterocarpus forest) of Tripura. The AGB ranged between 37.85 to 85.59 Mg ha^{-1} and AGBC range from 18.93 to 42.80 Mg C ha^{-1}.

Borah *et al.* (2015) estimated the AGB and AGBC stock in two protected areas (Gibbion WL sanctuary and Kholahat reserve forest) of Assam harbouring tropical forests using allometric models. The AGB and AGBC ranged from 135.3 to 146.40 Mg ha^{-1} and 67.60 to 73.22 Mg C ha^{-1} respectively.

Shahid and Joshi (2015) recorded total tree biomass and biomass carbon stock in the range of 338 to 438 Mg ha^{-1} and 169 to 219 Mg C ha^{-1} respectively in moist deciduous forests of Doon valley.

Devagiri *et al.* (2013) enumerated the biomass of tropical dry deciduous forest using MODIS spectral bands and found that AGB ranged between 7.25 to 287.05 Mg ha^{-1} (dry weight) with a mean carbon density of 33 Mg C ha^{-1}.

Mani and Parthasarathy (2007) enumerated the biomass of tropical dry evergreen forests in peninsular India using allometric equations. They recorded the AGB in the range of 39.69 to 170.02 Mg ha^{-1} by using basal area as single variable and 73.06 to 173.10 by using two variables basal area and tree height.

2.2.2 Biomass and carbon sequestration in Odisha forests

The carbon stock of Odisha Forest is 453.68 million tonnes in which the share of biomass and soil organic carbon (SOC) was 41.39% (187.75 Mt) and 58.61% (265.93 Mt) respectively (ISFR 2023). Mohanta *et al.* (2020) compared the biomass carbon stock in sal and xylia dominated forests within the Similipal biosphere reserve of Odisha. They observed higher biomass carbon stock of in sal dominated forests (239.78 Mg C ha^{-1}) as compared to the xylia dominated forests (206.51 Mg C ha^{-1}). The variations in SOC stock in both the forest types was non-significant ($P<0.05$).

Pattnayak *et al.* (2020) studied the biomass and SOC stocks in six plant functional groups including natural forests, plantations and degraded scrub land in Chandaka-Damapara wild life (WL) sanctuary. They observed high basal area have a significant positive correlation with above ground biomass carbon (AGBC) stock. In natural forests the AGBC stock ranged from high 37.10 Mg C ha^{-1} in peninsular sal forest to low 13.40 Mg C ha^{-1} in semi-evergreen forest.

Khadanga and Jayakumar (2020) assessed the variation in biomass and carbon stock along altitudinal gradients in Mahandragiri hill ranges of Odisha within the Eastern Ghats using allometric equation. The total biomass of these tropical dry deciduous forests ranged from 129.09 to 255.87 Mg ha^{-1} and 64.52 to127.93 Mg C ha^{-1} respectively.

Pradhan *et al.* (2019) compared the biomass carbon stock of Debrigarh WL sanctuary with Andhari sacred forest managed under two different regimes adopting

non-destructive method. The WL sanctuary was protected and managed by state forest department whereas the sacred group was by tribal communities. Although plant diversity was high in sacred forest, total biomass carbon stock of WL sanctuary was high (155.48 Mg C ha^{-1}) as compared to the Andhari sacred forest (140.80 Mg C ha^{-1}).

Sahu *et al*. (2016a) through field inventory method estimated the AGB and C stock in tropical dry deciduous forests of Deogarh district of Odisha. The AGB of sampled plots ranged from 13.96 to 514.50 Mg ha^{-1} and the carbon stock (AGBC) from 6.98 to 257.35 Mg C ha^{-1}. Tree species contributing higher percentage to the total AGB were *S. robusta* (sal), *M. latifolia* (mahua), *M. indica* (amba), *T. alata* (asana) and D. *melanoxylon* (kendu).

Mangrove forests also store considerable amount of carbon in their biomass as well as soil. The ecosystem carbon stock (biomass and SOC) of mangrove vegetation in the Mahanadi mangrove wet land was estimated as 1.60 times more (147.00 Mg C ha^{-1}) than other forest types of Odisha (Sahu *et al.,* 2016c; Pattnayak *et al.,* 2019).

2.3 Litter production, decomposition and carbon stock in tropical forest ecosystem

Vegetative or reproductive plant parts stern across the ground or buried in the soil due to senescence or mechanical damage are known as litter. Various kinds of macro and microorganisms such as fungi, bacteria, actinomycities, insects and Mollusca act upon the fallen litter on the ground for their nourishment, make it to decompose and finally the litter mass disappears in the soil. This process of litter fall and decomposition are fundamental ecosystem processes in any terrestrial ecosystems. Litter decomposition ensures organic carbon input to soil which mediate pathways of nutrient flux and soil fertility. It acts as a gateway for nutrient elements in the biogeochemical process, facilitates energy transfer among trophic levels, enhances biological productivity and helps in re-translocation of nutrients (Hattenschwiler *et al.,* 2005). Understanding different source of litter to the pool, rate decomposition, major paths of nutrient release are requisite in assessing the biogeochemical processes in any ecosystem. Climatic variations, litter chemistry and

diversity of detritus community define the fate of litter decomposition, mineralization rate of complex compounds and ultimately availability of nutrients to plants in ionic forms (Getaneh *et al.,* 2022; Prescott, 2005).

In the forest ecosystem, plant litter is the main pool in the nutrient flow process. Plant litter mass in a forest ecosystem includes fallen leaves, reproductive parts (inflorescence, flower, fruit and seeds), small branches and dead roots. However, leaf biomass constitutes the major share (22-81%) of total litter mass in various forest ecosystems (Pande *et al.,* 2002). Litter production in a forest is regulated by species diversity, eco-physiology of littering species (productive capacity, phenology and seasonality), site quality, climatic patterns and stress induced by natural or manmade disturbances (Becker *et al.,* 2015; Morffi-Mestre *et al.,* 2020). A wide range in litter production can be observed among different forest types of the world ranging from 3.0 Mg ha^{-1} y^{-1} to 11.0 Mg ha^{-1} y^{-1} (Zhang *et al.,* 2014). Variation in litter production was observed with respect to physiographic conditions and forest types across India. In the Western Ghats region, litter production ranged from 6.14 to 14.2 t ha^{-1} yr^{-1} in tropical evergreen forest, 13.0 to 15.0 t ha^{-1} yr^{-1} in tropical moist deciduous forest and 6.73 t ha^{-1} yr^{-1} in tropical semi-evergreen forest (Swamy and Proctor, 1994; Parthasarathy, 1992). In tropical dry evergreen forests of the Coromandel Coast annual litter fall was 13.3 to 13.5 t ha^{-1} yr^{-1} (Pragasan and Parthasarathy, 2005). Rajendraprasad *et al.* (2000) recorded annual litter production in the range of 4.4 to 6.4 t ha^{-1} yr^{-1} in the tropical evergreen forests of Kerala. In the Himalayan region annual litter fall range from 2.95 to 4.04 t ha^{-1} yr^{-1} in North-West Himalaya (Bisht *et al.,* 2014), 1.73 to 3.85 t ha^{-1} yr^{-1} in chir-pine mixed oak forests of central Himalaya (Verma and Garkoti, 2020), 1.25 to 6.90 t ha^{-1} yr^{-1} in various forests types of Gharwal Himalaya (Sharma *et al.,* 2020). In the North-Eastern states of Meghalaya, litter fall ranged from 6.68 t ha^{-1} yr^{-1} in coniferous forests to 11.74 t ha^{-1} yr^{-1} broad leaved forests (Nonghulooi *et al.,* 2020).

Litter fall in forest ecosystems may be unimodal or bimodal depending on the physiology of the littering plant species in a particular set of environments. It is more often regulated by atmospheric temperature and precipitation. Generally, heavy litter fall occurs during the dry months, often coinciding with summer or winter in the Indian subcontinent, as plants shed their leaves to reduce transpiration loss. Peak

litter fall during summer season was observed in Gharwal Himalaya (Saha *et al.,* 2016), Western India (Yadav *et al.,* 2008) and parts of central India (Thakur and Thakur, 2014). However, peak litter fall during winter is also observed in some places *viz*. sub-tropical forests of North East India (Bijayalaxmi Devi and Yadava, 2010) and moist tropical forests of Western Ghats (Bhat, 1990). Sometimes biotic disturbances such as heavy infestation of defoliators, skeletonizers or diseases induce heavy leaf fall (Pande *et al.,* 2005 The peak of litter fall may occur in different seasons in temperate broad-leaved and needle-leaved evergreen forests, while it peaks during autumn in temperate deciduous broad-leaved forests (Zhang *et al.,* 2014).

Litter decomposition is a major component of carbon and nutrient cycling in terrestrial ecosystems of the world. Litter decomposition seems a very simple process but actually involves many complex biotic and abiotic interactions. Litter shed from mother plant undergoes some physical as well as chemical changes by the action of environmental factors such as temperature, moisture and wind. Some chemical compounds lost rapidly, some disappears slowly and few undergo modifications with time scale. During the process of decomposition some nutrients are imported to the decomposing substrate and then released to the soil after being mineralized. Whatever may be the mechanism involved, decomposition process can be segregated into three steps: fragmentation of coarse litter into finer particulates is the first one, secondly mineralization of complex organic compounds by microorganisms and finally leaching of soluble compounds into mineral soil (Ahirwal *et al.,* 2021). Once these processes are complete, the litter mass stabilizes at a non-zero level, with the remaining undecomposed material contributing to soil organic matter. While analyzing the litter decay process we generally focus on the mass loss rate, chemical modifications occurred in the residual undecomposed mass and derived chemical products by decomposers. Much work has been conducted to understand the litter decay process and nutrient dynamics in tropical forests.

2.4 Carbon stock Assessment in forest soil (SOC)

SOC refers to the carbon stored in the organic matter of soil. This includes decayed plant and animal materials, microbial biomass and other biological

originated material. SOC plays a vital role in maintaining soil structure, nutrient cycling, carbon sequestration and biodiversity support irrespective of ecosystem type. Soil carbon pool can be grouped as labile, recalcitrant and inert fraction depending their turnover time. Organic matter consisting of cellulose, hemicellulose and polysaccharides originating from plant and animal debris or soil organisms having turnover time varying from few weeks to month are referred as labile carbon fraction. The non-labile pool includes materials such as lignin, lipids, suberin, fats etc. which takes years to decay. The inert pool is consisting of charcoal and pyrolyzed carbon, take centuries to decay (Chan *et al*., 2001). The SOC content of first three meters of soil is 2344.0 Pg C of which maximum stock found in upper one meter depth (Jobbágy and Jackson, 2000). Forest soil is the greatest terrestrial carbon storehouse stockpiling 50% of C stock in tropical forest to 85% of taiga forest (Lal, 2005). Majority of SOC in forest is stored in organic matter which varies spatially and temporally. The primary source of C input to SOC pool is through plant or animal origin organic matter and its decomposition by microbial decomposition. The C output from soil stock is through microbial respiration and carbon exchange with atmosphere. Thus, it influences the carbon cycle and atmospheric C balance. Various factors such as climate, soil properties, vegetation, perturbations (natural and anthropogenic) and forest management practices influence forest SOC stocks. Measuring forest SOC help to understand its potential for C sequestration and global climate change mitigation. The C stock in forest soils of India is 4010.12 Mt in which share of tropical dry deciduous forest is 1276.50 Mt tropical moist deciduous forest is 750.82 Mt and tropical semi-evergreen forest is 372.35 Mt (ISFR 2023).

Gogoi *et al.* (2022) compared SOC stock of six major forest types (tropical wet evergreen, montane sub-tropical temperate, bamboo, quercus and jhum-land forest) in the Eastern Himalaya and found high SOC in temperate forest (3.77%) and low in jhum-land forest (1.16%).

Deb *et al.* (2020) studied the impact of anthropogenic disturbances on SOC stock of tropical forest in Tripura. The SOC stock ranged from 91.47 to 72.10 Mg C ha^{-1} in lower disturbed and high disturbed sites respectively.

Borah *et al.* (2015) estimated the SOC two protected areas (Gibbion WL sanctuary and Kholahat reserve forest) of Assam harbouring tropical forests at three different layers *viz*, 0-30 cm, 30-60 cm, and 60-90 cm. The SOC ranged from 57.73 to 78.43 kg m^{-2} in upper layer, from 39.2 to 64.9 kg m^{-2} in middle layer and from 30.31 to 42.85 kg m^{-2} in lower layer.

Gupta (2011) studied the SOC stock of soil at 0-30 cm depth in different land use systems of Haridwar district and found SOC content of 73.63 t ha^{-1} in natural forest ecosystem.

Many researchers studied the SOC stock of forest soil in various forest types of Odisha (Pattnayak *et al.,* 2020; Banerjee *et al.,* 2018; Sahu *et al.,* 2015). The organic C stock of forest soils in Odisha is 263.45 million tonnes which constitutes about 59.23% of the total carbon stock of the forest resources of the state (ISFR 2021). Pattnayak *et al.,* (2020) studied SOC stocks in six plant functional groups (PFG) including natural forests, plantations and degraded scrub land in Chandaka-Damapara wild life (WL) sanctuary and found that C allocation to SOC pool in various PFG varied from 51-91%. SOC stock has a positive correlation with above ground biomass and importance value index of tree species. The SOC percentage of tropical dry deciduous forests in Mahendragiri hill ranges varied from 0.70 to 1.43% in upper layer (0.15 cm and 0.55 to 1.13% in lower layer (15-30 cm) (Khadanga *et al*., 2023).

2.5 Net primary production, net ecosystem production and carbon flux

Through carbon sequestration and release, forest ecosystem influence carbon budget of the world. Small change in any C pool of the forest, great change in atmospheric chemistry and climatic phenomenon is noticed. Various C pools in forest ecosystem is primarily regulated by net assimilation of phytobiomass, otherwise called as net primary production (NPP). NPP refers to the net assimilated organic C and energy in the ecosystem at a specific time interval. Simply it is the difference between gross primary production (GPP) and autotrophic respiration (AR). Estimating NPP of an ecosystem is crucial for understanding ecosystem functioning, managing resources and addressing environmental challenges. Various

methodologies employed by researcher for NPP estimation includes biomass sampling through field inventories, satellite imagery using remote sensing technology and regression models following machine learning. Measuring spatiotemporal variations in forest ecosystem NPP is required to evaluate sink or source status of a particular forest type in world carbon budget. Forest ecosystem NPP includes all sorts of organic material such as wood, foliar and fine root fixed during the time interval. Its measurement simply includes the determination of net gain/retention in above and below ground biomass after subtracting organic matter loss (AG and BG) including carbohydrate export to symbionts (Clark *et al.,* 2001). Biometric inventory approach employed for forest NPP measurement focus on measuring diameter increment of woody plants, foliar growth including twigs and fine root accumulation (Whittaker, 1961; Ohtsuka *et al.,* 2016). This is because, wood including coarse root, foliage and fine root biomass comprises nearly about 93% of the total NPP in a forest ecosystem (Drake *et al.,* 2011). Global terrestrial GPP is about 121.60 Pg C yr^{-1} out of which 49.52% occurred in forest ecosystems. Global terrestrial NPP accounts half of the GPP (62.60 Pg C yr^{-1}), 35% of which is contributed by tropical forests (Pan *et al.,* 2013).

Measuring net ecosystem production (NEP) is essential for understanding the carbon balance of ecosystems and assessing their role in the global carbon cycle. NEP represents the difference between the amount of carbon fixed by plants through photosynthesis (GPP) and the carbon released through ecosystem respiration which includes respiration by plants, soil organisms, and decomposers. It essentially represents the balance between NPP and heterotrophic respiration in an ecosystem. The empirical methods commonly used for measuring forest NEP are the eddy-covariance technique (ECM) and biometric assessment approaches (BAM) and chamber method (CHM). The basic principle of these methods to quantify the net ecosystem CO_2-fluxes. The eddy-covariance method measures spatiotemporal variation in net ecosystem level CO_2-fluxes by tracking the turbulent fluxes of gases without disturbing vegetation and soil. This method provides high temporal resolution and can be applied over large spatial areas, making it highly effective for capturing the dynamics of ecosystem carbon balance (Campioli *et al.,* 2016). In biometric inventory method heterotrophic respiration (respiration from root, dead

wood and soil biological organisms) is subtracted from NPP to get NEP (Clark *et al.,* 2001). The chamber method involves using closed or open chambers to measure the exchange of CO_2 gas between the ecosystem and the atmosphere over a specified time period. These chambers are placed on the soil or over vegetation to capture and quantify the CO_2-fluxes from both plant respiration and soil processes (Speckman *et al*., 2015). Each method of measuring NEP has its own advantage and limitations. It is widely acknowledged that sensor-based micrometeorological ECM provides accurate estimates of CO_2 flux (Baldocchi, 2020; Waring *et al.,* 1998). However, in calm climatic conditions, the accuracy of estimated CO_2 release from the ground vegetation layer and soil surface may be compromised (Loescher *et al.,* 2006). It has been reported that biometric assessments of CO_2 flux (NEE) and NEP are conceptually comparable to ECM-based measurements (Ohtsuka *et al.,* 2005).

Wang *et al.* (2017) evaluated the consistency of ECM, BAM and CHM methods used for estimating carbon budget of forest ecosystems. They observed that the ECM method overestimates NEP by 25% and underestimates ecosystem respiration by 10%. They opined that, the uncertainties involved can be eliminated through cross validation of data sets with precise measurements and careful data processing approaches.

Through field inventory of plant biomass gain and heterotrophic soil respiration (soil respiration chamber Li-COR), Sierra *et al.* (2007) measured the NEP value between 4.03 to 2.22 Mg C ha^{-1} yr^{-1} in tropical primary forest of Colombia during 2000-2002. They concluded that, tropical forests essentially not act as a carbon sick indefinitely rather C fluxes vary spatially and temporally.

Rodda *et al.* (2016) measured the NEP and net ecosystem exchange of CO_2 through eddy covariance method in Sundarban mangrove ecosystem. The net ecosystem exchange (NEE) ranged from -6 to -10 mmol m^2 s^{-1} during summer and winter season respectively. Sundarban mangrove ecosystem act as carbon sink having NEP of 249 g C m^2 yr^{-1}.

Singh *et al.* (2019) studied the NPP and C flux in a Western Himalayan deciduous pine (*Pinus roxburghii*) forest using micrometeorological, eco-physiological and biophysical data during 2010-2011. The average NPP and soil

respiration during peak growth period was 11.75 µmol CO_2 m^{-2} s^{-1} and 9.2 µmol CO_2 m^{-2} s^{-1} respectively. The net C flux (net ecosystem exchange) of the forest was negative during growth period with a mean value of -3.3 µmol CO_2 m^{-2} s^{-1}.

Yashiro *et al.* (2010) through biometric method calculated the NPP and soil respiration of Japanese ceder plantation as 7.90 Mg C ha^{-1} yr^{-1} and 6.80 Mg C ha^{-1} yr^{-1} respectively. The NEP of the plantation was 4.30 Mg C ha^{-1} yr^{-1} and act as carbon sink for the area.

Ohtsuka *et al.* (2007) observed the NEP and carbon flux in a temperate deciduous broadleaved forest of Japan adopting field biometric methods. The NPP and heterotrophic respiration (R_H) was 1.1 Mg C ha^{-1} yr^{-1} and 4.4 Mg C ha^{-1} yr^{-1} respectively. The soil surface CO_2 efflux was 7.1 Mg C ha^{-1} yr^{-1} with annual soil organic matter decay rate 3.9 t ha^{-1} yr^{-1}. The biometrically estimated NEP of the forest was 2.1 Mg C ha^{-1} yr^{-1} which was comparable with the value obtained through eddy-covariance based NEP.

Tateno *et al.* (2004) measured the biomass (AG and BG) and NPP in temperate broad leaved deciduous forest in Japan and recorded NPP range between 8.80 to 14.10 Mg ha^{-1} yr^{-1}. They also observed that, aboveground NPP is positively correlated with the soil nitrogen mineralization and nitrification rate whereas the below ground NPP have a reverse trend.

Van Do (2017) measured the NEP in tropical broadleaved ever-green forest in Vietnam using biometric inventory approach. The annual carbon accumulation rate of this forest type was 2.59 Mg C ha^{-1} yr^{-1}.

Yan *et al.* (2006) measured the NPP indirectly using soil respiration and litter fall inventory data in three forest types (coniferous, broad-leaved mixed and monsoon evergreen broad-leaved forest) of Dinghushan BR in S China. The NPP in these forests ranged between 0.48 to 1.15 kg C m^2 yr^{-1}. The share of below ground NPP ranged from 37% in broad leaved mixed forest to 62% in monsoon evergreen forest.

O'Connell *et al*. (2003) measured the NPP and NEP of two *Picea mariana* forest communities having similar biological growth behavior under variable edaphic situations (feather-moss and sphagnum-moss covered soil conditions) in Saskatchewan, Canada. The total carbon stock of the forest ranged from 107 to 113 Mg C ha^{-1}, while annual soil respiration varied from 319 to 564 g C m^{-2} yr^{-1}. NEP in the black spruce community growing under sphagnum-moss edaphic situation have higher NEP (-0.128 kg m^2 yr^{-1}) than the community grown on feather-moss soil (-0.222 kg m^2 yr^{-1}) and acts as a source of atmospheric carbon.

Raj and Jhariya (2021) measured the carbon stock and flux rate in sal forests growing under various site qualities (I-IV) of Chattishgarh adopting a biometric assessment approach. The total carbon stock varied from 79.86 to 163.63 Mg C ha^{-1}, with the contribution of above-ground biomass ranging from 10.42% to 14.13%. Carbon input to the forest ecosystem through NPP ranged from 3.55 to 2.33 Mg ha^{-1} yr^{-1} (site quality I-IV) from which 1.77 to 1.33 Mg ha^{-1} yr^{-1} transferred to the soil through litter fall. The carbon sequestration rate of the sal forest in four site qualities was in the order S-I (14.63 Mg ha^{-1} yr^{-1}) > S-II (10.81 Mg ha^{-1} yr^{-1}) > S-III (8.19 Mg ha^{-1} yr^{-1}) > S-IV (6.83 Mg ha^{-1} yr^{-1}).

Devi and Yadava (2009) compared the NPP among two dipterocarpus stands in Manipur using the biometric inventory method and observed the NPP range between 8.86 to 10.43 Mg ha^{-1}. Based on NPP and biomass accumulation portioning, they inferred that these forests are in the successional stage having high productive potential.

Pathak *et al.* (2018) studied biomass production and carbon flux (NEE) in the traditionally managed imperata grassland of Assam through a biometric assessment approach. The biomass production ranged from 91 to 214 g m^2 m^{-1} with high during monsoon season. The annual biomass C and NEP of the grass land was 889.0 g C m^2 and 91.0 g C m^2 yr^{-1} respectively. With a positive NEE value, this grassland ecosystem acts as a C sink.

The above review of literature reveals that although works pertaining to biomass and carbon inventories of forest ecosystems have been widely undertaken,

there is a lack of studies focusing on carbon losses through various pathways, such as litter decomposition, fine root turnover and soil respiration. Further efforts to assess net ecosystem productivity in forest ecosystems are also negligible within the Indian context. Therefore, this study aims to fill these gaps in our understanding of the major drivers of carbon gains and losses in forest ecosystems, which may contribute to more effective forest management.

CHAPTER-3

MATERIALS AND METHODS

3.1 Introduction

Odisha, the eastern Indian state bestowed with wide range of ecological habitats ranging from hilly forest peaks to long coastal plains and brackish water lagoons, harbor rich granaries of floristic assemblages. The diverse forest resource plays pivotal role in the state's ecology and socioeconomic fabric. Forests spread over 52,155.59 km^2 encompassing 33.50% of the total geographical area of the state (ISFR 2023). These tropical forests broadly classified into four groups *viz*. semi ever green, moist deciduous, dry deciduous, and littoral-swamp forests (Champion and Seth, 1968). In high mountain ranges, patches of subtropical broad leaves hill forests can also be observed. Floristic assemblage accounts to 726 species of flowering plants which belongs to 496 genera (G) and 120 family (F). *Shorea robusta* (Sal) is the predominant timber species covers nearly about 43% of the forest cover of the state forming various sub-types such as dry peninsular sal, moist peninsular sal and moist mixed deciduous forests (Saxena and Brahmam, 1996). In dry localities sal commonly found associated with *Pterocarpus marsupium, Bridelia retusa, Ougenia oojeinensis, Dalbergia sissoo, Madhuca latifolia, Buchanangia lanzan, Adina cordfolia, Xylia xylocarpa* and *Diospyros melanoxylon*. On the other hand, in moist localities depending upon the parent rock and edaphic mass *Terminalia tomentosa*, *Pterocarpus marsupium, Terminalia alata, Careya arbora, Litsea species, Lannea coramandelica, Syzygium cumini*, *Diospyros malabarica, Lagerstroemia speciosa, Bombax ceiba, Schleichera oleosa* and *Mallotus philippensis* shares canopy layer with sal. Aboriginal tribals and fringe villagers extract various non-timber forest produce (NTFPs) for their domestic consumption and remnants barter in local hataas (market) for livelihood. Major NTFPs extracted from these forests include lac, honey, sal leaf, kendu leaf, sal seed, chara seed, mahua flower and kernel, siali leaf and fiber, tamarind, wild mushrooms, wild fruits, bamboos and many medicinal plants providing substantial contribution to the state economy.

3.2 Description of study sites

The present study was carried out in Kandhamal district of Odisha. It lies between 19^0 34' to 20^0 36' N latitude and 83^0 34' to 84^0 34' E longitude with a geographical area of 8021 km^2. Kandhamal is a land locked district, bounded by Boudh district in North, Rayagada and Gajapati districts in south, Nayagarh and Gunjam districts in the east and Kalahandi district in the west. The district possesses rich forest resource mostly tropical dry/moist deciduous type covering 67.37% of the geographical area the district (ISFR 2021). As per the classification of Champion and Seth (1968), forest of the district is classified into two major sub-groups *viz*. North Indian Tropical Moist Deciduous Forest (3C) and Northern Tropical Dry Deciduous Forests (5B). These forest sub-groups are classified as moist peninsular sal forest (3C/C2), moist mixed deciduous forest (3C/C3), dry peninsular sal forest (5B/C1), dry mixed deciduous forest (5B/C2) and dry bamboo brakes (5B/E_9). Three tired canopy strata dominated by sal (*Shorea robusta*) can distinctively be observed in these forests (Behera and Mishra, 2006). Sal forms pure or mixed crop depending on the site quality and elevation. Present phytosociological inventory carried out in three forest communities based on dominance of sal i.e. pure sal forest community, mixed sal forest community and mixed forest community without sal within tropical moist deciduous forests to understand forest structure and regeneration status of dominant tree species. For this purpose, four reserve forests (Khajuripada RF, Dutimundi RF, Dakapalla-B RF and Sudurukumpa RF) having minimal anthropogenic disturbance were selected in Phulbani and Sudurukumpa Range of the Phulbali Forest Division. The geographical coordinates, location and altitude of each study sites are given in Table 3.1 and Figure 3.1.

Table 3.1 Location and geocoordinates of the study sites

Forest Community	Study site	Location of forest site	Geocoordinates	Altitude (m- amsl)
Pure sal Forest (PSF)	S-I	Dakapalla-B RF, Phulbani Range	20^0 26′ 48″ N 84^0 13′ 53″ E	557
	S-II	Dutimundi RF, Phulbani Range	20^0 16′ 59″ N 84^0 21′ 26″ E	561
	S-III	Khajuripada RF, Phulbani Range	20^0 25′ 56″ N 84^0 27′ 40″ E	423
Sal dominated moist deciduous forest (SDMDF)	S-I	Dakapalla-B RF, Phulbani Range	20^0 58′ 04″ N 84^0 05′ 83″ E	547
	S-II	Dutimundi RF, Phulbani Range	20^0 16′ 42″ N 84^0 17′ 57″ E	553
	S-III	Khajuripada RF, Phulbani Range	20^0 21′ 97″ N 84^0 48′ 07″ E	448
Mixed deciduous forest without sal (MDFWS)	S-I	Dutimundi RF Phulbani Range	20^0 17′ 44″ N 84^0 48′ 56″ E	582
	S-II	Khajuripada RF, Phulbani Range	20^0 35′ 25″ N 84^0 28′ 86″ E	453
	S-III	Sudurukumpa RF, Sudurukumpa Range	20^0 36′ 28 ″ 84^0 20′ 17 ″	584

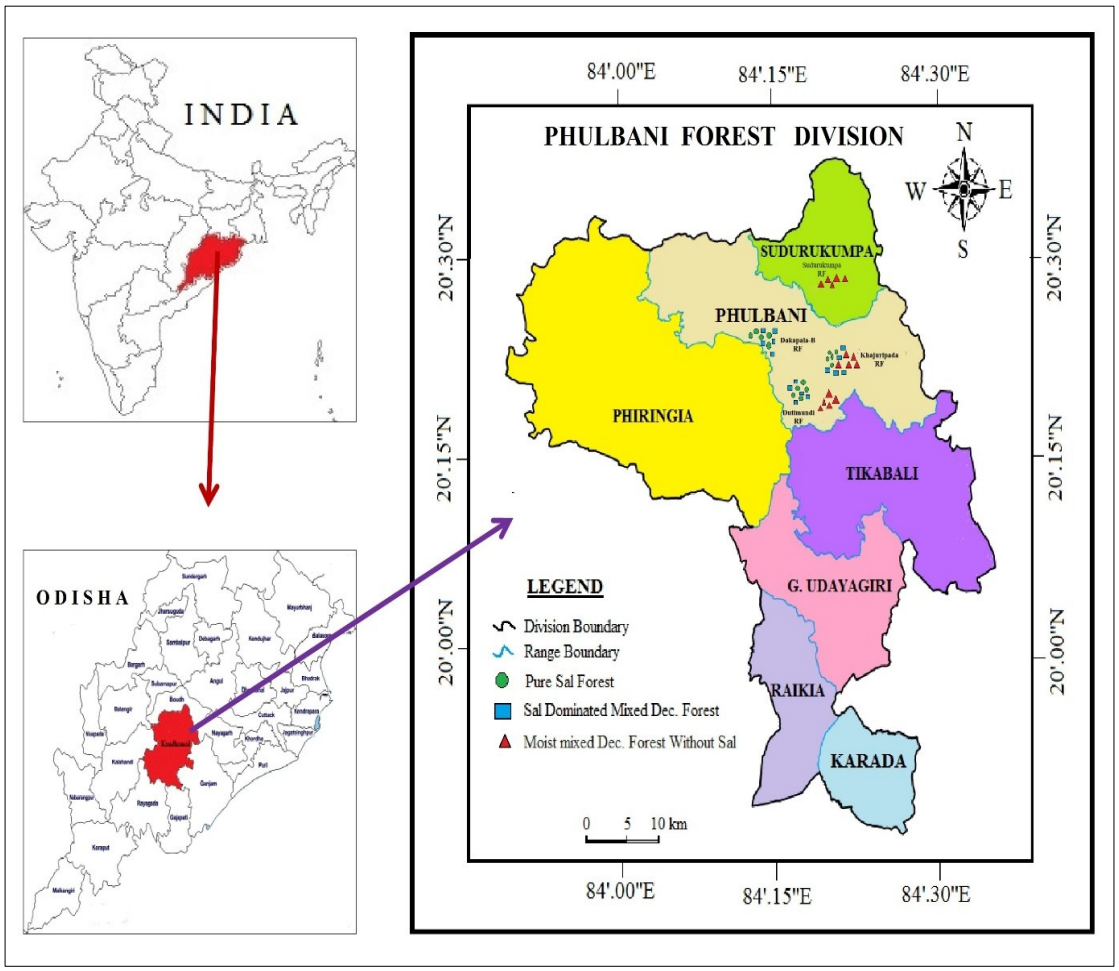


Figure 3.1 Map showing location of sampling sites

3.3 Climate

By virtue of its location at south of the tropic of cancer Odisha experiences a warm tropical climate. Many parts of Odisha fall within tropical savannah climate type (AW) in the climatic classification map of Koppen (Kottek *et al*., 2006). The tropical climate of Odisha is characterized by scorching temperature, higher humidity, moderate to heavy rainfall and mild winter. The state has a long coast line along shores of the Bay of Bengal, hence oceanic currents greatly influence weather of Odisha. Three well marked seasons notably summer (March to June), rainy (July to October) and winter (November to February) exists but because of high temperature and elevated humidity one experience the feel summer season in almost 7-8 months of the year. During summer months the maximum temperature ranges from 35.0 to 40.0 ˚C and minimum 12.0 to 14.0 ˚C. It is during the last few years the

mercury even raises up to 43-45 ˚C in the land locked districts of the state. Winter is very mild except for few places in Koraput and Kandhamal district where the temperature drops down to 3.0 to 4.0 ˚C. The state receives approximately 1500 mm monsoonal rainfall annually in 109.64 rainy days. The majority of rainfall (80-85%) is received from south west monsoon during July to September and the rest from the retreating monsoon in the months of October to November. Based on climate, soil entire state has been grouped in to ten agroclimatic zones. The studied district Kandhamal comes under North Eastern Ghat agroclimatic zone and have hot-moist-sub humid climate with mean maximum temperature 37.0 ˚C, mean minimum temperature 10.4 ˚C and mean annual rainfall of 1597 mm (Figure 3.2).

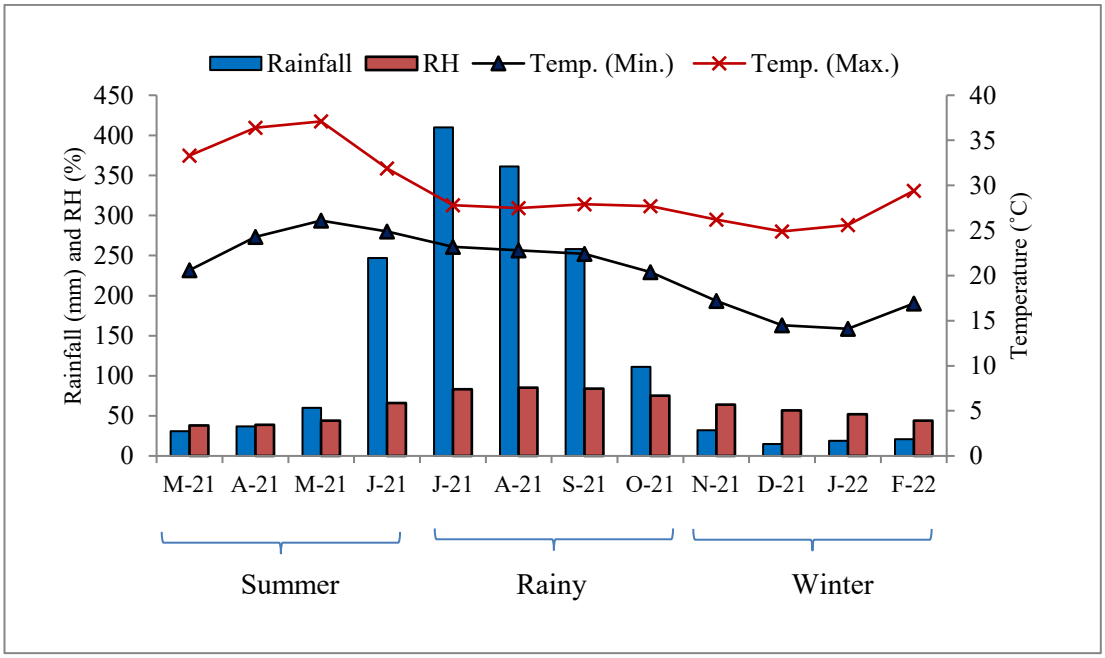


Figure 3.2 Ombrothermic diagram of the study site for period March-2021 to February-2022

3.4 Topography

The Phulbani Forest Division is part of the hilly ranges of the Eastern Ghats. The topography is highly undulating characterized by high hillocks interspersed with small patches of flat land and plateaus. The division contains a number of high hill peaks with elevations ranging from 600m to 1150m. In the northern area, there are

flat tracts of land along the nala beds in the Donga, Ranipather, Kalabagh, and Sudrukumpa hill ranges. Plain lands are mainly found in pockets within the Khajuripada, Lainpada, Phulbani, Tikabali, and Phiringia areas displaying a benching pattern. The Eastern part forms the Chakapad forest block having large chunk of flat land. On account of undulating terrain, this tract is well drained with the presence of number of small nalahs and streams draining into river Salki and Baghnadi which subsequently drain into the river Mahanadi.

3.5 Geology, rock and soil

The major rocks found in the division belong to the older Archean rock groups such as Charnockite and Khondalite groups. Along with these rocks younger rocks such as Diorites, Quartzites, calcareous granites, laterites, clay stones, sandstones, shales and micaschists were also present. Sandstones typically form the hills, while limestone and shale make up the valleys. Granite and Gneiss found mainly in the north-western parts including Kalabagh, Palchi, Chakapad, Burtang, Sudrukumpa, Ranipather and Donga blocks. Hornblende, schist and charnockites produce heavy clay soil. Its magnesium content gives it a grey colour and its high water retention supports good cultivation. Khondalite-derived red soil composed of quartz, clay and iron oxide, is poor in water retention and unsuitable for agriculture. Weathered plateaus and hill slopes form red clay and laterite soil, found on higher hilltops along the northern and eastern boundaries.

The soils in the division are generally immature, broadly grouped as clayey-loam (black), sandy loam (alluvial) and red soil. Clayey-loam soils are common in the valleys of forest blocks with deeper calcareous clay on plateaus but in hill slopes often found mixed with boulders. Sandy loam predominates along nala banks and moderate slopes. Kanker formation occurs in Khajuripada, Ranipathar and Palchi blocks. Red and laterite soils are found in various forest blocks with red soil on contours and laterite on higher hills. Soil depth varies across forest blocks, ranging from shallow (25-50 cm) to moderately deep (75-100 cm) and deep (>100 cm) in lowland areas like Chakapad, Kalabagh, Ranipather and Burtanga where forest growth is lush. Soils are generally acidic, well-drained and support good vegetation. In most forest blocks of the division, soils are rich in potash but have low levels of

carbon, nitrogen and phosphorus. However, rampant Podu cultivation and current organic turmeric farming have led to vegetation removal, exposing rocks to weathering and causing topsoil erosion. As a result, the soil lacks structure, becoming massive with poor water retention (Forest working Plan, Phulbani division).

Plate 1. Forest types A. Pure Sal Forest (PSF), B. Sal dominated moist deciduous forest (SDMDF), C. Moist Deciduous Forest Without Sal (MDFWS)

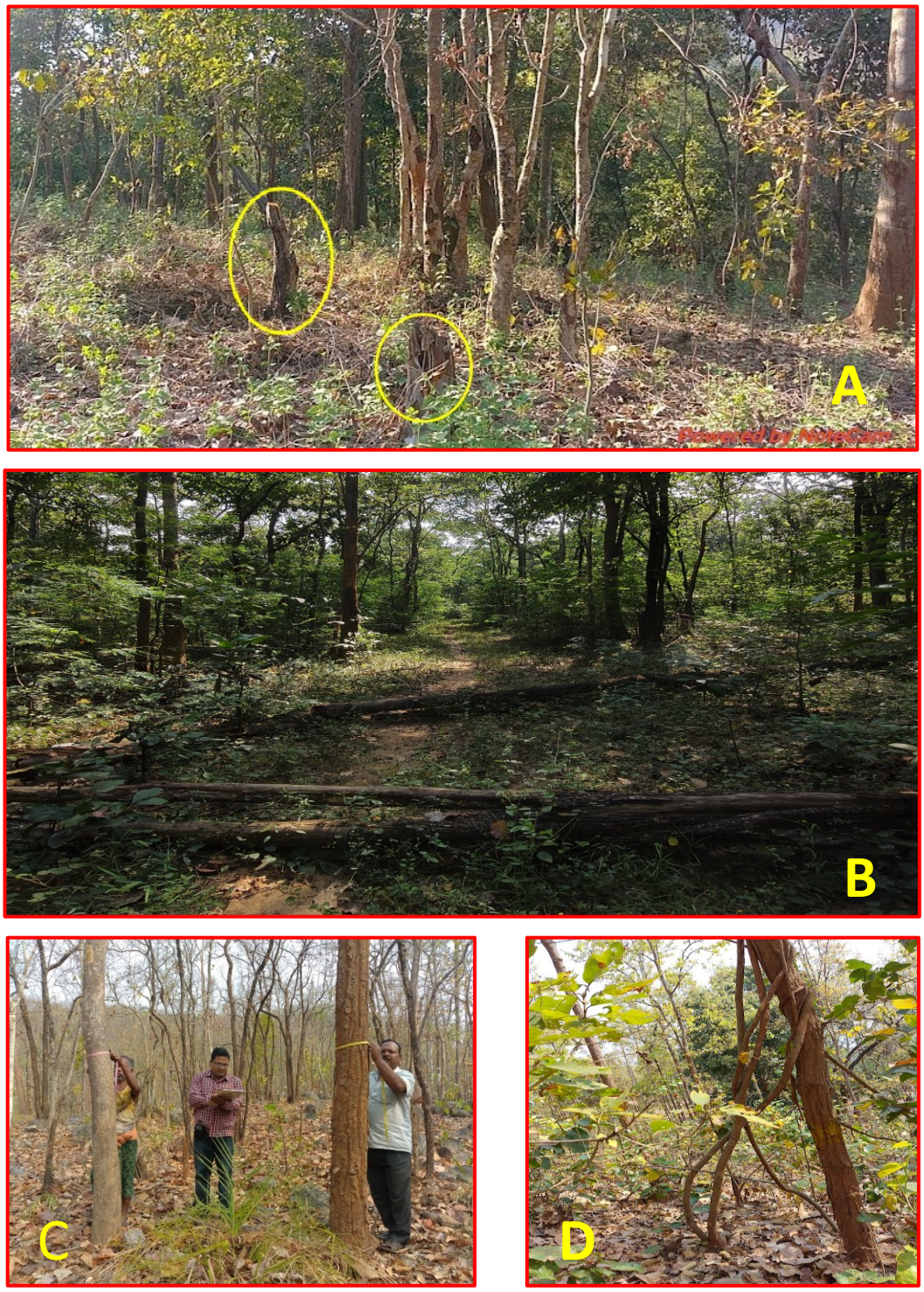


Plate 2 Phytosociological survey A. Cut stem analysis, B. Dead wood analysis, C. GBH recording, D. Liana study

CHAPTER-4

SOIL CHARACTERISTICS AND DISTURBANCE REGIME OF STUDY SITES

4.1 Introduction

Climate and soil are key factors governing the distribution of vegetation across the globe, with climate influencing vegetation patterns on a large scale, while soil affects them on a more localized basis (Andino *et al.,* 2021). Topography also plays a crucial role in shaping vegetation characteristics at an intermediate scale. To understand the soil-vegetation relationship it is essential to introspect how individual edaphic factors influence the growth and development of plant species particularly trees as they significantly influence the vegetation characteristics. Soil texture (proportion of sand, silt and clay) affects water retention, drainage, nutrient availability and root penetration. These characteristics directly influence tree growth and survival determining the types of forests and the species that inhabit them. For this reason, in tropical region dry deciduous forests are found in loamy-sand or lateritic soils with predominance of draught tolerant species *Anogeissus latifolia*, *Acacia catechu* and *Boswellia serrate*. On the other hand, well drained clay or clay-loam soil support growth of moist deciduous forests or moist evergreen forest where much exacting species like *Shorea robusta*, *Lagerstroemia speciosa* and *Dipterocarpus indicus* were grown luxuriantly (Sahu *et al.,* 2019). Soil moisture is another crucial edaphic factor that directly influences forest structure, species composition and biodiversity by controlling water availability for plant growth. It plays a key role in determining forest types, with moisture-rich areas supporting dense, lush vegetation, while drier regions favor drought-tolerant species. Soil reaction (pH) directly influences plant growth by influencing nutrient availability at rhizosphere zone. Highly acidic or alkaline soils limit nutrient uptake, promoting the growth of species adapted to these conditions. Many tropical timber species prefer slightly acidic to neutral soils. Sal prefers more acidic soils, while teak requires a neutral pH for optimal growth (Behera *et al.,* 2024).

In addition to soil and climatic factors, various interacting parameters, such as elevation, topographic gradients, and biotic pressure especially from human activities shape the vegetation characteristics of a region (Rahman *et al.,* 2021). Tropical forests are particularly vulnerable due to their location in densely populated areas. Anthropogenic activities like timber harvesting, mining, fires, livestock grazing, mono-cropping, agriculture expansion, changes in land use pattern and so on factors not only reduce the extent of tropical forests but also alter their structure and functionality (Bisht *et al.,* 2022). These actions threaten the sustainability of forests and compromise critical ecosystem services such as soil and water conservation and food availability. An area-specific assessment of anthropogenic disturbances is essential to identify how different human actions impact ecosystems based on regional characteristics. Customized strategies are required to address the unique environmental social and economic factors of each area. Such assessments are key to developing effective mitigation plans and ensuring sustainable resource management

4.2 Material and methods

4.2.1 Soil sampling and analysis

For analyzing the soil physicochemical properties representing pedon form each forest types in each reserve forest were selected during the month of March 2020. Rectangular pit of size 1 m (length) x 1 m (breadth) x 60 cm (height) was dug within each sub sample plot (31.62 m x 31.62 m) fixed for phytosociological analysis. The walls of the pit were made vertical and smoothed using a khurpi and precaution was taken to undisturb the natural state of soil profile. Soil horizon was marked at 15 cm intervals up to 45 cm depth. Soil samples were collected at three depths *viz*. 0-15 cm, 15-30 cm and 30-45 cm from four sides properly and packed in soil collection bags after removing plant roots, stones and any kind of foreign materials. A total of 96 soil samples were collected [(12 pits x 3 layers for PSF and SDMDF community) + (8 pits x 3 layers for MDFWS community)] from the studied three forest communities. Similarly equal numbers of soil samples were collected in metallic cores of known volume for determining the soil bulk density. The collected soil samples were brought to the laboratory of Forest resource management, College of Forestry, Odisha University of Agriculture and Technology, Bhubaneswar and

shade-dried (at 25-28 ^{0}C) for 5-6 days. The air-dried soil samples were grinded with wooden hammer, sieved through 2 mm sieve and stored in glass jar after proper labeling for further analysis.

The colour of air-dried soil samples were established by matching with Munshell colour chart. The percentage of sand, silt and clay was determined through boucoyoucos hydrometer method following the procedure described by Bouyoucos (1962) and then the textural classes of respective soil samples were established by comparing the calculated values of soil aggregates with the USDA textural triangle. Bulk density and moisture content was determined after drying the soil samples in a hot air oven maintained at 105 ^{0}C for 48 hours. Water holding capacity (WHC) was determined gravimetrically adopting Keen's box method. Soil pH and electrical conductivity was determined in 1:2.5 soil-deionized water suspension through glass electrode pH meter (Model: Systronics 361) and conductivity meter (Model: Systronics 306) respectively (Jackson, 1967). The organic carbon content in samples was determined through wet digestion followed by rapid titration against ferrous ammonium sulphate (FAS) as described by Walkley and Black (1934). For this 1 g of soil sample was taken in a 500 ml capacity conical flask, added with 10 ml of 1N $K_2Cr_2O_7$ followed by 20 ml H_2SO_4 (Conc.) and allowed to react. After 30 minutes of digestion the flask was added with 200 ml of distilled water followed by 5-10 drops of ferroin indicator and titrated against FAS till maroon or wine-red end point. Simultaneously a blank reading was taken without soil sample. The organic carbon content in sample was calculated using the mathematical formulae of Walkley and Black (1934). The available nitrogen was determined adopting the alkaline KMnO4 method of Subbiah and Asija (1956). Available phosphorus was estimated through chlorostannus-reduced-molybdophosphoric blue colour method in HCl acid system (Jackson, 1967). The available potash was determined through ammonium acetate method using a flame photometer (Systronics -128) following the procedure of Merwin and Peech (1951).

4.2.2 Sources of disturbance in the study site

The level of disturbance at each site was assessed using a relative score on a 3-point scale for each anthropogenic activity, along with a tree stump-based disturbance index (SDI). The SDI was determined by dividing the basal area of felled trees by the total of the basal areas of both felled and standing trees (Rao *et al.,* 1990). Various other anthropogenic disturbances were scored relatively as a) number of linked forest road to the site (FR) ≤1 road-1, 2-3 road-2, ≥4 road-3; b) Proximity to human settlement (PHS): ≥8.0km-1, 4-7km-2, ≤3 km-3; c) forest fires in the previous year (FR): surface fire-1, ground fire-2, crown fire-3; d) grazing intensity (GI): ≤50 cattle units/day-1, 51-100 cattle units/day-2, ≥101cattle units/day-3; e) NTFPs collection (NC): ≤5 items-1, 6-9 items-2, ≥10 items-3; f) fuel wood collection (FWC): 2-3 months-1, 4-5months-2, >5 months-3; g) damages by wild animals (DWL): ≤5 spots-1, 6-9 spots-2, ≥10 spots-3; h) densitometer based canopy cover (CC): ≥70%-1, 40-70%-2, <40%-3. Based on the cumulative resulted disturbance value studied forest sites were categorized as undisturbed (≤ 10%), low disturbed (11-40%), moderate disturbed (41-70%) and High disturbed (≥71%).

4.3 Results

4.3.1 Soil physical properties

Various parameters relating to the physical properties *viz*. colour, textural class, bulk density, soil moisture content, and water holding capacity in PSF, SDMDF and MDFWS are presented in Table 4.1. Soil colour in all three forest types was brown with colour notion varying from 7.5 YR 5/4 to 7.5 YR 5/3 except in the upper layer (0-15 cm) of the SDMDF community in which the colour was strong brown with notion 7.5 YR 5/6. Significant variation ($P<0.01$) in per cent of sand, silt, clay content, bulk density and water holding capacity was noticed in soils of PSF, SDMDF and MDFWS. The sand content varied from 75.70% in MDFWS community to 87.57% in PSF community. The silt content ranged from 6.21% in SDMDF to 9.30% in PSF. The silt content in soils of PSF (9.30%) and MDFWS (8.97%) were statistically indifferent ($P<0.01$). Similarly, the clay content in the soils of three forest communities were in the order PSF (3.31%) < SDMDF (11.34%) < MDFWS (15.33%) and significantly differed from each other. As far as variation in

soil aggregate per cent with respect to depth was concerned no definite trend was noticed in the soil profile of SDMDF and MDFWS community. In PSF community the sand per cent increased with depth from surface layer (0-15 cm) to lower layer (30-45 cm). The textural class was loamy-sand in PSF and MDFWS where as it was sandy-loam in SDMDF. Bulk density ranged from 1.52 in PSF to 1.72 in MDFWS. Similarly, the WHC varied from low 38.81 % in SDMDF to high 42.08% in MDFWS. An increasing trend in BD and WHC was noticed from surface layer (0-15 cm) to lower layer (30-45 cm) along the vertical section of soil profile.

Table 4.1 Soil physical properties in PSF, SDMDF and MDFWS

Forest type	Soil depth (cm)	Soil colour and notion	Textural class	Sand	Silt	Clay	BD (g cm^{-3})	SMC (%)	WHC (%)
PSF	0-15	Brown (7.5YR5/4)	LS	77.45 (2.58)	7.18 (1.13)	15.37 (2.24)	1.36 (0.14)	18.07 (0.15)	37.77 (0.59)
	15-30	Brown (7.5YR5/3)	LS	84.45 (2.11)	6.18 (1.14)	9.37 (1.11)	1.57 (0.12)	12.27 (0.81)	39.54 (0.74)
	30-45	Brown (7.5YR5/3)	LS	85.45 (1.24)	5.28 (1.21)	9.27 (1.34)	1.63 (0.01)	8.31 (0.49)	43.00 (0.38)
SDMDF	0-15	Strong brown (7.5YR5/6)	SL	74.30 (2.30)	8.50 (2.07)	17.20 (2.23)	1.54 (0.08)	17.40 (0.17)	37.85 (0.59)
	15-30	Brown (7.5YR5/4)	SL	75.40 (1.50)	9.20 (2.16)	15.40 (1.54)	1.55 (0.04)	13.42 (0.07)	38.17 (0.52)
	30-45	Brown (7.5YR5/3)	SL	77.40 (1.14)	9.20 (1.22)	13.40 (2.21)	1.78 (0.06)	12.21 (0.06)	40.41 (0.28)
MDFWS	0-15	Brown (7.5YR5/4)	LS	89.30 (1.67)	8.50 (1.14)	2.20 (1.25)	1.60 (0.03)	14.08 (0.15)	39.34 (0.71)
	15-30	Brown (7.5YR5/3)	LS	87.20 (2.15)	8.70 (1.21)	4.10 (1.11)	1.76 (0.02)	12.03 (0.59)	42.26 (0.58)
	30-45	Brown (7.5YR5/3)	LS	86.20 (1.24)	10.70 (1.20)	3.10 (1.64)	1.79 (0.04)	11.64 (0.35)	44.65 (1.16)
MEAN (0-45 cm)	PSF	Brown	LS	87.57^{c} (0.91)	9.30^{b} (0.70)	3.13^{a} (0.55)	1.52^{a} (0.10)	12.88^{ns} (1.49)	40.10^{ab} (0.56)
	SDMDF	Brown	SL	82.45^{b} (2.52)	6.21^{a} (0.58)	11.34^{b} (2.02)	1.62^{ab} (0.01)	14.34^{ns} (0.10)	38.81^{a} (0.48)
	MDFWS	Brown	LS	75.70^{a} (0.91)	8.97^{b} (0.23)	15.33^{c} (1.10)	1.72^{b} (0.02)	12.58^{ns} (0.70)	42.08^{b} (0.64)
P value	-	-	-	<0.01	<0.01	<0.01	0.04	0.53	0.015

Values in parenthesis indicate standard errors of mean values, values in the same column followed by different alphabet are significantly differing at $p<0.05$ by Duncan's multiple range tests. Textural class SL-Sandy-Loam, LS- Loamy-sand, BD-bulk density, SMC-soil moisture content, WHC-water holding capacity.

Table 4.2 Soil chemical properties in PSF, SDMDF and MDFWS

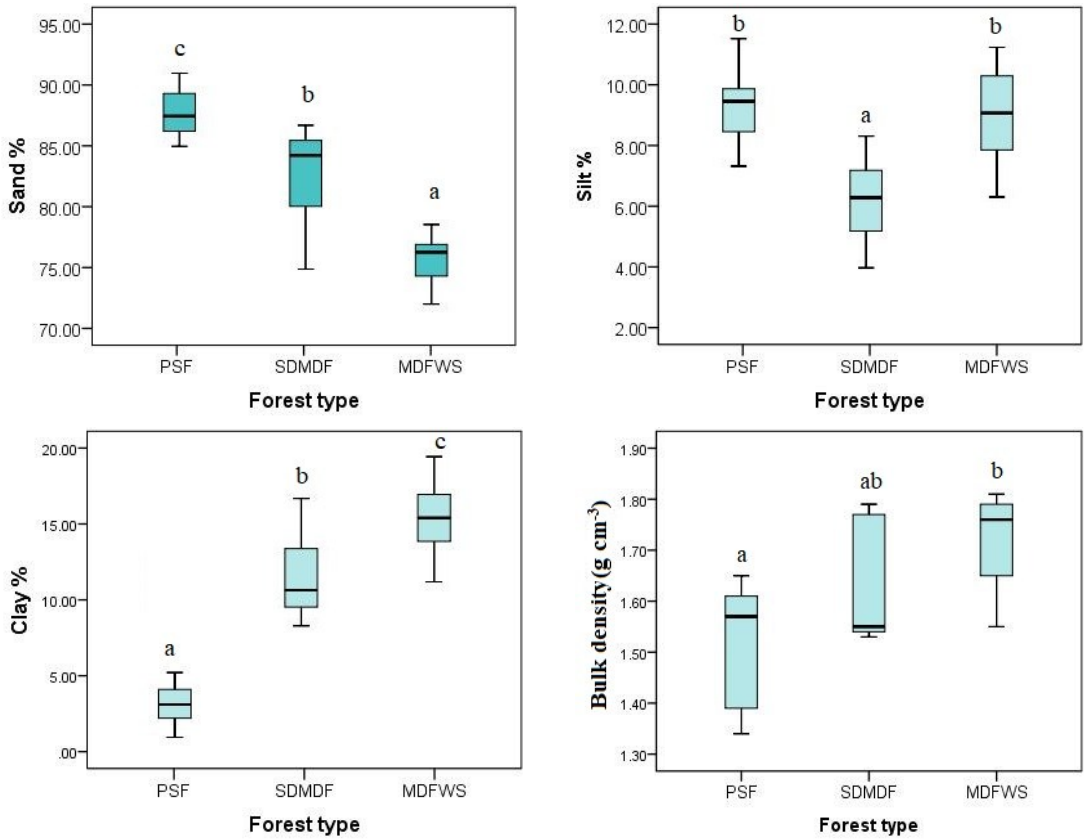
Forest type	Soil depth (cm)	pH	EC (dSm^{-1})	SOC (%)	N_{Av} (kg ha^{-1})	P_{Av} (kg ha^{-1})	K_{Av} (kg ha^{-1})
PSF	0-15	5.31 (0.17)	0.016 (0.0001)	2.37 (0.10)	129.74 (12.05)	12.90 (1.08)	459.16 (21.09)
	15-30	5.90 (0.14)	0.018 (0.0002)	1.58 (0.22)	113.80 (1.18)	8.43 (0.56)	414.35 (12.41)
	30-45	6.02 (0.07)	0.025 (0.0001)	1.06 (0.06)	100.91 (0.75)	7.60 (0.34)	386.58 (2.65)
SDMDF	0-15	5.88 (0.06)	0.019 (0.001)	1.39 (0.01)	116.92 (1.15)	10.35 (0.11)	527.15 (8.82)
	15-30	6.06 (0.03)	0.023 (0.002)	0.89 (0.05)	102.70 (0.57)	9.25 (0.14)	507.60 (4.04)
	30-45	5.92 (0.01)	0.035 (0.0001)	0.66 (0.04)	95.12 (1.10)	8.60 (0.09)	476.00 (5.57)
MDFWS	0-15	5.82 (0.06)	0.012 (0.0001)	0.84 (0.03)	94.80 (0.65)	14.08 (0.20)	581.74 (5.24)
	15-30	6.90 (0.04)	0.015 (0.0004)	0.69 (0.04)	91.64 (1.22)	12.66 (0.11)	518.85 (3.08)
	30-45	7.46 (0.02)	0.017 (0.001)	0.59 (0.02)	69.52 (1.07)	10.57 (0.03)	548.70 (6.55)
MEAN (0-45 cm)	PSF	5.74 [a] (0.52)	0.019[a] (0.01)	1.67 [c] (0.16)	114.82 [c] (13.32)	9.64 [a] (0.65)	420.03 [a] (15.06)
	SDMDF	5.95 [a] (0.05)	0.025[b] (0.001)	0.98 [b] (0.01)	104.91 [b] (0.77)	9.40 [a] (0.79)	503.58 [b] (6.21)
	MDFWS	6.73 [b] (0.06)	0.015[a] (0.001)	0.71 [a] (0.02)	85.32 [a] (0.96)	12.44 [b] (0.89)	549.76 c (12.52)
P value		0.001	0.01	0.008	0.009	0.007	0.004

Values in parenthesis indicate standard errors of mean values, values in the same column followed by same alphabet are significantly indifferent at $p<0.05$ by Duncan's multiple range tests. EC-Electrical conductivity, SOC-Soil organic carbon, N_A-available nitrogen, P_A-available phosphorus, K_A-available potash

4.3.2 Soli chemical characteristics

Perusal of data from Table 3.2 revealed that there exists significant variation (P < 01) in pH, EC, soil organic carbon, available nitrogen, available phosphorus, available potash among three forest types. Soil reaction in PSF and SDMDF was acidic in nature with pH 5.74 and 5.95 respectively. However, the soil in MDFWS was neutral in nature (pH 6.73) and significantly differed from other two forest types. The pH of soil in PSF and MDFWS was acidic at upper layer and the concentration

of H^{+} ions reduced with depth along the vertical section of the soil profile. But no specific trend in soil reaction was observed in SDMDF. The EC ranged from low 0.015dSm^{-1} in MDFWS to high 0.025dSm^{-1} in SDMDF. The SOC content ranged from 0.71 % to 1.67% and it was in the order of PSF (1.67%) > SFMDF (0.98%) > MDFWS (0.71%). The available nitrogen, available phosphorus, and available potash was high at surface layer (0-15 cm) and decreased across the profile depth and found low in the lower layer (30-45 cm). However, deviation was observed in available potash content in the soils of MDFWS community in which the lower K_{Av} was recorded at middle layer (15-30 cm depth). The available NPK ranged from 85.32 kg ha $^{-1}$ to 11.82 85.32 kg ha $^{-1}$, 9.40 kg ha $^{-1}$ kg ha $^{-1}$ to 12.44 kg ha $^{-1}$ and 420.03 kg ha $^{-1}$ to 549.76 kg ha $^{-1}$ in the three studied forest types respectively.



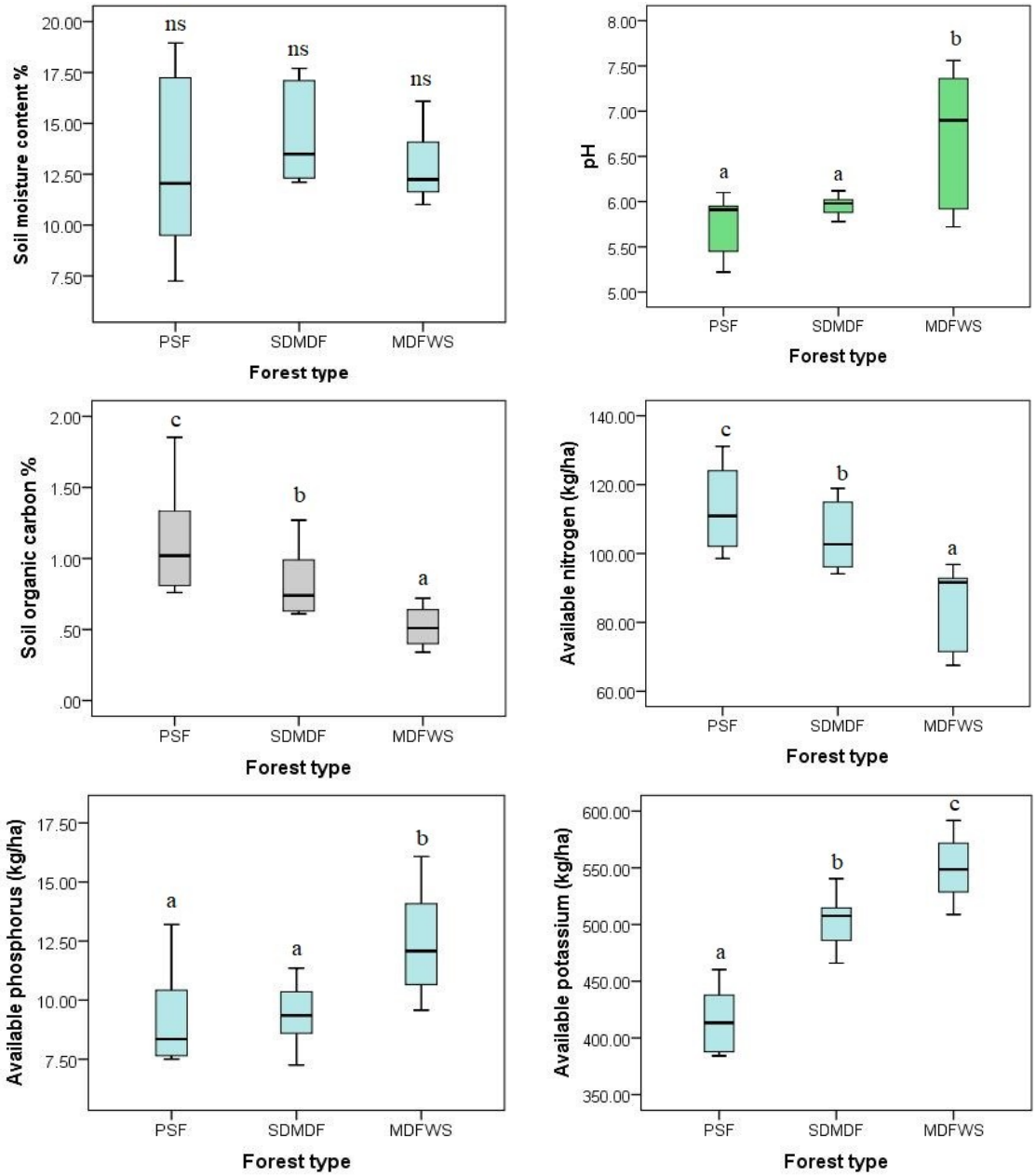


Figure 4.1 Variations in soil physic-chemical properties of three forest types

4.3.3 Pearson correlation coefficient between soil physiochemical properties

The bulk density (BD) is positively correlated with pH (0.752**) but negatively correlated with soil moisture content (SMC -.633**), soil organic matter (SOM -0.882**) and available nitrogen (N_{Av} -0.868**). Soil pH is negatively correlated with SOM (-0.842**) and NAv (-0.841**), indicating that more acidic soils tend to have higher organic matter and nitrogen content. The soil organic matter is strongly positively correlated with NAv (0.966**), showing that higher organic matter

enhances nitrogen availability in the soil. Available phosphorus (P_{Av}) has a moderate positive correlation with SMC (0.524**) but weak correlations with other attributes, suggesting phosphorus availability is slightly influenced by soil moisture. Available Potassium (KAv) is positively correlated with PAv (0.688**) but negatively correlated with SOM (-0.389*) and NAv (-.347), implying that higher organic content may reduce potassium availability (Table 4.3).

Table 4.3 Pearson correlation coefficient between soil physiochemical properties

Attributes	BD	SMC%	pH	SOM	N_{Av}	P_{Av}
SMC	-0.633**					
pH	0.752**	-0.429*				
SOM	-0.882**	0.588**	-0.842**			
N_{Av}	-0.868**	0.585**	-0.841**	0.966**		
P_{Av}	-0.202	0.524**	0.033	-0.010	0.027	
K_{Av}	0.215	0.362	0.321	-0.389*	-0.347	0.688**

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed). BD-bulk density, SMC-soil moisture content, N_{Av}-available nitrogen, P_{Av}- available phosphorus, K_{Av}-available potash

4.3.4 Anthropogenic disturbances in the study sites

The cumulative disturbance index value based on cut stump and relative score form other eight kind of disturbances revealed that, the there was no significant difference in disturbances between the three forest types. The cumulative disturbance index value in three forest types ranged between 31.00 to 38.33 and come under low disturbance category. However different levels of disturbance were observed among the study sites within each forest types. The disturbance index value in PSF ranged from 13.75 to 63.50, in SDMDF from 12.00 to 61.00 and in MDFWS from 10.25 to 64.75 (Table 4.4).

Table 4.4 Sources of anthropogenic disturbances in the studied forest sites

Forest type	Study site	Forest Road	Distance form Human settlement	Forest Fire	Grazing intensity	NTFP collection	Fire wood collection	Damage by Wild animal	Canopy cover	Cut stem	D I	DL
PSF	I	1.00	1.00	1.00	0.00	1.00	1.00	3.00	1.00	4.75	13.75	UD
	II	3.00	2.00	1.00	2.00	1.00	2.00	1.00	2.00	23.75	37.75	LD
	III	2.00	2.75	1.00	3.00	2.00	2.50	1.25	2.00	47.00	63.50	MD
SDMDF	I	0.00	1.00	1.00	0.00	1.00	0.00	2.00	1.00	6.00	12.00	UD
	II	3.00	2.00	1.00	2.00	1.00	2.00	0.00	2.00	24.25	37.25	LD
	III	3.00	3.00	1.00	3.00	2.00	3.00	1.00	2.00	43.00	61.00	MD
MDFWS	I	1.00	1.00	1.00	0.00	1.00	0.00	2.00	1.00	3.25	10.25	UD
	II	1.00	1.00	1.25	0.75	1.00	1.00	2.00	1.00	9.00	18.00	LD
	III	3.00	3.00	1.00	3.00	2.00	3.00	1.00	2.00	46.75	64.75	MD
Mean	PSF	2.00 (0.58)	1.92 (0.51)	1.00 (0.00)	1.67 (0.88)	1.33 (0.33)	1.83 (0.44)	1.75 (0.63)	1.67 (0.33)	25.17 (12.22)	38.33 (14.36)	LD
	SDMDF	2.00 (1.07)	2.00 (0.58)	1.00 (0.00)	1.67 (0.88)	1.33 (0.33)	1.67 (0.88)	1.00 (0.58)	1.67 (0.23)	24.22 (10.68)	36.75 (14.15)	LD
	MDFWS	1.67 (0.67)	1.67 (0.67)	1.08 (0.08)	1.25 (0.90)	1.33 (0.33)	1.33 (0.88)	1.67 (0.33)	1.33 (0.19)	19.67 (13.64)	31.00 (17.02)	LD
P-value	-	0.94	0.918	0.422	0.930	1.00	0.897	0.577	0.729	0.987	0.978	-

Note: PSF- Pure sal forest, SDMDF- Sal dominated moist deciduous forest, MDFWS- Moist deciduous forest without sal; DI-Disturbance index; DL-Disturbance level; Disturbance category UD- undisturbed (≤ 20%), LD-low disturbed (21-50%), MD-moderate disturbed (51-80%) and High disturbed (≥81%). Values in parenthesis are mean values ± standard error.

4.4 Discussion

The soil color in all forest types ranged from dark brown, brown, reddish brown, to dark yellowish brown. These colors were consistently observed across all three soil layers, with a gradual reduction in brownness from the surface to the sub-surface layers. The observed soil colors are attributed to the combination of iron oxide and forest litter, which resulted in shades of brown, reddish brown and dark reddish brown. The soils were derived from Khondalite group of parent material which up on weathering give rise to quartz, clay and iron oxide (Sahu and Mishra, 2005). Significant variation ($P<0.01$) in the percentage of sand, silt, clay content, bulk density and WHC among the three forest types could be attributed to the complex interplay of species composition and their littering abilities, activity of biological communities involved in the weathering of parent materials and surface relief. It was also noticed that, clay content in the soil profile increases with depth across all sites of the three forest types. This could be due to hydromorphic illuviation where dispersed clay particles are transported downward resulting in reduced porosity in the deeper layers (Parimanik *et al.,* 2020). The increase in bulk density with soil depth is caused by a decline in organic carbon levels and soil compaction along the vertical axis (Hossain *et al.,* 2015). As in other tropical forests, the soil was acidic (pH 5.74 to 6.73) due to the release of organic acids from decomposing organic matter in the upper soil layers (Narayan and Anshumali 2016). The high annual rainfall (1597 mm) in these regions also contributes to soil acidity by leaching bases from the A horizon, which are then deposited in the B horizon (Nanda *et al.,* 2008). The SOC content was in the order of PSF > SDMDF > MDFWS, likely due to the slow decomposition of sal leaves, which contribute significantly to the floor litter in PSF and SDMDF (Singh *et al.,* 2001). A direct relationship exists between SOC and total nitrogen (Cools et al., 2014), so the higher organic carbon content in PSF led to greater available nitrogen (114.82 kg ha^{-1}) compared to SDMDF (104.69 kg ha^{-1}) and MDFWS (85.32 kg ha^{-1}). Organic carbon in tropical moist deciduous forests typically ranges from 1.73% to 2.64% (Chhabra *et al.,* 2003) and in sal forests it varies from 2.42% in pure sal forests to 1.74% in mixed sal forests (Paudel and Sah,

2003). The lower organic carbon content observed in the studied forest types is likely due to the accelerated decomposition of litter in the warm-humid climatic conditions.

The available phosphorus in the soils of these forests (PSF 9.60 kg ha^{-1} to MDFWS 12.11 kg ha^{-1}) was similar to the values reported for tropical forest soils (Digal *et al.*, 2018). The lower available phosphorus in PSF and SDMDF compared to MDFWS can be attributed to the acidic soil conditions caused by the accumulation of un-decomposed or partially decayed floor litter. Another reason for the lower level of available phosphorus was the fixation by iron and aluminum oxides, which were released through the weathering of Khondalite group parent rocks (Penn and Camberato, 2019). These groups of parent rock are rich in potash bearing feldspar (potassium alluminium sillicate) and up on weathering forms potash rich soils. These parent rock groups are rich in potash bearing feldspar (potassium aluminum silicate) and upon weathering they form potash rich soils (Dash *et al.,* 2019). The available potash levels observed in this study (549.76 kg ha^{-1} in MDFWS to 420.03 kg ha^{-1} in PSF) falls within the range reported by Nayak and Sahoo (2020) for forest soils neighboring forest division.

Soil bulk density (BD) is a key indicator of soil health and structure with high BD indicating compacted soil that restricts water, air movement and root growth while low BD reflects looser more porous soil that enhances water retention, root growth and microbial activity. In this study BD is positively correlated with pH but negatively correlated with SMC, SOM and nitrogen availability. The increase in BD with pH is attributed to the reduced leaching of basic cations like Ca^{2+} and Mg^{2+} which enhances soil aggregation and compaction. Conversely, at lower pH, organic acids from decomposing litter can disperse clay particles, resulting in lower bulk density (Curtin *et al.,* 1998). Organic matter being less dense than mineral soil enhances structure, porosity and water retention. The increase water retention promotes greater pore space and reduces soil compaction. The decaying of organic matter releases nitrogen further improving soil aeration and structure (Chaudhari *et al.,* 2013). The pH is negatively correlated with SOM and available nitrogen because of slower microbial activity under acidic conditions led to reduced decay rate and organic matter accumulation. Further, acidic soils suppress microbial nitrification,

limiting the conversion of organic nitrogen into available forms, while reduced ammonia volatilization retains nitrogen in its organic state (Chadwick *et al.,* 1998). Available Phosphorus (PAv) is positively correlated with SMC because higher moisture content facilitates phosphorus availability by reducing fixation in soil minerals and increasing microbial activity that mineralizes phosphorus (Richardson *et al.,* 2009). Available Potassium (KAv) decreases with higher SOM due to increased soil porosity causing leaching while its immobilization within organic complexes further limits immediate availability (Penn and Camberato, 2019).

CHAPTER-5

PHYTOSOCIOLOGICAL INVENTORY AND VEGETATION ANALYSIS

5.1 Introduction

Phytosociological explorations provide information related to species diversity, floristic composition and community structure which are much required to classify forests into various groups and sub-groups. Apart from these floristic attributes, many derived indices and mathematical ratios also help to assess the status of natural forests in an area. In a forest, though many kinds of plant species can be found it is the trees that determine the structure and functionality of the ecosystem through resource allocation and regulation (Brockerhoff *et al.,* 2017). Understanding tree species richness and evenness is crucial to draw a picturesque of the overall biodiversity of forest. Tree stem density-diameter distribution pattern represents the population structure of forest. The population structure of individual tree species gives an insight into the regeneration behavior. The proportion of seedlings, saplings and trees in forests are indicative of population behavior and the information can be used to predict the composition of the future crop (Papilaya, 2016).

Species richness (number of species) is a key component in ecological studies that provide the overall biodiversity of the forest or region under study. There is a general acceptance that higher species richness is good for a forest but from management perspective it is not always true. Because the relationship between forest productivity and species number or functional types varies with ecosystem properties which may be linear, unimodal or no pattern (Waide *et al.*, 1999). During recent decades the influence of global climate change and accelerated species erosion has made the issue more complex. It is quite noticed that many early colonizers in a successional forest occupy substantial space and utilize a larger share of resources jeopardizing the productive capacity of valuable species. Hence it is imperative to have a comprehensive understanding of species diversity, composition and structure of forests focusing towards tree species diversity to evaluate biodiversity status (Waide *et al., 1999;* Zhang *et al.*, 2013).

Another important aspect of phytosociological analysis of vegetation is to have a lucid understanding on biodiversity – productivity relationship in a particular ecosystem. Biodiversity – productivity relationship is prime areas of research in the field of ecology today (Duffy, 2009). The main reason behind this is the accelerated biodiversity erosion in pace with variations in global climatic patterns. Climate change influences individual species behaviour at microhabitat level and at broader scale it modify community composition and ecosystem functioning. Measuring species richness and evenness variations along environmental niche axes can elucidate the link between species traits to niche occupancy and partitioning (Silvertown, 2004). Apart from climate change, deforestation and various forms of habitat degradation threatening tree species diversity in forests which ultimately cause accelerated species loss at regional and global scale. This consequently creates uncertainty in ongoing forest management practices and biodiversity conservation efforts. Thus, it is imperative to have an accurate estimate of local tree diversity in a forest and find out life history variations in constituent species. The trait-based approach (nitrogen fixing ability, growth rate, species interaction) can diligently elicit the relation between forest productivity and biodiversity of the area. Most of the forest biodiversity-productivity study use species richness as a principal factor for defining and interpreting the diversity linked productivity study. However, species evenness (relative abundance) is equally desired for explaining diversity linked ecosystem functioning in a forest (Kirwan *et al.*, 2007).

Kandhmal district being a part of the Eastern Ghats, endowed with biologically rich forest resources which spread over 67.37% of the total geographical area the district (Indian State of Forest Report 2021). As per the classification of Champion and Seth (1968) forest of the district are classified into two major sub-groups *viz*. North Indian Tropical Moist Deciduous Forest (3C) and Northern Tropical Dry Deciduous Forests (5B). In these forest sub groups moist peninsular sal (3C/C2), moist mixed deciduous forest (3C/C3), dry peninsular sal forest (5B/C1), dry mixed deciduous forest (5B/C2) and dry bamboo brakes (5B/E_9) were major forest types harbor wide range of plant species. Many valuable tree species belonging to family Dipterocarpaceae, Fabaceae, Comberataceae, Rubiaceae can be found in Tropical

Moist Deciduous Forest and Dry Deciduous Forests of the district. Sal (*Shorea robusta)* often found to dominate the canopy strata and forms pure or mixed crop depending up on site characteristics. In some places mixed deciduous forest without sal can be found. These forest resources provide food, fodder, fuel wood, fibre and other basic requirements to the fringe villagers. Major non-timber forest produce (NTFPs) collected include sal leaf, siali leaf, kendu leaf, mahua flower, mahua seed, sal seed, marking nut seed, chara seed, myrobalans (harida, bahada, anola seed), hill broom grass, wild mushrooms, siali fibers, bamboo and araguna (*Cycas circinalis*) tuber etc. Large scale collection of NTFPs, illegal timber harvesting, shifting cultivation, developmental activities and stone quarrying are among few driving forces of deforestation in the area. Limited segregated floristic explorations have been conducted to assess the status of forest wealth of the district. Hence present study aims to assess the species diversity and composition of three major forest communities *viz*. pure sal forest community (PSF), sal dominated mixed deciduous forest community (SDMDF) and moist mixed deciduous forest without sal community (MDFWS) of the district. It also emphasized to study the population structure, distribution pattern and regeneration status of major timber yielding tree species in these forests.

5.2 Materials and Methods

5.2.1 Study Area

In this present study three forest community *viz*. pure sal forest (PSF), sal dominated moist deciduous forest (SDMDF) and moist deciduous forests without sal (MDFWS) were selected within tropical moist deciduous forest of Phulbani Foret Division. Sampling units of 2.0 ha area were demarcated in three reserve forests namely Khajuripada RF, Dutimundi RF, Dakapalla-B for PSF and SDMDF. Three sampling units of 2.0 ha each were demarcated in Dakapalla-B, Khajuripada RF and Sudurukumpa RF for MDFWS community. Thus 18.0 ha of tropical moist deciduous forest (6 ha for each forest community) spreading over four reserve forest were sampled (Figure 3.1).

5.2.2 Sampling design and data collection

After through field visit to the tropical moist deciduous forest of Phulbani Forest Division, three forest communities (FC) *viz*. pure sal forest (PSF), sal dominated moist deciduous forest (SDMDF) and moist deciduous forest without sal (MDFWS) were selected. The sampling sites spread over four reserve forests (Khajuripada RF, Dutimundi RF, Dakapalla-B RF and Sudurukumpa RF) in Phulbani Forest Division harboring tropical moist deciduous forest (Figure 3.1). The sample plots of PSF and SDMDF forest community were demarcated in three reserve forests (Khajuripada RF, Dutimundi RF, Dakapalla-B) each having two-hectare area. The sample plots of MDFWS community were demarcated in Dutimundi RF, Khajuripada RF and Sudurukumpa RF each having 2.0 ha. Thus, a total of 18.0 ha [(2.0 ha sample unit x 3 RF x 2 FC) + (2.0 ha sample unit x 3 RF x 1 FC)] forest land was enumerated to study the vegetation composition of the tropical moist deciduous forest of the division. In each sample plot permanent sampling area of 250 m x 250 m size was demarcated following the protocols of Singh and Dadhwal, (2009). Within each permanent sample plot four sub-sample plots of size 31.62 m x 31.62 m were demarcated at each corner for tree species enumeration. Within each sub-sample plots two sample plots of 5 m x 5 m size were demarcated at each diagonal corner for enumerating shrubs and liana. Similarly for enumerating herbs and regenerating plants two number of 1 m x 1 m plot were demarcated within the shrub plots as shown in Figure 5.1. Hence for each forest community vegetation data were collected from 20 numbers of 31.62 m x 31.62 m size plot for trees, 40 numbers of 5 m x 5 m size plot for shrubs and lianas and 80 numbers of 1 m x 1 m size plot for herb and regenerating species.

The major sample plots were selected in such a manner that there is minimal or negligible anthropogenic disturbance and existence of homogeneity in sample plots within a particular forest type. Location of each sample plot was noted using Gramin Etrex 10x GPS device.

Field surveys and periodic data collection from various experiments were done during the period 2021-2022. Before the execution of phytosociological field explorations secondary information about the study site was collected from various

sources and measuring instruments were calibrated. Enumerated plants were identified in the field itself. Plant species that could not be properly identified in the field were photographed and relevant plant parts were collected and taken to the Forest Resource Management Laboratory at the College of Forestry, Odisha University of Agriculture and Technology for further identification. They were identified with the help of taxonomist from state biodiversity board and published literatures by Saxena and Brahmam (1996) and Mishra *et al.*, (1999) on floras of the region.

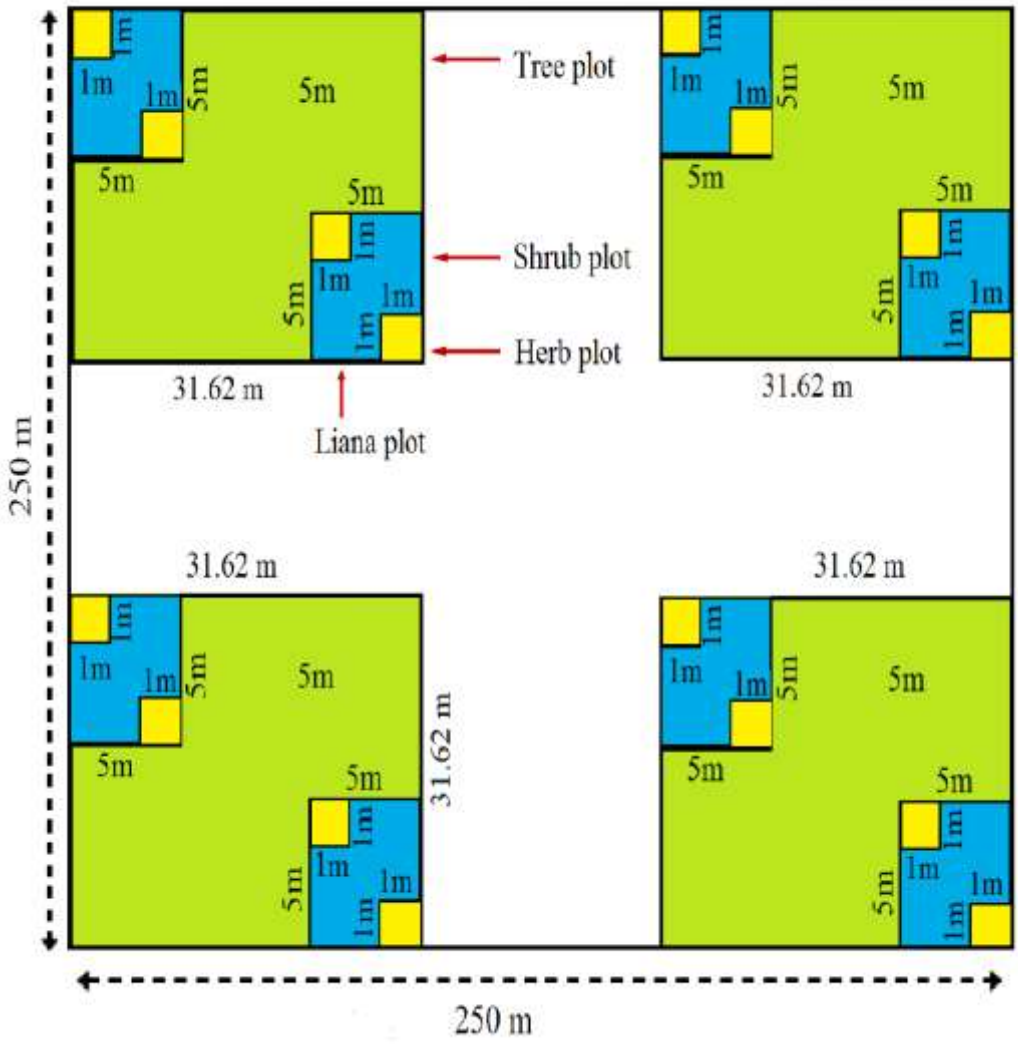


Figure 5.1 Layout of sampling plots and their respective size for tree, shrub and herbs

5.2.3 Vegetation analysis

All plant species within the sample plot were identified and measured according to their category. The diameter of tree and liana species was measured with the help of a caliper over bark at breast height (1.37 m from ground). The basal diameter of shrubs and tree sapling were measured over bark at 10 cm above the ground using a digital vanier caliper. Seedlings and herbaceous plants present within 1 x 1 m sample plot were identified and counted. Based on stem size (dbh) individuals of tree species were categorized as seedlings (dbh <3.3 cm), sapling (dbh >3.3 cm to 10.0 cm) and tree (dbh >10.0 cm) (Shankar, 2001; Jayakumar and Nair, 2013). Both sapling and seedlings were considered as regenerating plants. The relative proportion of seedling, sapling and tree category of a species was taken into account to determine its regeneration status. The regeneration status was expressed in five levels depending up on number of individuals in each category as: (a) "good" if seedling > sapling > adult; (b) 'fair' if seedling > sapling ≤ adult; (c) 'poor', if a species is having only saplings but no seedlings (may be saplings less, equal or more than adult; (d) "none', if a species survives in adult category without any seedling and saplings and (e) 'new', if a species exists in sapling or seedling category without any adult ones (Shankar, 2001). Structure of plant community in each forest was analyzed at five diameter classes 10 - 20 cm, 21 - 30 cm, 31- 40 cm 41 - 50 cm and > 51 cm. Based on abundance to frequency ratio (A/F) value distribution pattern of each species was expressed as regular (<0.025), random (0.025 – 0.05) or contagious (>0.05) (Curtis and Cottam, 1956). Various descriptive variables for plant community *viz.* density, relative density, frequency, relative frequency, basal area, relative basal area, importance value index was determined as per Mishra (1968). Diversity indices such as Shannon-Weiner diversity index (H'), Simpson's dominance index (Cd), Pielou's evenness index (E), Margalef's species richness index (R) and Sorensen's index for similarity (S) were calculated as per the following formulae.

a) $\text{Frequency } (\%) = \frac{\text{Sample plots in which species found}}{\text{Total sample plots studied}} \times 100$

b) $\text{Relative frequency } (\%) = \frac{\text{Frequency of a species}}{\text{Frequency of of all species}} \times 100$

c) $\text{Density} = \frac{\text{Number of individuals of a species}}{\text{Number of sample plots studied}}$

d) $\text{Relative Density} = \frac{\text{Number of individuals of a species}}{\text{Total number individuals of all species}}$

e) $\text{Basal area} = \pi D^2/4$

f) $\text{Relative BA} = \frac{\text{BA of desired species}}{\text{Sum of BA of all species}} \times 100$

D- dbh, $\pi = 3.141$

g) $\text{Abundance} = \frac{\text{Sum of individuals of a species}}{\text{Sum of sample plots in which the species actually found}}$

h) Importance value Index (IVI) = Relative density + Relative frequency + Relative BA

i) Species diversity index (H')

$H' = -\sum_{i=1}^{s}\left(\frac{n_i}{N}\right)\log\left(\frac{n_i}{N}\right)$ (Shannon and Weaver, 1949)

j) Species dominance index (Cd):

$Cd = \sum_{i=1}^{s}\left(\frac{ni}{N}\right)^2$ (Simpson, 1949)

k) Species evenness index (E) = H'/ln(S) (Pielou, 1966)

l) Species richness index (R) = (S - 1)/N (Margalef, 1968)

Where n_i – Sum of individuals of species i

N- Total number of individuals

S - Number of species

m) Species similarity Index (S) = 2C/(A + B) (Sorensen, 1948)

Where, C = number of species common to both the sites

A = the total number of species in stand 'A'

B = the total number of species in stand 'B'.

The species rarity was determined based on density of individuals and categorized as very rare (species having < 2 individuals ha^{-1}), rare (species having 2-10 individuals ha^{-1}), common (species having 10-20 individuals ha^{-1}), dominant (species having 20-50 individuals ha^{-1}) and Pre-dominant (species having > 50 individuals ha^{-1}) (Kadavul and Parthasarathy, 1999).

5.2.4 Statistical analysis of data

The collected field data were analyzed using MS Excel and IBM SPSS-21 software for deriving various descriptive statistical inferences. Means of various parameters were analyzed through one way ANOVA (analysis of variance) to determine the significance ($P<0.05$) of difference among three forest types and LSD post hoc test was conducted to see the significance ($P<0.05$) of difference among means of the concerned attribute. The Bray curties species similarity clustering graph was prepared by using PAST-4.03 software. Species rank abundance curve was prepared following the steps of Magurran and Mc Gill, (2011).

5.3 Results

5.3.1 Floristic composition and species diversity

The floristic analysis revealed presence of 168 numbers of plant species (138 genera and 55 families) out of which 61 were trees, 26 shrubs, 8 lianas and 46 herbs (Table 5.1). The number of tree species was recorded high in mixed deciduous forest without sal (MDFWS) type (51 number of tree species belonging to 41 genera and 22 families) followed by sal dominated moist deciduous forest (SDMDF) type (39 number of tree species belonging to 36 genera and 19 families) and pure sal forest (17 number of tree species belonging to 17 genera and 11 families) (Figure 5.2).

Table 5.1Distribution of plant species (numbers) in sampled sites of PSF, SDMDF and MDFWS

Forest type	Sites	Tree	Shrub	Liana	Herb	Total
PSF	S-I	13	24	4	21	62
	S-II	10	17	5	22	54
	S-III	8	17	5	26	56
	Over all	17 (G17, F11)	30 (G29, F20)	5 (G5, F4)	26 (G32, F25)	78 (G75, F42)
SDMDF	S-I	28	24	3	25	80
	S-II	20	22	3	30	75
	S-III	21	18	2	32	73
	Over all	39 (G36, F19)	31 (G29, F20)	3 (G3, F2)	32 (G23, F18)	98 (G71, F40)
MDFWS	S-I	44	22	5	28	99
	S-II	41	19	7	34	101
	S-III	36	19	8	41	104
	Over all	51 (G41, F22)	26 (G25, F17)	8 (G8, F5)	46 (G44, F24)	130 (G86, F48)
∑All forest types		61 (G51, F24)	40 (G37, F22)	8 (G8, F6)	59 (G53, F28)	168 (G138, F55)

Note: G- Genus, F- Family

The familial distribution of tree species revealed that out of the 11 families present in PSF Dipterocarpaceae was the dominant family with high FIV of 178.99 followed by Anacardiaceae (36.62), Fabaceae (17.83) and Combretaceae (17.59). These four families constitute about 83.68% of the species composition in the forest. As far as species richness is concerned Anacardiaceae family was the most conspicuous family with three species and three genera followed by Phyllanthaceae, Fabaceae and Dipteracarpaceae having two species and genera each. The rest of the six families (Burseraceae, Ebenaceae, Lecythidaceae, Malvaceae, Sapindaceae and Sapotaceae) were having single genera and species.

Out of the nineteen families present in SDMDF Dipterocarpaceae was the dominant family with FIV of 95.87 followed by Phyllanthaceae (32.84), Anacardiaceae (31.12) and Combretaceae (25.97). These four families constitute about 61.97% of the species composition in the forest. As far as species richness is

concerned nine families were singleton, five families were doubleton and rest five families were having more than three species. The family Rubiaceae was the most conspicuous family with five species and five genera.

Out of the 22 families present in MDFWS Combretaceae was the dominant family with FIV of 54.34 followed by Fabaceae (51.71), Anacardiaceae (29.06), Phyllanthaceae (24.36) and Rubiaceae (22.15). These five families constitute about 60.53% of the species composition in the forest. As far as species richness is concerned nine families were singleton, two families were doubleton and rest families were having more than three species. The family Fabaceae was the most conspicuous family with nine species and seven genera (Appendix 5).

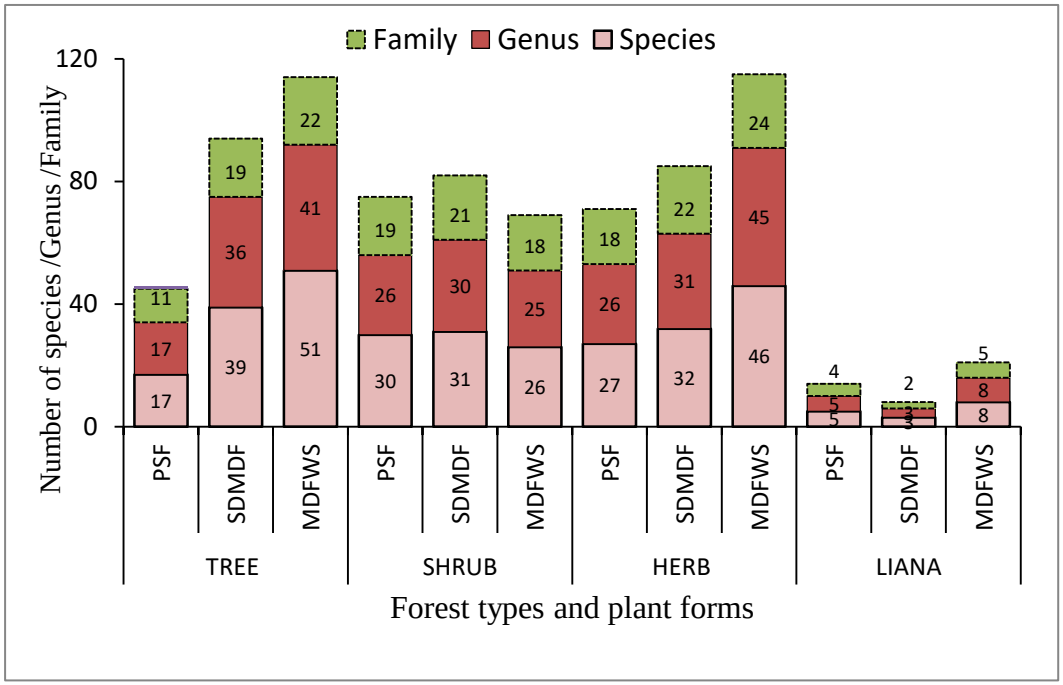


Figure 5.2 Diversity of tree, shrub, herb and liana species in PSF, SDMDF and MDFWS

Based on the importance value index (relative frequency + relative density + relative basal area) it was found that *Shorea robusta* (IVI 170.43) was the dominant tree species in PSF and five major associate species were *Semecarpus anacardium* (IVI 15.96), *Cleistanthus collinus* (IVI 13.43), *Buchanania lanzan* (IVI 13.11), *Terminalia alata* (IVI 12.42) and *Pterocarpus marsupium* (IVI 10.34) **(**Appendix 1.1**)**. In SDMDF as obvious *Shorea robusta* (IVI 87.65) was dominant in the

community and five major associate species were *Cleistanthus collinus* (IVI 18.94), *Madhuca latifolia* (IVI 13.02), *Buchanania lanzan* (IVI 12.19), *Schleichera oleosa* (IVI 11.31) and *Lannea coromandelica* (IVI 10.0) **(**Appendix 1.2**)**. In MDFWS community Terminalia *alata* (IVI 19.04) was the dominant species and five major associates were *Diospyros melanoxylon* (IVI 15.73), *Anogeissus latifolia* (IVI 15.39), *Mitragyna parvifolia* (IVI 13.98), *Schleichera oleosa* (IVI 13.93) and *Cleistanthus collinus* (IVI 12.25) **(**Appendix 1.3**)**.

Comparison of Margalef's species richness index, Shannon–Weiner diversity index, Simpson's dominance index and Pielou's evenness index for tree species in PSF, SDMDF and MDFWS showed significant difference ($P<0.05$) among the forest types. The species richness index ranged from 2.82 to 6.49, diversity index from 1.11 to 3.47, dominance index from 0.04 to 0.57 and evenness index from 0.41 to 0.96. The species richness was high in MDFWS (6.49) followed by SDMDF (4.79) and PSF (2.82). The Shannon–Weiner diversity index was high in MDFWS (3.47) followed by SDMDF (2.55) and PSF (1.11). Simpson's dominance index was high in PSF (0.57) followed by SDMDF (0.15) and MDFWS (0.04). The Pielou's evenness index was high in MDFWS (0.96) followed by SDMDF (0.83) and PSF (0.41). No significant difference in diversity indices for shrub species was observed among the three forest types. For liana species significant difference was observed with respect to evenness index only ($P < 0.003$). As far as herb species diversity was concerned significant difference was observed in species richness index only **(**Table 5.2**).**

The analysis of species dominance from rank-abundance curve of three forest types revealed higher equitability or lower dominance in the MDFWS community and dominance of single species (*Shorea robusta*) in other two forest types (SDMDF and PSF). From the flatness of rank-abundance curve it is inferred that the equitability pattern was in the order MDFWS > SDMDF > PSF (Figure 5.3 and 5.4).

Table 5.2 Variations in density, basal area and floristic diversity indices between three forest types

Floristic attributes	Growth form	PSF	SDMDF	MDFWS	*F value*	*P*-value
Density (ha^{-1})	Tree	545.00 ± 40.93^{a}	609.67 ± 81.84^{a}	746.75 ± 81.00^{b}	10.89	0.045
	Saplings	948.67 ± 129.07^{b}	921.00 ± 100.37^{b}	681.50 ± 66.50^{a}	1.44	0.048
	Shrub	9300.00 ± 1429^{ns}	10183.33 ± 2066^{ns}	9325.00 ± 2875^{ns}	0.06	0.67
	Liana	126 ± 28.42^{a}	244 ± 19.34^{b}	295 ± 21.64^{b}	30.18	0.002
	Herb	71250 ± 4542.43^{a}	82500 ± 4241.78^{b}	118625 ± 3250.0^{c}	0.018	0.024
Basal area ($m^{-2}\,ha^{-1}$)	Tree	21.82 ± 4.17^{a}	17.83 ± 3.11^{a}	27.15 ± 4.90^{b}	8.24	0.047
	Saplings	2.77 ± 0.32^{a}	3.59 ± 0.69^{b}	4.10 ± 1.85^{c}	5.55	0.41
	Shrub	7.63 ± 0.62^{ns}	7.87 ± 1.22^{ns}	9.13 ± 2.55^{ns}	0.31	0.75
	Liana	0.67 ± 0.41^{ns}	0.79 ± 0.17^{ns}	1.31 ± 0.22^{ns}	2.75	0.34
Margalef's species richness index	Tree	2.82 ± 1.14^{a}	4.79 ± 0.49^{ab}	6.49 ± 0.75^{b}	5.99	0.04
	Shrub	3.92 ± 0.54^{ns}	3.77 ± 0.49^{ns}	4.28 ± 0.25^{ns}	0.24	0.79
	Liana	7.01 ± 0.26^{a}	5.73 ± 0.18^{b}	5.52 ± 0.33^{b}	52.81	0.002
	Herb	5.01 ± 0.12^{a}	5.34 ± 0.23^{a}	8.46 ± 0.02^{b}	100.32	0.000

Floristic attributes	Growth form	PSF	SDMDF	MDFWS	*F value*	*P*-value
Shannon –Weiner diversity index	Tree	1.11 ± 0.24^{a}	2.55 ± 0.09^{b}	3.47 ± 0.16^{c}	38.67	0.001
	Shrub	2.74 ± 0.15^{ns}	2.70 ± 0.22^{ns}	2.80 ± 0.11^{ns}	0.06	0.94
	Liana	1.14 ± 0.21^{ns}	0.89 ± 0.11^{ns}	1.66 ± 0.17^{ns}	1.68	0.28
	Herb	3.20 ± 0.12^{ns}	3.24 ± 0.13^{ns}	3.75 ± 0.01^{ns}	5.15	0.62
Simpson's dominance index	Tree	0.57 ± 0.09^{a}	0.15 ± 0.02^{b}	0.04 ± 0.001^{b}	20.56	0.004
	Shrub	0.08 ± 0.02^{ns}	0.09 ± 0.03^{ns}	0.08 ± 0.02^{ns}	0.13	0.88
	Liana	0.40 ± 0.01^{ns}	0.47 ± 0.03^{ns}	0.25 ± 0.01^{ns}	7.88	0.28
	Herb	0.04 ± 0.01^{ns}	0.15 ± 0.11^{ns}	0.03 ± 0.001^{ns}	0.92	0.46
Pielou's evenness index	Tree	0.41 ± 0.04^{a}	0.83 ± 0.04^{b}	0.96 ± 0.02^{b}	69.16	0.000
	Shrub	0.91 ± 0.03^{ns}	0.89 ± 0.05^{ns}	0.90 ± 0.04^{ns}	0.04	0.96
	Liana	0.37 ± 0.04^{c}	0.29 ± 0.02^{b}	0.54 ± 0.01^{a}	22.26	0.003
	Herb	0.96 ± 0.02^{ns}	0.97 ± 0.01^{ns}	0.97 ± 0.01^{ns}	0.16	0.85

Note: Values are mean ± standard error, Values in the same row (forest types) followed by different alphabet are significantly differing at $P < 0.05$ by Duncan's multiple range tests.

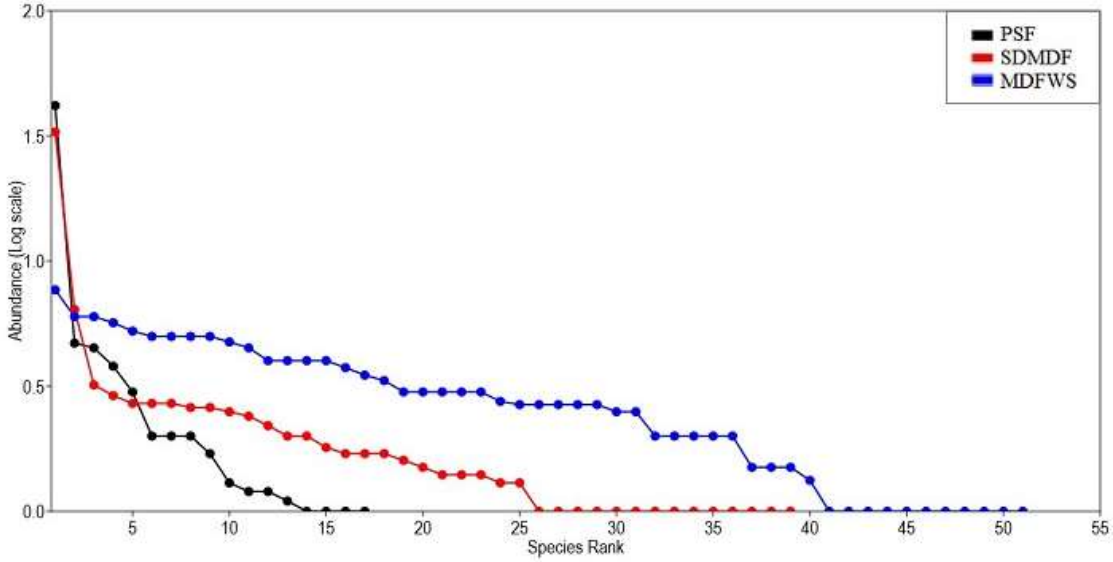
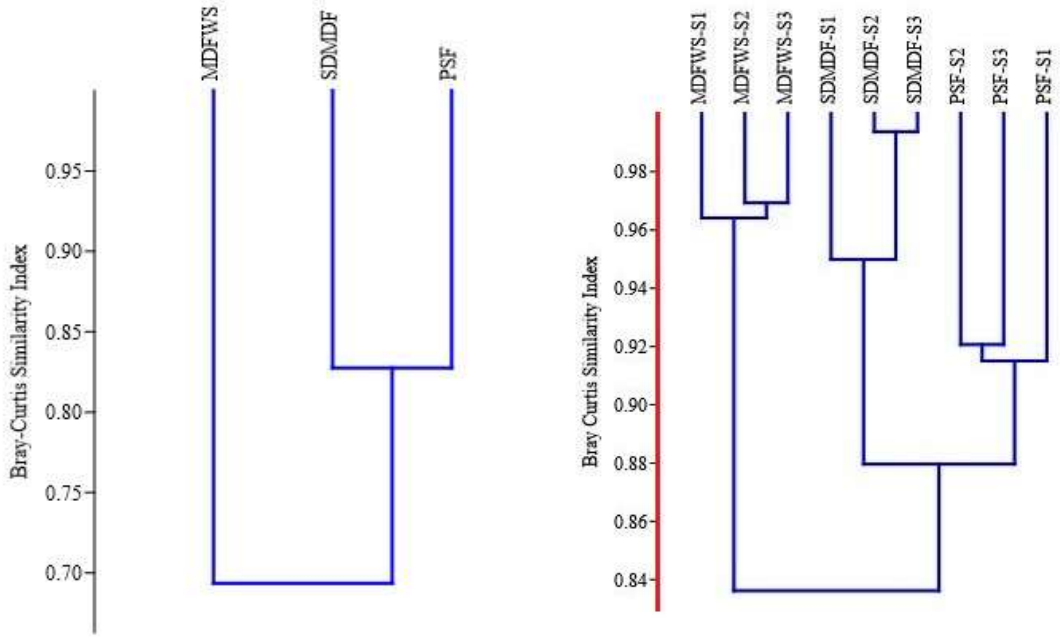


Figure 5.3 Rank-abundance curves for tree species in MDFWS, SDMDF and PSF



A. **B.**

Figure 5.4 Bray Curtis cluster dendrogram (single-linkage) for trees (≥10cm DBH), A). among forest types PSF- pure sal forest, SDMDF- sal dominated moist deciduous forest, MDFWS- moist deciduous forest without sal type; B), among sites S1-site I, S2-site II and S3-site III

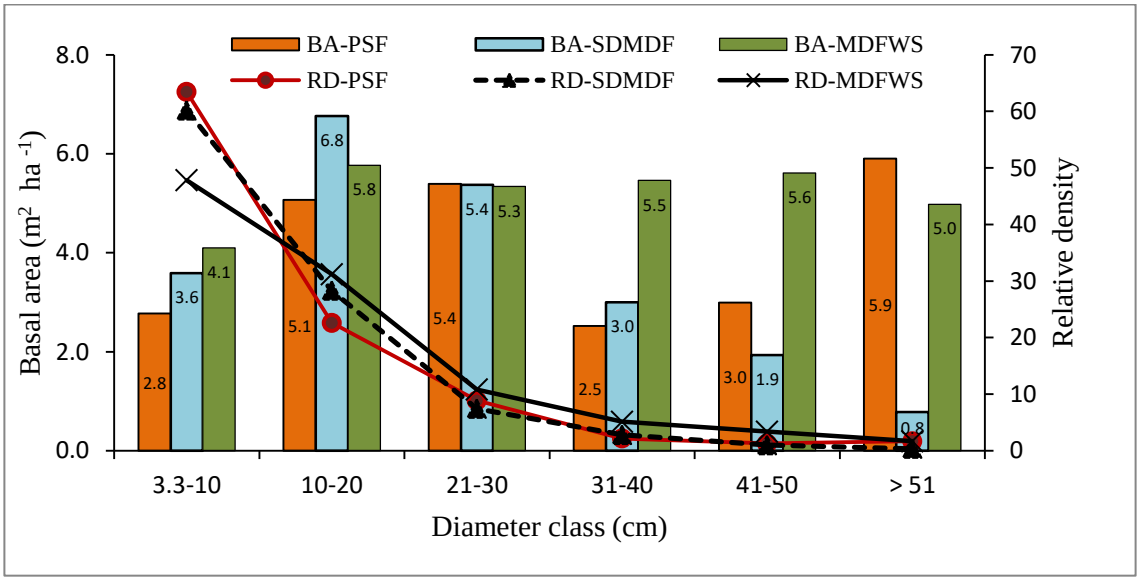
5.3.2 Forest structure and distribution pattern of tree species

The density values of trees, saplings, lianas and herbs were significantly varied among the three forest types. However, shrub density did not show any significant difference among the forest types. Comparison of the LSD post hoc test results between forest types revealed that tree density in MDFWS was significantly differed from SDMDF and PSF. The order of tree density in the three forest types was MDFWS (746.75 trees ha^{-1}) > SDMDF (609.67 trees ha^{-1}) > PSF (545.00 trees ha^{-1}). The basal area (BA) values of trees also followed a similar trend as density values within and between forest types but the difference in BA values of saplings were statistically insignificant (Table 5.2).

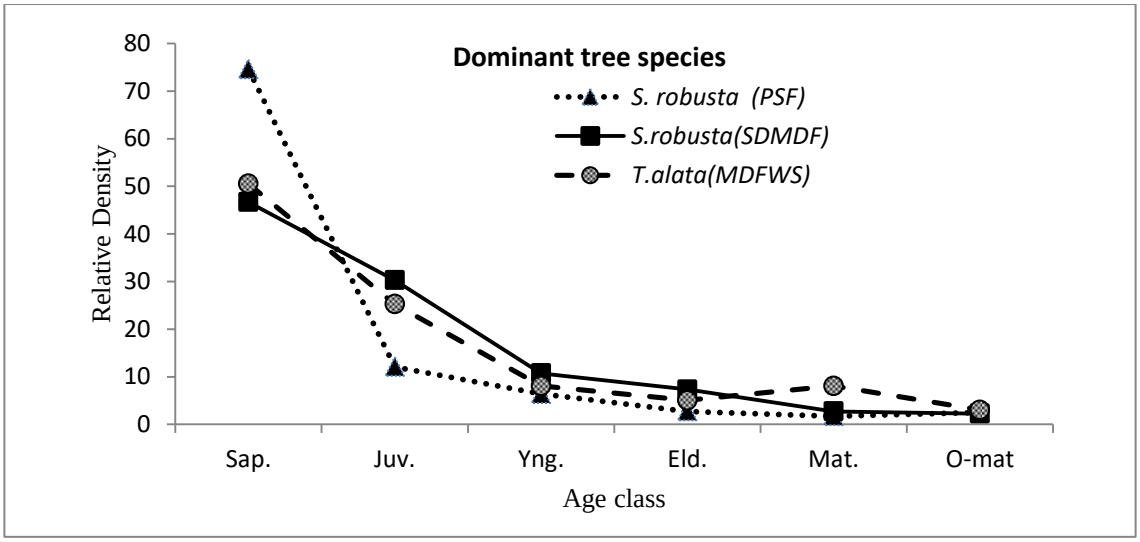
Relative density distribution of trees across various diameter classes indicated higher density in lower diameter classes (3.30 - 10.00 cm) and gradually decreased with increasing diameter classes in all the three forest types. Basal area distribution showed a mixed trend within and among forest types. In PSF the basal area was high in over mature (>51 cm) and young (21-30 cm) diameter classes but in SDMDF and MDFWS types BA was found high in juvenile (10-20cm) class. It was observed that basal area distribution among all diameter classes in MDFWS have a more or less uniform distribution (>5.0 m^2 ha^{-1}). In PSF the relative density and BA decreased gradually with increase in diameter classes from juvenile to over mature classes (Figure 5.5).

Tree species rarity classification based on density (individuals per hectare of forest) revealed that about 39 -51% of trees are rare followed by common (31-47%) and dominant (0-27%) category. Out of the recorded 17 species in pure sal forest, 8 (47%) species belonged to rare category, 7 (41%) species common category, one species (6%) each in dominant and very rare category. Out of the 39 species in sal dominated moist deciduous forest, in all the forest types 20 (51%) species belonged to rare category followed by 12 (31%) species in common category, 3 (8%) species in very rare category and 2 (5%) species each in dominant and predominant category. Similarly, out of the 51 species recorded in moist deciduous forest without sal community 20 (39%) species

belonged to rare category followed by 16 (31%) species in common category, 14 (27%) in dominant category and one species in very rare category (Table 5.3 and Figure 5.6).



A



B

Figure 5.5 Relative density and basal area distribution among various diameter classes in PSF, SDMDF and MDFWS. A. All species, B-Dominant trees. Diameter class sapling: 3.3-10.0 cm, juvenile: 10-20 cm, young: 21-30 cm, elder: 31-40 cm, mature: 41-50 cm, over mature: >51 cm

Table 5.3 Density based rarity classification of tree species (numbers) in three forest types

Density based rarity classification	Forest types		
	Pure sal forest	Sal dominated moist deciduous forest	Moist deciduous forest without sal
Very Rare (< 2 individuals ha $^{-1}$)	1	3	1
Rare (2-10 individuals ha $^{-1}$)	7	20	20
Common (10-20 individuals ha $^{-1}$)	8	12	16
Dominant (20-50 individuals ha $^{-1}$)	0	2	14
Pre-dominant (> 50 individuals ha $^{-1}$)	1	2	0
Total	17	39	51

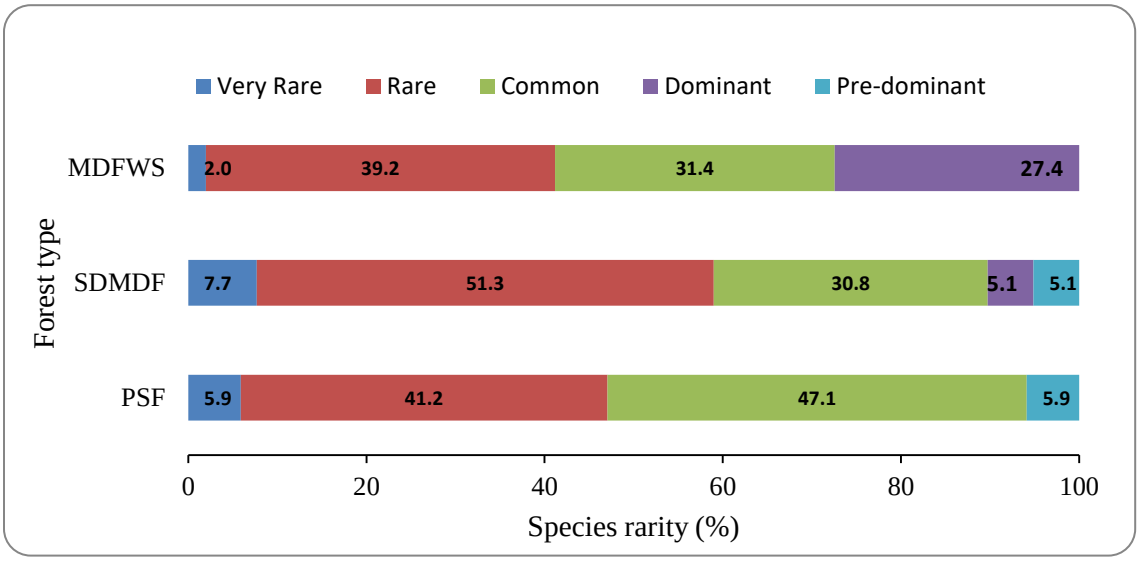


Figure 5.6 Percentage rarity distributions of tree species in PSF, SDMDF and MDFWS

Population distribution pattern in three forest types revealed that majority of tree species exhibited contagious (37%) distribution pattern followed by regular (33%) and random (30%) distribution pattern. In pure sal forest out of 17 tree species 8 (47%) species exhibited random distribution pattern followed by 6 (35%) species contagious and 3 (18%) species regular distribution pattern. Out of the 39 tree species in sal

dominated moist deciduous forest 16 (41%) species exhibited regular distribution pattern followed by 13 (33%) species random and 10 (26%) species contagious distribution pattern. Similarly in moist deciduous forest without sal type out of 51 tree species 24 (47%) species exhibited contagious distribution pattern followed by 16 (31%) species regular and 11 (22%) species random distribution pattern. As far as shrub species is concerned majority of species exhibited contagious (60%) distribution pattern followed by random (31%) and regular (9%) distribution pattern. The distribution pattern in herb species exhibited similar trend as that of shrub species (Table 5.4 and Figure 5.7).

Table 5.4 Distribution pattern of plants in PSF, SDMDF and MDFWS

Distribution Pattern	Tree			Shrubs			Herbs		
	PSF	SDMDF	MDFWS	PSF	SDMDF	MDFWS	PSF	SDMDF	MDFWS
Regular	3	16	16	5	2	1	0	1	1
Random	8	13	11	8	10	9	12	8	12
Contagious	6	10	24	17	19	16	22	26	37
Total	17	39	51	30	31	26	34	35	49

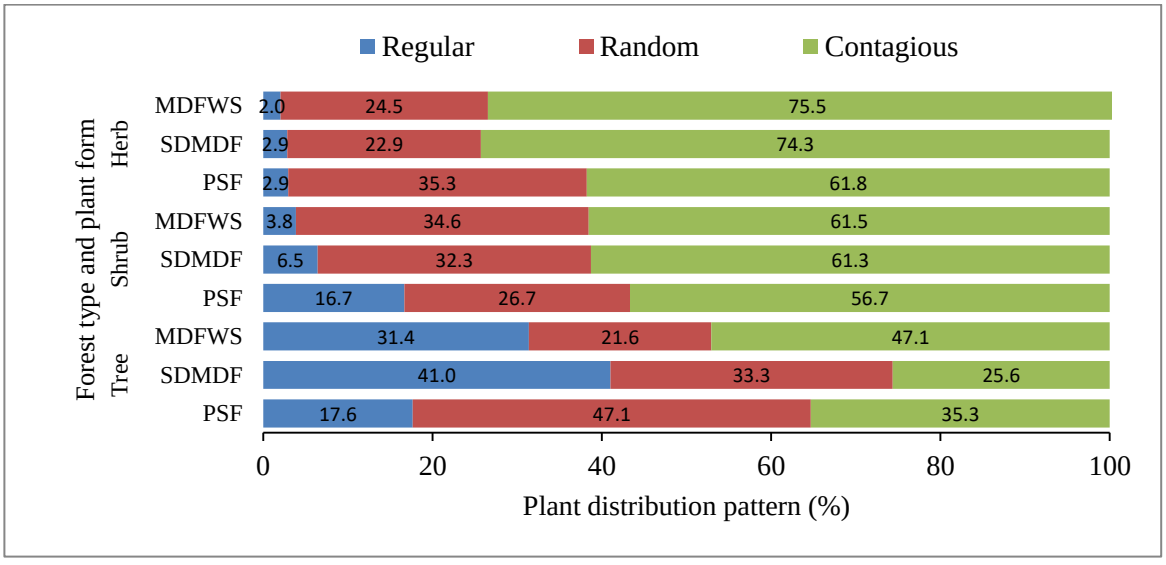


Figure 5.7 Percentage of population distribution pattern plants in PSF, SDMDF and MDFWS

5.3.3 Regeneration status of tree species

The overall regeneration status of trees in all three forest types was fair. In pure sal forest 15 species were found regenerating which constitutes to 88.21% of the total population and 27 new colonizing species recorded in the forest. Out of the 15 regenerating species seven species (41.18%) exhibited fair regeneration pattern followed by four species (23.53%) with good regeneration and four species (23.53%) poor regeneration pattern (Figure. Two species namely *Garuga pinnata* and *Terminalia bellirica* were found not regenerating (Appendix 1.1). In sal dominated moist deciduous forest 38 species were found regenerating which constitutes to 97.44% of the total population and 28 new colonizing species recorded in the forest. Out of the 38 regenerating species 23 (58.97%) species exhibited fair regeneration pattern followed by 13 (33.33%) species with good regeneration and two (5.13%) species poor regeneration pattern. One species namely *Holoptelea integrifolia* was found not regenerating (Appendix 1.2). In moist deciduous forest without sal type 46 species were found regenerating which constitutes to 90.20% of the total population and 14 new colonizing species recorded in the forest. Out of the 46 regenerating species 20 (39.22%) species exhibited fair regeneration pattern followed by 17 (33.33%) species with good regeneration and 9 (17.65%) species poor regeneration pattern (Table 5.5 and Figure 5.8). Five species namely *Ficus hispida, Phyllanthus emblica, Pterospermum xylocarpum, Schrebera swietenioides* and *Strychnos potatorum* did not regenerate (Appendix 1.3).

Table 5.5 Regeneration status of trees in three forest types

Tree classification	Pure Sal Forest	Sal Dominated Moist Deciduous Forest	Moist Deciduous Forest Without Sal
Good	4	13	17
Fair	7	23	20
Poor	4	2	9
None	2	1	5
New arrival	27	28	14
Total	44	67	65

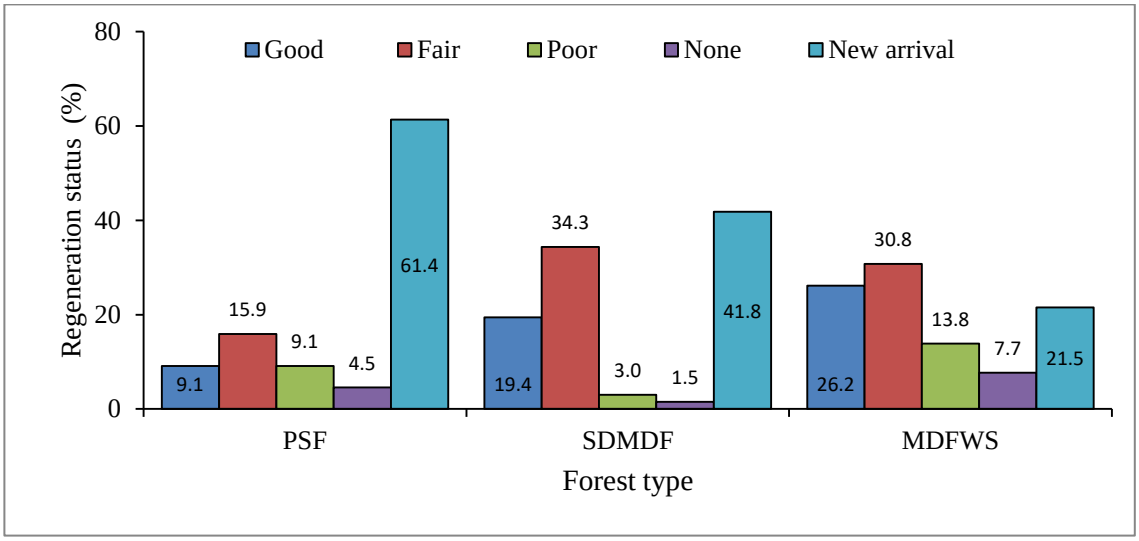


Figure 5.8 Regeneration statuses of trees in PSF, SDMDF and MDFWS

Seedling density was highest in MDFWS (135938 seedlings ha^{-1}) followed by PSF (113958 seedlings ha^{-1}) and SDMDF (112125 seedlings ha^{-1}). The sapling density was highest in PSF (949 saplings ha^{-1}) followed by SDMDF (921 saplings ha^{-1}) and MDFWS (681 saplings ha^{-1}) (Table 5.6).

Table 5.6 Density (number ha^{-1}) of tree, sapling and seedlings in PSF, SDMDF and MDFWS

Plant category	PSF	SDMDF	MDFWS
Tree (dbh > 10 cm)	545	610	744
Sapling (dbh 3.3 - 10 cm)	949	921	681
Seedling (dbh < 3.3 cm)	113958	112125	135938
Total	115452	113656	137363

5.4 Discussion

Phytosociological inventory provides lucid information on vegetation-environment relationships, which aims to predict the diversity pattern of any ecosystem. It also assists biologists in identifying and quantifying ecological status of economically valuable species as well as the species of special concern such as rare, endangered and endemic species. Increased menace of invasive alien species jeopardizing growth of

endemic and native species is also a major concern at present. Numerical assessment of alien invasive plants is also required for increasing tropical forest productivity (Richardson and Rejmánek, 2011). Therefore, quantitative inventory has a significant role in framing micro level planning for conservation and management of tropical forests.

High species diversity in tropical forests is attributed to warm climate, abundant rainfall, high rate of nutrient turnover, where even subtle shifts in micro habitats influence a substantial variation in species distribution. Phyto-diversity in tropical forests range from as high as 307 sp. ha^{-1} in Amazonian Ecuador forests (Valencia *et al.*, 1994) to low 24 sp. ha^{-1} in Amazon Negro River floodplains (Householder *et al.,* 2021). The overall measurable value of 169 plant species (trees 61, shrubs 40, lianas 8 and herbs 60) in 18.0 hectare of studied forest area of Kandhamal district reflects a moderate level of diversity. The species diversity is well comparable with the species richness of 162 sp. ha^{-1} in tropical humid forests of South East Asia (Sullivan *et al*., 2017), 134 species in tropical moist deciduous forests of Tripura (Majumdar *et al.,* 2014) and 187 species in tropical dry deciduous forest of Boudh district (Sahu *et al.,* 2007). The recorded plant diversity in tropical moist deciduous forest (TMDF) of the Eastern Ghats is much higher than the reported species richness of 54-72 plant species in TMDF of Shiwalik Himalayas (Gautam *et al*., 2016), sal dominated TMDF of Assam (Dutta and Devi, 2013) but somehow lower than species richness (388 sp.) of Nayagarh forest division (Sahoo *et al.,* 2020a) and Similipal biosphere reserve (266 sp.) of Odisha having moist deciduous forest (Mishra *et al.,* 2012). Site-specific edaphic factors, such as slope gradient, soil texture, moisture level and reaction are some crucial factors influencing the reduced diversity of plants in this area. Variation in species richness was observed among PSF, SDMDF, and MDFWS. These communities differed in terms of species composition, canopy stratification and stockings. The PSF and SDMDF communities are intermixed at the foothills, where they share similar edaphic conditions, while the MDFWS found in relatively moisture areas of the Eastern Ghats.

In PSF and SDMDF *Shorea robusta* was predominant in the community with respect to density (>50 ind. ha^{-1}) as well as in the canopy stratification (IVI 170.43 and 87.65 respectively) but in MDFWS none of the species was found predominant in the community though *Terminalia alata* was having high IVI (16.87 to 21.21). Top five families sharing high species diversity (29-41%) in the studied forest types were Fabaceae, Anacardiaceae, Combretaceae, Phyllanthaceae and malvaceae. In MDFWS community, Fabaceae (9species, FIV 51.71) and Combretaceae (5 species, FIV 54.34) were taxonomically and quantitatively dominant families. The family Rubiaceae (5 species) was taxonomically dominant in SDMDF community but quantitatively Combretaceae (FIV 95.87) was dominant. The prevalence of leguminous tree species (Fabaceae) in tropical moist forests of Eastern Ghats was reported by Sahoo *et al.,* (2017), Kadavul and Parthasarathy (1999). The Fabaceae is considered one of the most successful groups of flowering plants because of versatile adaptability found abundant in neotropical forests of the world (Sahu *et al.,* 2012c; Martin and Aber, 1997). The number of families having single species ranged from 6 to 9 which is could be ascribed to competitive disadvantage, ecological specialization and regeneration limitation. The common associates sharing upper canopy strata with sal in PSF were *Schleichera oleosa, Careya arborea, Pterocarpus marsupium* and *Syzygium cumini* in moist localities but in drier sites *Diospyros melanoxylon, Madhuca latifolia*, *Buchanania lanzan* were found prevalent. Similarly, in SDMDF abundance of *Buchanania lanzan*, *Anogeissus latifolia, Careya arborea, Lagerstroemia parviflora* can be noticed in the upper canopy layer of the forest. In all the forest types *Cleistanthus collinus* is found abundantly in varying degrees sharing a considerably to the density and basal area of the forests. Prevalence of *Cleistanthus collinus* in sal dominated forests is reported earlier (Raj, 2018).

Structure and composition of tropical forests are determinant of edapho-climatic factors, anthropogenic disturbances and resilience power of communities to the activities of disturbing agents. For describing various ecological processes and functioning in a forest ecosystem it is very much essential to have a proper understanding on its structure. Tree density and basal area are indicative of status of community in a forest.

Tree density of (≥ 10cm dbh) in PSF (490-625 stem ha^{-1}), SDMDF (473-756 stem ha^{-1}) and MDFWS (663-831 stem ha^{-1}) was well comparable with the reported tree densities of 404-1029 trees ha^{-1} in moist sal forests of Doon Valley (Gautam *et al.*, 2014), 484 trees ha^{-1} in sal dominated forests of the eastern Himalayas (Shankar, 2001) and 355-741 tree ha^{-1} in moist deciduous forests of Nayagarh forest division (Sahoo *et al.*, 2017). However, it is lower than the stand density of 1150-1920 trees ha^{-1} in sal forests of the central Himalaya (Pande, 1999). The total stand basal area of trees recorded in PSF (16.66-30.12 m^2 ha^{-1}), SDMDF (11.69-21.70 m^2 ha^{-1}) and MDFWS (22.25-32.05 m^2 ha^{-1}) were well comparable with the basal area range found in similar forest types of the region (Sahoo *et al.*, 2020b). Stand basal area in tropical forests of the Indian region vary from low 1.30 m^2 ha^{-1} in the Vindhyan Hills (Sagar *et al*., 2003) to a high of 98.60 m^2 ha^{-1} in Namdapha National Park (Nath *et al*., 2005). Stand basal area of moist tropical forests of Nayagarh division vary from 7.76 to 31.61 m^2 ha^{-1} (Sahoo *et al.*, 2017), Similipal biosphere reserve from 18.30 to 39.73 m^2 ha^{-1} (Mohanta *et al.*, 2020), and Mahendragiri hills from14.32 to 27.13 m^2 ha^{-1} (Khadanga *et al.*, 2023). The observed variation in stand basal area (11.69-32.05 m^2 ha^{-1}) among study sites as well as forest types in this present study is primarily due to selective harvesting of trees from higher girth classes for timber, girdling of trees for fire wood collection, unscientific pollarding of trees for NTFP collection. A similar pattern in stand density and basal area resulting from human-induced disturbances has been reported previously (Rao *et al*., 1990; Tripathi and Shankar, 2014; Opuni-Frimpong *et al*., 2021). The reverse "J" shaped DBH-density distribution curve in all three studied forest types (Figure 5.4 A and B) indicates towards a stable, climax and expanding vegetation (Mishra *et al.*, 2005). However high tree density in lower age group is attributed to repeated occurrences disturbances, rapid colonization and attrition of gaps in the forest.

Species diversity is an important attribute of natural community influence functioning of ecosystem. It has been observed that MDFWS is fairly rich in species number as compared to the SDMDF and PSF in tree, liana and herb strata (Table 5.1). The number of tree species in MDFWS (51) and SDMDF (36) is thrice and twice more

than PSF (17). The observed number of tree species in this part of moist deciduous forest is low as compared to the tree diversity in moist sal forests of Eastern Himalaya (Kushwaha and Nandy, 2012), Khasi hill sal forests of Meghalaya (Tripathy and Sankar 2014) but high as compared to the sal forests of central Himalaya in Darjeling (Shankar, 2001). The observed low number of tree species as compared to moist deciduous forests of Nayagarh district (Sahoo *et al.,* 2017), and dry deciduous forests Boudh district (Sahu *et al.,* 2007) was due to variation in sampling size, location and edaphic characteristic of the study sites. Biodiversity indices are frequently used in floristic studies to normalize species diversity and richness across various habitats, enabling effective comparisons. A higher value of these indices signifies a greater richness of species. It is well established that high tree abundance is essential for robust forest ecosystem functioning. They are fundamental to the structure of forests and influence both living organisms and environmental factors. Consequently, higher diversity index values reveal a forest with greater tree species diversity. The Shannon-Weiner index (SWI) for trees ranged from 1.11 (PSF) to 3.47 (SDMDF) was within the reported range for tropical forests (0.80 to 4.86) of Indian sub-continent (Devi *et al.,* 2018; Parthasarathy *et al.,* 1992). High tree diversity per unit area in MDFWS as compared to SDMDF and PSF was ascribed to presence of synusiae, variations in soil moisture content, nutrient turnover rate and elevation. The observed Simpson's dominance index (SDI) value ranged between 0.04-0.57 for trees, 0.08-0.09 for shrubs, 0.25-0.47 for lianas and 0.03-0.15 for herbs is well comparable with the reported dominance value range from 0.03 to 0.92 for Indian tropical forests (Joshi *et al.,* 2023; Kushwaha and Nandy, 2012). The SDI value observed in PSF was towards higher side due to the dominance of single species sal and towards lower side in SDMDF due sharing of dominance by more than one species (Figure 5.1). The Pielou's evenness index value for trees layer ranged between 0.41 to 0.96 are in line with the evenness values (0.37 to 0.91) reported for similar forest types of the region (Sarkar and Devi, 2014). The equitability of resources was found high in SDMDF (0.96) as compared to other two forest communities (SDMDF 0.83 and PSF 0.41). High species richness associated with

equitable sharing of resources in moist tropical forest was reported earlier (Tripathy and Shankar, 2014).

Several ecological factors influence spatial distribution pattern of trees in a forest. These patterns can be random, uniform or clumped depending on the interplay of abiotic and biotic influences. Among the abiotic factors, characteristics of edaphic mass *viz*. soil type, reaction, moisture content and climate determine where specific tree species can thrive, while topography influences local variations in light, moisture, and temperature. Biotic factors, including competition for resources, herbivory and symbiotic relationships, also shape tree distribution (Wang *et al.,* 2019). Commonly trees with similar ecological requirements tend to cluster in areas where those conditions are met, whereas species with more competitive traits may be evenly spaced to minimize resource sharing (Kunstler *et al.,* 2012). Disturbances such as fire, storm or human activities further impact tree distribution by creating gaps that either promote or limit regeneration. Ultimately, the spatial arrangement of trees is a dynamic result of both natural processes and environmental adaptations, forming a unique distribution pattern within each forest ecosystem. Analysis of spatial distribution pattern of trees revealed prevalence of random distribution pattern (47.1%) in PSF, regular (41%) in SDMDF and contagious pattern (47.1%) in MDFWS (Figure 5.6). Contagious distribution pattern is most prevalent among plant species in nature. In the study area, most tree species regenerate through seeds. However, a disturbance such as fire, heavy grazing, soil compaction and the dense growth of herbaceous plants reduces soil moisture availability and hinder natural seed regeneration. This leads to an increased random distribution pattern. The randomness in distribution pattern of trees in present study is closely linked with sal tree density in these forests. This is attributed to intensive human intrusion for various forest produce harvesting leading to impaired natural regeneration form seed as well as coppice shoots. The decreasing trend in stem density from site-I to site-III due to increased disturbance supports to the earlier observations of Sagar *et al.,* (2003) in dry tropical forests.

The proportionate number of juveniles (seedlings and saplings) in a population is considered as regeneration potential of a species. High density value of juveniles of a species in a community indicates conduciveness of environmental gradients in the forest ecosystem. Edaphic and climatic factors, along with biotic interactions, affect the regeneration of species in vegetation (Dhaulkhndi *et al.,* 2008). Generally, the density of seedling gets reduced at sapling stage due to competition for space, light and nutrients (Khurana, 2007). In our study, it has been observed that the density of seedlings was high in site-II as compared to site-I and site-III irrespective of forest types. This is because of openness of canopy as a result of illegal timber harvesting and other sources of anthropogenic disturbance at moderate level (disturbance index 36.25-38.25). In PSF and SDMDF community, sal is the dominant species and its regeneration is much influenced by canopy density. Being a light demander sal prefers canopy openness and gap for seedling establishment (Chapagain *et al.,* 2021). In PSF and SDMDF regeneration status of dominant species *S. robusta* was good. The observed high seedling and sapling density in site-II aligns with the observations of Sapkota *et al.* (2009), Baral and Ghimire (2020). High biotic pressure in site-III was the cause of lower seedling and sapling density in spite of open canopy. The observed sal seedling density of 38125 ha^{-1} to 41250 ha^{-1} (Table 5.7) is very close to the seedling density in Western Nepal tarai sal forest (35835 seedlings ha^{-1}, Baral and Ghimire, 2020) and lower than seedling density of Ranchi sal forests (22072 seedlings ha^{-1}, Kumar and Saikia, 2021), moist deciduous forests of similipal biosphere reserve (22333 seedlings ha^{-1}, Mohanta *et al.,* 2021). In MDFWS community the seedling density of major species ranged from 416 to 8625 numbers per hectare which is close to the seedling density of moist deciduous forest of the state reported earlier (Mishra *et al.*, 2008; Sahoo *et al.* 2017). Disproportionately less adult and sapling number than seedling indicates recurrent occurrence of disturbance invents such as forest fire and intensive grazing impending growth and establishment of recruits. This kind of phenomenon was also observed in the moist deciduous forests of neighbouring Nayagarh district by Sahoo *et al.* (2017). Percentage of species having good regeneration was high in MDFWS (26.2%) and low

in PSF (9.1%, Figure 5.8). Thick layer of floor litter, recurrent forest fire and heavy biotic pressure from grazing animals and NTFP collection attributed to this lower percentage of regeneration in PSF. Lower seedling density because of heavy biotic pressure especially grazing and NTFP collection in the buffer zone of Similipal biosphere reserve was reported by Mishra *et al.* (2008).

Table 5.7 Density of saplings and seedlings (ha^{-1}) of major tree species in PSF, SDMDF and MDFWS

Species name	**PSF**		**SDMDF**		**MDFWS**	
	Sapling	**Seedling**	**Sapling**	**Seedling**	**Sapling**	**Seedling**
Shorea robusta	540	41250	514	38125	24	2462
Madhuca latifolia	11	2292	22	2165	-	-
Buchanania lanzan	30	1250	27	2083	-	-
Pterocarpus marsupium	8	1458	11	1458	-	-
Terminalia alata	-	-	-	-	35	8625
Bridelia retusa	-	-	-	-	37	5166
Diospyros melanoxylon	-	-	-	-	26	5150
Mitragyna parvifolia	-	-	-	-	18	4791
Anogeissus latifolia	-	-	-	-	27	1041
Schleichera oleosa	-	-	12	833	9	416
Other	360	67708	335	68461	529	110749
Total	949	113958	921	112125	681	135938

We also observed that many species are locally rare, with low abundances, but have a wide distribution across the regional species pool. This can be attributed to factors such as habitat discontinuity, the unsuitability of altered niche conditions, and the preferential growth of certain plant species. It is often the case that tropical tree species, which thrive abundantly in one area, appear to be relatively scarce in other areas.

CHAPTER-6

INVENTORIES ON BIOMASS, CARBON STOCK AND CARBON SEQUESTRATION POTENTIAL OF FOREST TYPES

6.1 Introduction

Forests in the tropical region play a substantial role in the global carbon cycle, influencing spatiotemporal variation in atmospheric CO_2 concentration. These ecosystems cover ~15% of the earth's surface area but harbor half of the living species of the world, contributing nearly one-third of the global primary productivity (Gandhi and Sundarpandian, 2017; Laurance *et al.,* 2012). Photoautotrophs particularly trees absorb CO_2 from the atmosphere, convert it into organic matter and store carbon (C) in their biomass. This C remains sequestered in the ecosystem for decades, centuries or even millennia, depending on the age of the trees. Additionally, tropical forests store large amounts of carbon in soil, where decomposed organic matter contributes to long-term carbon storage. According to recent estimates, tropical forests store around 253 billion metric tons of carbon (FAO, 2020) and are responsible for absorbing nearly 25% of the world's carbon dioxide emissions from fossil fuels (IPCC, 2021). This process helps to mitigate the impacts of climate change by reducing the concentration of greenhouse gases in the atmosphere. Thus, tropical forests act as carbon sinks during peak vegetation growth. It is estimated that forests sequester approximately twelve percent of anthropogenic carbon emissions to which tropical forests contribute substantially (Hurteau *et al.,* 2019).

However, severe deforestation and forest degradation due to monoculture, agriculture expansion in forest areas, lumbering, tourism, NTFPs collection and land diversification shrinking tropical forests at the rate of 0.79 to 2.0% per year (Curtis *et al.,* 2018; Pattnayak *et al.,* 2020). Deforestation, intensified land use and population pressure reduce the capacity of carbon pools in tropical forests, releasing huge quantities of CO_2. The exponential increase in atmospheric emissions over the last few decades is threatening the functionality of tropical forest ecosystems and their

carbon storage capacity (Sparry *et al*., 2019). During the past two decades of the 21st century, the concentration of the major greenhouse gas CO_2 in the atmosphere has increased at an alarming rate of 2.22 ppm per year, resulting in rapid changes in the earth's surface temperature as well as the global climate.

Global climate change is driving extreme weather events, rising sea levels, and loss of biodiversity. These disruptions threaten ecosystems, economies and the well-being of communities worldwide. Reducing the impact of climate change is the call of the hour. Carbon capture and storage (CCS) is a prime strategy among various approaches adopted by countries to mitigate the effects of global climate change. Terrestrial carbon sequestration, through large-scale planting initiatives or sustainable forest management, particularly in tropical forests offers a cost-effective method to reduce or prevent the release of greenhouse gases (GHGs) into the atmosphere, thereby limiting the severity of global warming ($UNREDD^{+}$).

Assessing temporal variations in biomass and C stock of tropical forests is important for understanding their role in climate regulation. Accurately estimating both aboveground and belowground vegetation biomass is a crucial step in this regard (Djomo *et al.,* 2011). The biomass accumulation of trees in tropical forests is high with varying degrees of annual increments. Therefore, a precise estimation of the annual increment is needed to minimize uncertainties in the net carbon budgets of tropical forests over a particular year. These estimates also provide supportive data sets for developing mathematical models for similar under-represented sites of the tropics. Field-based biomass inventory approach is a very cost-effective method often adopted by ecologists for accurately estimating carbon stock, emissions and absorption of a forest ecosystem (Kaul *et al.,* 2011; Liski *et al.,* 2002). Forest Survey of India, an apex organization under the Ministry of forests, environment and climate change estimates the growing stock and carbon stock of various forest types of the country on a two-year cycle basis. The differences in vegetation biomass and total carbon stock (biomass, soil and litter) between two consecutive inventories are used to know the carbon fluxes in various pools and this is also recommended by IPCC.

Very few studies have been conducted so far to estimate the biomass and C stock of forests in Odisha; the majority of which is concentrated in protected areas like Simlipal Biosphere Reserve (Mohanta *et al.,* 2020), Bhitarakanika National Park

(Sahu *et al.*, 2016b), Chandaka-Damapara wildlife sanctuary (Pattnayak *et al.*, 2020), Debrigarh wildlife sanctuary (Pradhan *et al.*, 2019), Mahendragiri hills (Khadanga and Jayakumar, 2020) and Gandhamardan hills (Sahu *et al*., 2012). Research in these forests has yielded varying estimates of biomass and carbon stock, reflecting the complexity of the forests' structure and composition. Biomass and carbon stock estimations in the tropical forests of Odisha face several limitations, hindering accurate assessments of their carbon storage potential. One key challenge is the lack of comprehensive, forest type or region-specific data sets to produce accurate and consistent carbon inventories across Odisha's forests. Many areas remain underrepresented in terms of long-term monitoring and data collection, resulting in uncertainties that affect the overall carbon budget of the state. Additionally, the region's complex topography, variability in tree species composition and differences in forest management practices further complicate accurate biomass estimation. Enhanced field measurements, improved remote sensing techniques, and better integration of local ecological variations are needed to strengthen biomass and carbon stock estimation efforts in Odisha. Kandhamal has having highest forest coverage among other districts of the state (ISFR, 2023) contributing substantially to the carbon budget of the state. The present study of biomass and carbon stock estimation in three forest communities *viz*. pure sal forest (PSF), sal dominated moist deciduous forest (SDMDF) and moist mixed deciduous forests without sal (MDFWS) of moist tropical forests of Kandhamal district will enrich the carbon inventory data sets of the state.

6.2 Materials and Methods

6.2.1 Study area

The present study was conducted in Phulbani forest division encompassing a rich forest resource classified as North Indian moist deciduous forest, moist mixed deciduous forest, semi evergreen forest and dry deciduous forest type (Champion and Seth, 1968). Three predominant forest communities *viz.* pure sal forest (PSF), sal dominated moist deciduous forest (SDMDF) and moist mixed deciduous forests

without sal (MDFWS) were selected within tropical moist deciduous forest of the division. Sampling units of 2.0 ha area were demarcated in three reserve forests namely Khajuripada, Dutimundi, Dakapalla-B for PSF and SDMDF communities. Similarly, three sampling units of 2.0 ha each were demarcated in Dakapalla-B, Khajuripada and Sudurukumpa reserve forest for MDFWS community. The sampling sites in all four reserve forests were selected in such a manner that there was minimal to no human disturbance to the vegetation. Thus, a total of 18.0 ha of tropical moist deciduous forest (6 ha for each forest community) spreading over four reserve forest were sampled (Figure 6.1).

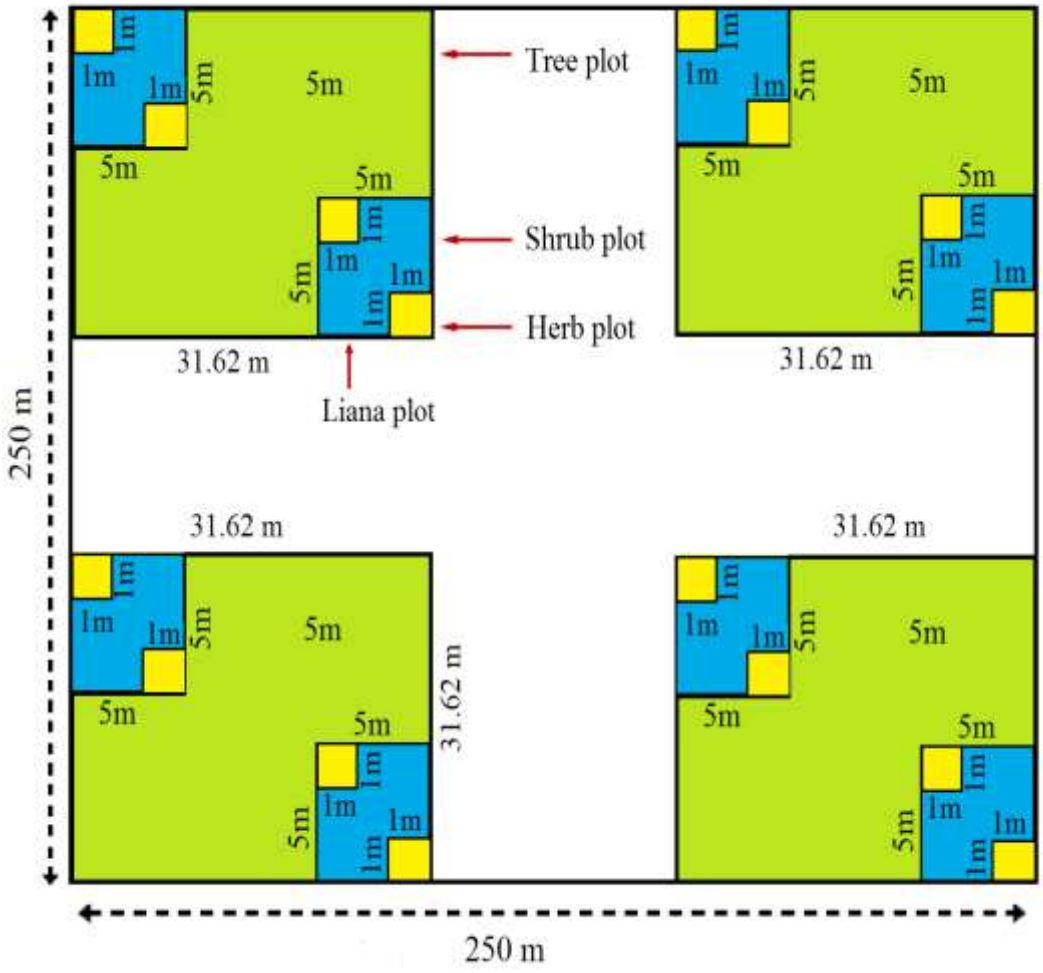


Figure 6.1 Layout of sampling plots and their respective size for tree, shrub and herbs

6.2.2 Vegetation analysis

After repeated field surveys the sampling area was demarcated and the first round of survey was conducted during the year 2021 and the same was repeated after one year. In each reserve forest two permanent sampling area of 250 m x 250 m size was demarcated following the protocols of Singh and Dadhwal (2009). The sample plot was selected in such a manner that there was minimal or no human interference in it. At each corner of every permanent sample plot, four sub-sample plots, each measuring 31.62 m x 31.62 m, were designated for tree species enumeration. Two sample plots, each measuring 5 m x 5 m, were marked at the diagonal corners of each tree plot for the enumeration of shrubs and lianas. Similarly, for the enumeration of herbs and regenerating plants, two 1 m x 1 m plots were marked within the shrub plots. In this way, vegetation and biomass data were gathered by establishing a total of 8 tree plots, 16 shrub plots, and 32 herb and litter plots in each major forest type as illustrated in Figure 6.1. All plant species within the sample plot were identified and measured according to their category. The diameter of tree and liana species was measured with the help of a caliper over bark at 1.37 m from ground (DBH). The individuals of tree species having diameter < 10 cm were categorized as (a) sapling (3.3 cm ≥ dbh < 10.0 cm), (b) seedling (dbh <3.3 cm) as described by Shankar, (2001). Deadwood, including snags (standing) and logs (fallen) was surveyed and measured within tree sample plots. DBH of logs was taken at three places (top, middle and bottom) along with other parameters such as species name and physical condition (freshly cut or decomposed). Roots and stumps with a dbh of 10 cm or more were also classified as dead wood. Herbs present in 1 m x 1 m plot were uprooted, washed to remove adhered soil at root and oven-dried at 80 ^{0}C to constant weight.

6.2.3 Soil sampling and estimation of organic carbon stock

Soil samples were systematically collected at three depths (0-15 cm, 15-30 cm and 30-45 cm) using a soil auger from two random locations within each sub-plot (31.5 m × 31.5 m). Thus, a sum of 144 soil cores (2 cores x 3 depths x 4 sub plot x 2 major plots x 3 reserve forest) was collected from each studied forest community type. Simultaneously soil samples of each depth were collected from undisturbed

plots separately for bulk density estimation by using soil core of known volume. Air -dried samples were grinded gently using a wooden hammer, sieved through 2 mm mesh and stored in glass jars for further organic carbon determination. The soil total carbon (TSC) and total nitrogen (TSN) in soil samples were estimated by combusting 0.2 g of sample in CHNS analyzer (Elementar UNICUBE, with accuracy; 99.7 ± 0.3 %). Soil inorganic carbon (SIC) was determined using dilute hydrochloric acid (1 M HCL) in 1:10 ratio (Jackson, 1967). The total organic carbon content in soil samples was estimated by subtracting SIC from TSC. Soil carbon stock (SOC) of each depth was estimated using SOC concentration, bulk density of fine soil fraction (< 2 mm) and soil depth. SOC stock was estimated using the following mathematical equation:

$$\text{SOC stock (Mg C ha}^{-1}) = \sum_{\text{SH}=1}^{\text{N}} \text{SOC} \times \text{Bulk density} \times \text{Soil depth} \times 100$$

Where SOC is the concentration of soil organic carbon (%), SH is the soil horizon, bulk density of fine soil fraction (Mg m^{-3}) and soil depth is the thickness of soil layer (m).

6.2.7 Biomass Estimation

The biomass woody species *viz*. tree, shrub and liana were determined through non- destructive allometric equation approach (Table 6.1). The above-ground biomass of tree species (DBH ≥10 cm) was estimated using local volume tables and wood specific gravity of each species (Table 6.2). Species specific local volume tables developed by the forest survey of India (FSI 1996) suitable for geographic region were used (Table 6.2). The wood specific gravity of each species was collected from the published literatures having similar tropical climatic conditions (Table 6.2). Few tree species for which wood density values were not found in any published literature, the universal wood density value (0.633) was used to determine the AGB (Rajashekar *et al.,* 2018). The biomass of branches and foliage of trees (DBH ≥10 cm) was determined adopting the allometric equations of FSI (Table 6.3). Tree species for which allometric equations for branch and foliage was not available in FSI data base, regression equations developed by Singh and Mishra

(1979) was used to estimate the AGB. The biomass of saplings and small tree was estimated using allometric equation of Chaturvedi *et al*., (2012). Shrub biomass was estimated using the equations of Singh and Singh (1991). For estimating biomass of dead wood and stumps the allometric equations developed by Cros and Lopez, (2009) was used. The liana (≥10 cm DBH) biomass was estimated following the equation of Schnitzer *et al.,* (2006). Herbaceous vegetation and above-ground litter biomass was estimated based on the dry weight (oven-dried at 80 ^{0}C to constant weight) of 1m x 1m sample plots. The litter input was measured from randomly placed 72 numbers (3 forest types x 3 sites x 8 numbers per site) of stone-block lined quadrats following the procedure of Pragasan and Parthsarthy (2005). The fine root (<5.0 mm diameter) litter production was determined from eight monoliths (30 cm x 30 cm x 30 cm) on each site during rainy (September), winter (January) and summer (May) months. The monoliths were washed in fine jet of water using 2 mm mesh screen. Live and dead fine roots were separated through visual observations (colour, texture and feel), oven-dried at 80 ^{0}C to constant weight and weighed. The dry weight of dead fine root mass was reported as fine root litter.

Table 6.1 Non-destructive approaches used for estimation of biomass estimation

<table>
<tr><th colspan="2">Vegetation component</th><th>Non-destructive approach</th><th>Reference</th></tr>
<tr><td rowspan="2">Tree</td><td>Bole</td><td>Volume table and wood density</td><td>[1]</td></tr>
<tr><td>Branch, foliage</td><td>Sp. specific biomass equations of FSI and Biomass expansion factor</td><td>[2]</td></tr>
<tr><td colspan="2">Sapling and small tree</td><td>AGBS = 3.344+(0.443× (ln (D^2))</td><td>[3]</td></tr>
<tr><td colspan="2">Liana</td><td>AGBS = exp(-1.484+2.657×ln(D)</td><td>[4]</td></tr>
<tr><td colspan="2">Shrubs</td><td>Log Y = a + b log (X)
Where the value of a and b as follows
<table>
<tr><th></th><th>bole</th><th>branch</th><th>root</th><th>leaf</th></tr>
<tr><td>a</td><td>-2.9407</td><td>-3.0225</td><td>-2.0849</td><td>-2.7795</td></tr>
<tr><td>b</td><td>2.6817</td><td>2.5422</td><td>2.4481</td><td>1.9953</td></tr>
</table></td><td>[5]</td></tr>
<tr><td colspan="2">Dead wood and stumps</td><td>$V = [\pi \times L \times D^2_{(middle)}]/4$</td><td>[6]</td></tr>
</table>

Note: AGBS= aboveground biomass stock, Y= biomass of shrub component (kg), X= Girth of shrub in cm, a and b are allometric constants (a= intercept, b =slope), V= Log volume, L= Log length in cm, D= Log diameter in cm.
References: [1] Ravindranath and Ostwald, 2007; [2] Rajashekar *et al.*, 2018; [3] Chaturvedi *et al.*, 2012; [4] Schnitzer *et al.*, 2006; [5] Singh and Singh, 1991; [6] Cros and Lopez, 2009

Table 6.2 Volume equation (FSI 1996) and wood density (g/cm^3) of tree species

Botanical Name	Volume equation	W. Density
Adina cordifolia	$\sqrt{V} = -0.15336+2.802965D$	0.58 [1]
Aegle marmelos	$V= 0.16609 -2.78851D+17.22127D^2 -11.60248D^3$	0.64 [2]
Albizia lebbeck	$\sqrt{V}= -0.07109+2.99732D-0.26953\sqrt{D}$	0.90 [2]
*Anogeissus acuminata**	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.88 [4]
Anogeissus latifolia	$V= 0.13928-2.87067D+20.22404D^2 -13.80572D^2$	0.78 [1]
Antidesma ghaesembilla	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.64 [13]
Bauhinia variegata	$V= -0.04262+6.09491D^2$	0.67 [1]

Botanical Name	Volume equation	W. Density
Bombax ceiba	$V/D^2 = 0.00331/D^2 - 2.85418/D + 15.03576$	0.33 [1]
Bridelia retusa	$V = 0.035142 - 0.839708D + 8.157614D^2$	0.50 [1]
Buchanania lanzan	$\text{Log}_e V = 2.2491 + 2.5206 \text{ Log}_e D$	0.458 [1]
Butea monosperma	$\sqrt{V} = -0.24276 + 2.95525D$	0.48 [1]
Careya arborea	$V = 0.003 - 0.848D + 7.342 D^2$	0.95 [5]
Cassia fistula	$\sqrt{V} = -0.144504 + 2.943115D$	0.71 [1]
*Ceiba pentandra**	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.23 [1]
Cleistanthus collinus	$\sqrt{V} = 0.12956 + 3.7819 D - 1.04671\sqrt{D}$	0.88 [1]
Dalbergia latifolia	$\sqrt{V} = 0.76896 + 7.31777D - 4.01953\sqrt{D}$	0.75 [1]
Dalbergia sissoo	$V/ D^2 = 0.00331/ D^2 + 0.000636$	0.68 [1]
Desmodium oojeinense	$\sqrt{V} = 0.03456 + 3.8192D - 0.80884\sqrt{D}$	0.865 [11]
*Dillenia aurea**	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.80 [13]
Dillenia pentagyna	$\sqrt{V} = 0.31202 + 4.75915D - 1.8394\sqrt{D}$	0.53 [1]
Diospyros malabarica	$V = 0.06206 - 1.43609D + 9.778164D^2$	0.70 [1]
Diospyros melanoxylon	$\sqrt{V} = 0.06728 + 4.06351D - 0.99816\sqrt{D}$	0.68 [1]
Erythrina variegata	$V = -0.07803 + 1.70258D - 9.1618D^2 + 33.91455D^3$	0.32 [1]
*Ficus hispida**	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.39 [1]
*Ficus racemosa **	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.39 [1]
*Gardenia latifolia**	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.64 [1]
Garuga pinnata	$V = 0.034 - 0.901D + 6.898D$	0.51 [1]
Gmelina arborea	$V = 0.25058 - 3.55124D + 16.4172D^2 - 8.32129D^3$	0.57 [3]
*Grewia tiliifolia **	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.45 [3]
*Holoptelea integrifolia**	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.64 [7]
*Ixora pavetta**	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.49 [6]
Lagerstroemia parviflora	$V = 0.10529 - 1.68829D + 10.29573D^2$	0.62 [1]
Lagerstroemia reginae	$V = 0.11740 - 1.58941D + 9.76464D^2$	0.92 [2]
Lannea coromandelica	$V = 0.057424 - 1.153088D + 8.542648D^2$	0.54 [1]
*Macaranga peltata**	$V = 0.088074 - 1.449236 D + 8.760534 D^2$	0.48 [9]

Botanical Name	Volume equation	W. Density
Madhuca latifolia	$V = 0.030925 – 0.567067\ D + 5.709471\ D^2$	0.74 [1]
Mallotus philippensis	$V=0.14749–2.87503D+19.61977D^2–19.11630D^3$	0.72 [3]
Mangifera indica *	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.588 [8]
Mitragyna parvifolia	$V/D^2=0.099768D^2–1.744274/D+10.086934$	0.56 [1]
Morinda coreia *	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.545 [5]
*Naringi crenulata**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.60 [12]
*Nyctanthes arbor-tristis**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.48 [10]
Phyllanthus emblica	$V = –0.406+3.54D–3.231D^2$	0.78 [2]
Pterocarpus marsupium	$\sqrt{V} = 0.16276+2.82002D+0.04034\sqrt{D}$	0.67 [1]
*Pterospermum xylocarpum**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.56 [6]
Schleichera oleosa	$V/D^2 = 0.016042/D^2-0.49647/D+6.2214$	0.96 [1]
*Schrebera swietenioides**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.82 [1]
Semecarpus anacardium	$\sqrt{V} = –0.07109+2.99732D-0.26953\sqrt{D}$	0.64 [1]
Shorea robusta	$\sqrt{V}= 0.19994+4.57179D-1.56823\sqrt{D}$	0.72 [1]
*Spathodea campanulata**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.71 [2]
*Sterculia urens**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.67 [1]
*Streblus asper**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.60 [12]
*Strychnos nux-vomica**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.89 [3]
*Strychnos potatorum**	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.88 [1]
Syzygium cumini	$\sqrt{V} = 0.30706+5.12731D-2.09870\sqrt{D}$	0.70 [1]
Syzygium heyneanum	$V = 0.088074 – 1.449236\ D + 8.760534\ D^2$	0.69 [1]
Terminalia alata	$V = 0.05061–1.11994D+8.77839D^2$	0.44 [2]
Terminalia bellirica	$V = 0.103171–1.684599D+10.107586D^2$	0.72 [1]
Terminalia chebula	$V = –0.05004–0.0344D+6.35715D^2$	0.96 [1]
Vateria indica	$V = –0.39452+2.7392D+6.03205D^2$	0.47 [1]

Note: *- Volume equation for miscellaneous species as per FSI 1996.

Values in bracket [ ] are literature sources: [1] Reyes *et al.*, 1992; [2] Tamang *et al.*, 2019; [3] Manikandan *et al.*, 2019; [4] Win and Kyi 2008; [5] Ganapathy,1981; [6] Mani and Parthasarathy 2007; [7] Meena et al., 2019; [8] Rajput *et al.*, 1996; [9] Kumar, 2017; [10] Chaturvedi *et al.*, 2012, [11] Orwa *et al.*, 2009; [12] Sahu *et al.*, 2016d; [13] Chowdhury *et al.*, 2013

Table 6.3 Allometric equations for biomass estimation of branch and foliage of trees

Sl. No	Species	Biomass equation
1	*Aegel marmelos*	BE1= -316.8777 D^2+401.7510D-28.8949
		BE2= -26.68D^2 +33.47D -2.394
2	*Albizia lebbeck*	BE1= -0.5537D^2+31.6459D-17.5544
		BE2= 13.3705D^2 +3.3486D -0.0903
3	*Bombax ceiba*	BE1= 199.7191 D^2+40.5382D+2.7931
		BE2= 5.1029D^2 + 1.0464D +0.0809
4	*Bridelia retusa*	BE1= 274.2959 D^2-15.3477D+6.6623
		BE2= 4.3652D^2 +5.8977D +0.0525
5	*Butea monosperma*	BE1= 34.3335 D^2-7.3049D+6.2960
		BE2= 13.7310D^2 -2.7107D +1.3816
6	*Buchanania lanzan*	BE1=371.3904D^2-24.8493D+11.8891
		BE2=11.5126D^2+11.7616D-0.4661
7	*Careya arborea*	BE1= 458.3502 D^2- 89.9168D+10.8998
		BE2= 36.5716D^2 – 7.1744D +0.8697
8	*ClInthus collinus*	BE1=267.9289d^2+203.8644d-13.2061
		BE2=4.1925D^2+0.6047D+0.1422
9	*Diospyros melanoxylon*	BE1= 454.7209D^2+91.0511D-0.7796
		BE2=6.0086D^2 + 14.4343 D - 0.6523
10	*Diospyros spp.*	BE1=164.0576D^2+98.0941D+1.3802
		BE2=7.4373$D^2$3.4612D-0.014
11	*Grewia tilitifolia*	BE1= 1088.6600 D^2-295.8026D+31.3839
		BE2= 31.8648D^2 -5.8728D +0.9027
12	*Holarrhena antidysenterica*	BE1= 140.3103 D^2+199.3693D-8.2801
		BE2= 6.6914D^2 + 11.6819D -0.7106
13	*Lannea coramandelica*	BE1= 271.6220 D^2-40.3564D+19.9687
		BE2= 11.1041D^2 -1.5074D +0.6238

Sl. No	Species	Biomass equation
14	*Lagerstroemia parviflora*	BE1=282.0677D^2+122.5817D-1.6765
		BE2=4.4738D^2-0.8760D-0.2022
15	*Madhuca longifolia*	BE1= 215.7248 D^2+189.782D-8.4775
		BE2= 14.6794D^2 +3.5935D -0.1774
16	*Pterocarpus marsupium*	BE1= 110.8192 D^2+214.1240D+3.5711
		BE2= 4.2573D^2 + 1.6800D +0.9568
17	*Schleichera oleosa*	BE1= -23.7715 D^2+374.0009D-11.3382
		BE2= 13.2675D^2 +10.6145D +0.7554
18	*Semecarpus anacardium*	BE1= 238.3735 D^2+154.6146D+0.4939
		BE2= -145.9652D^3 + 152.4208D^2 - 20.6768D+1.1954
19	*Shorea robusta*	BE1= 96.1525 D^2+141.9383D-7.6058
		BE2=17.2383D^2 +4.2380D -0.1970
20	*Syzygium cumini*	BE1= 986.1005 D^2+92.1288D+33.8089
		BE2= 11.5552D^2 + 17.0550D +0.7249
21	*Terminalia belerica*	BE1= 266.6358 D^2+290.2640D+23.9759
		BE2= 5.2817D^2 + 7.7464D +0.0264
22	*Terminalia tomentosa*	BE1=487.5527D2+151.9905D-10.5122
		BE2=20.6898D2+0.6700D+0.7183
23	*Terminalia sp.*	BE1= -40.7829 D^2+287.6667D-6.1942
		BE2= 5.9678D^2 + 12.1613D -0.0384
24	Other species*****	Branch = Exp (-3.2888+2.942 x Log (G)
		Leaf = Exp (-2.6977+2.0403 x Log (G)
BE1: Biomass equation to estimate biomass of small wood of tree having dbh≥10cm BE2: Biomass equation to estimate the biomass of foliage of trees dbh ≥10cm D: Diameter at breast height in meter; Unit of biomass is in kg		
*For other species branch and leaf biomass was estimated as per the equations of Singh and Mishra (1979); G- Girth in cm		

6.2.8 Biomass carbon stock determination

The carbon content of woody components (tree, small tree and saplings, shrubs and liana) was estimated by multiplying the biomass with 0.47 (default value for carbon content in woody species as per IPCC, 2006). The carbon percentage of carbon content in herbaceous vegetation and litter mass (aboveground litter and fine root) was analysed by combusting 0.2 g of oven-dried sample in CHNS auto-analyzer (Elementar UNICUBE) and then the value was multiplied with the corresponding dry biomass amount (Campbell and Plank, 1998). The above and belowground biomass carbon stock of each component was summed up to determine the ecosystem carbon content of each forest.

6.2.9 Determination of carbon sequestration rate

The carbon sequestration rate in each forest type was determined by adopting the stock difference methodology based on the IPCC guidelines (IPCC-2003 and IPCC-2006). This carbon inventory procedure includes all the processes of the ecosystem that leads to the variations in the concerned carbon pool. The carbon stock was estimated for each pool at two time points, *viz*. t_1 and t_2. In this present study the period between two time points was two years (t_1 = 2021 and t_2 = 2022). Therefore, the estimated total carbon stock in the year 2023 was subtracted from the estimated total carbon stock at time t_1 (2021) and the differential value was divided by the number of years between the two periods (t_2 - t_1). The stock difference was determined separately for each carbon pool and later summed up for each forest type.

6.2.10 Statistical analysis of inventoried data

Descriptive statistical tools were used to calculate replicated sample mean and standard error of means. The mean values of various attributes were compared using one-way analysis of variance (ANOVA) at 95% confidence level. Turkey honest significance difference (HSD) post hoc test was performed to indicate significant differences ($P<0.05$). All the statistical analysis was carried out using MS EXCEL and SPSS statistical package SPSS-20 (SPSS Inc. Chicago, USA). The correlation coefficient analysis between vegetation characters, biomass stock, SOC

and carbon stock of forest types were analyzed using software R vegan and correlogram plot was drawn in corrplot package.

6.3 Results

6.3.1 Biomass stock variations in different forest types

The biomass stock of three forest types exhibited significant variations ($P<0.05$) across different biomass components (Table 6.4). The total biomass comprising both living biomass (aboveground and belowground) and non-living showed notable differences among the studied forest types. Significantly ($P<0.05$) highest biomass accumulation was found in MDFWS (401.13 Mg ha^{-1}) and lower in PSF (217.16 Mg ha^{-1}). However, the difference between PSF and SDMDF was not statistically significant. The aboveground biomass varied significantly among the forest types with MDFWS (313.04 Mg ha^{-1}) showing the highest accumulation followed by PSF (202.95 Mg ha^{-1}) and SDMDF (165.55 Mg ha^{-1}). The LSD value for aboveground biomass was 65.21 Mg ha^{-1}, indicating that MDFWS had a significantly higher biomass stock compared to both PSF and SDMDF, while the difference between PSF and SDMDF was not significant. Similarly, belowground biomass followed the same trend, with MDFWS (75.12 Mg ha^{-1}) having significantly higher values than PSF (47.09 Mg ha^{-1}) and SDMDF (35.95 Mg ha^{-1}).

Table 6.4 Biomass stock (Mg ha^{-1}) variations in of PSF, SDMDF and MDFWS

Forest type	**Living biomass**		**Non-living biomass**	**Total biomass**
	Aboveground biomass	**Belowground biomass**		
PSF	202.95±20.76^{b}	47.09±5.45^{b}	12.86±0.35^{b}	262.86±26.31^{b}
SDMDF	165.55±9.05^{b}	35.95±2.61^{b}	15.67±0.39^{a}	217.16±11.56^{b}
MDFWS	313.04±32.05^{a}	75.12±8.44^{a}	12.94±0.34^{b}	401.13±40.52^{a}
Mean	226.86±16.54	53.01±4.36	13.83±0.29	293.72±20.81
LSD ($P<0.05$)	65.21	17.24	1.02	82.54

Values presented as mean ± Standard error, Different alphabetical letters indicate significant differences within the same column at $P<0.05$

6.3.2 Biomass stocks in different vegetation components

The biomass stocks among the forest types varied significantly ($P<0.05$) across different vegetation components except for shrubs (Table 6.5). The MDFWS forest exhibited significantly (LSD = 83.54, $P<0.05$) higher tree biomass (364.35 Mg ha^{-1}), followed by PSF (232.15 Mg ha^{-1}) and SDMDF (174.20 Mg ha^{-1}). Sapling biomass ranged from 4.25 Mg ha^{-1} (PSF) to 2.38 Mg ha^{-1} (MDFWS). The liana biomass was significantly (LSD = 3.46, $P<0.05$) higher in SDMDF (14.70 Mg ha^{-1}) and MDFWS (12.47 ± 1.10 Mg ha^{-1}) compared to PSF (6.09 Mg ha^{-1}). The herbaceous biomass was found significantly higher in MDFWS (1.14 Mg ha^{-1}) and lower in PSF (0.41 Mg ha^{-1}). Dead wood biomass was significantly greater in MDFWD (4.01 Mg ha^{-1}) compared to SDMDF (2.89 Mg ha^{-1}) and PSF (2.02 Mg ha^{-1}) (LSD = 0.37, $P<0.05$). The aboveground litter biomass showed significant differences (LSD = 0.71, $P<0.05$) among forest types with highest value in SDMDF (11.56 Mg ha^{-1}) and lowest in MDFWS (7.89 Mg ha^{-1}). Similarly fine root litter biomass showed significant differences among forest types, with the highest values in PSF (1.44 Mg ha^{-1}) and the lowest in MDFWS (1.04 Mg ha^{-1}).

Table 6.5 Biomass stocks (Mg ha^{-1}) in various vegetation components (AGB+BGB)

Vegetation component	PSF	SDMDF	MDFWS	Mean	LSD (P<0.05)
Tree	232.15 ^{b} (26.39)	174.20 ^{b} (12.65)	364.35 ^{a} (40.89)	256.89 (21.11)	83.54
Saplings	4.25 ^{a} (0.44)	3.34 ^{b} (0.21)	2.38 ^{c} (0.25)	3.32 (0.22)	0.90
Shrubs	7.10 ^{ns} (0.85)	8.53 ^{ns} (0.93)	7.88 ^{ns} (1.07)	7.83 (0.54)	2.75
Liana	6.09 ^{b} (0.32)	14.70 ^{a} (1.73)	12.47 ^{a} (1.10)	11.09 (0.91)	3.46
Herbs	0.41 ^{c} (0.06)	0.72 ^{b} (0.05)	1.14 ^{a} (0.13)	0.75 (0.07)	0.24
Dead wood	2.02 ^{c} (0.12)	(2.89 ^{b} (0.16)	4.01 ^{a} (0.12)	2.97 (0.16)	0.37
Aboveground litter	9.40 ^{b} (0.08)	11.56 ^{a} (0.35)	7.89 ^{c} (0.23)	9.62 (0.29)	0.71
Fine root litter	1.44 ^{a} (0.12)	1.21 ^{b} (0.02)	1.04 ^{b} (0.02)	1.23 (0.05)	0.21

Values presented in parenthesis are mean ± Standard error, Different alphabetical letters indicate significant differences within the same row at P<0.05

6.3.3 Biomass stocks across different ecosystem components

The biomass stocks in various ecosystem components of three forest types exhibit significant variations (Table 6.6).The over-story biomass was significantly highest in MDFWS (289.16 Mg ha^{-1}), followed by PSF (184.24 Mg ha^{-1}) and SDMDF (138.26 Mg ha^{-1}). The under-story biomass comprising saplings, shrubs and lianas was significantly (LSD = 5.32, P<0.05) higher in SDMDF (26.58 Mg ha^{-1}) compared to PSF (17.45 Mg ha^{-1}) and MDFWS (22.71 Mg ha^{-1}). Herbaceous plant biomass followed a distinct trend with MDFWS recording the highest value (1.14 Mg ha^{-1}), followed by SDMDF (0.71 Mg ha^{-1}) and PSF (0.41 Mg ha^{-1}). The forest floor litter

biomass was in the order SDMDF (14.46 Mg ha^{-1}) > MDFWS (11.89 Mg ha^{-1}) > PSF (11.43 Mg ha^{-1}). The belowground root biomass followed a pattern similar to over-story biomass, with MDFWS exhibiting the highest value (76.22 Mg ha^{-1}) followed by PSF (49.34 Mg ha^{-1}) and SDMDF (37.16 Mg ha^{-1}).

Table 6.6 Biomass stocks (Mg ha^{-1}) across various ecosystem components of three forest types

Ecosystem component	PSF	SDMDF	MDFWS	Mean	LSD (P<0.05)
Over-story biomass	184.24±20.94^{b}	138.26±10.04^{b}	289.16±32.46^{a}	203.89±16.75	66.30
Under story biomass	17.45±0.83^{b}	26.58±2.42^{a}	22.71±1.93^{ab}	22.24±1.21	5.32
Herbaceous plant biomass	0.41±0.05^{c}	0.71±0.46^{b}	1.14±0.13^{a}	0.75±0.07	0.25
Forest floor litter biomass	11.43±0.35^{b}	14.46±0.36^{a}	11.89±0.29^{b}	12.59±0.29	0.97
Belowground biomass	49.34±5.49^{b}	37.16±2.60^{b}	76.22±8.46^{a}	54.24±4.36	17.31

Note: Over-story biomass includes tree biomass (dbh ≥10cm), Under-story includes saplings (dbh 5 cm ≤ dbh <10cm), shrubs and liana having diameter ≥ 10 cm,

6.3.4 Carbon stock

6.3.4.1 Carbon stock variations in three forest types

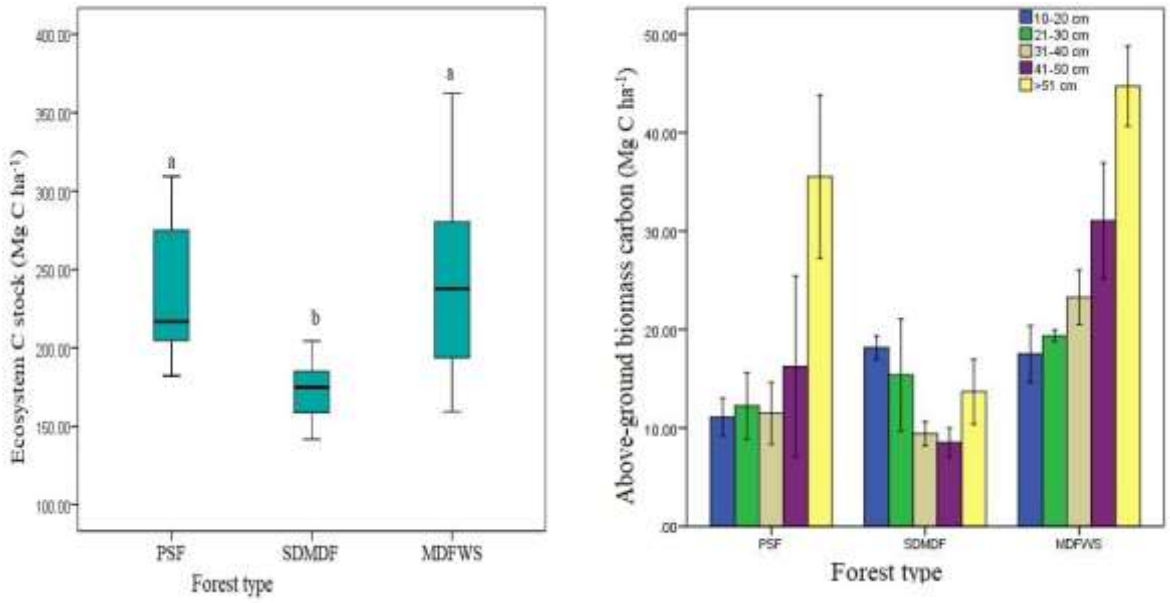
The living biomass carbon stock, non-living biomass carbon stock, soil organic carbon (SOC) stock, ecosystem carbon stock (ECS) and SOC: ECS ratio varied significantly (P<0.05) across three forest types (Table 6.7). The living biomass carbon stock comprising of aboveground biomass carbon stock (AGBCS) and belowground biomass carbon Stock (BGBCS) found significantly higher in MDFWS (AGBCS 147.09 Mg C ha^{-1} and BGBCS 35.34 Mg C ha^{-1}) and lowest in SDMDF (AGBCS 77.80 Mg C ha^{-1} and BGBCS 16.89 Mg C ha^{-1}). The share of older diameter tree classes (dbh >51 cm) to AGBCS was high in PSF and SDMDF whereas it was the juvenile trees (dbh 10-30 cm) which contributed maximum to the

AGBCS in SDMDF (Figure 6.2 A). The non-living biomass carbon stock which primarily comprised of dead wood biomass was found higher in SDMDF (6.97 Mg C ha^{-1}). The non-living biomass carbon stocks found in PSF (5.73 Mg C ha^{-1}) and MDFWS (5.71 Mg C ha^{-1}) was more or less equal and statistically indifferent. The highest SOC stock was found in PSF followed by SDMDF and MDFWS. Similar trend was observed in SOC: ECS ratio. The ecosystem carbon stock which comprises all sources of carbon including living biomass, non-living biomass and soil carbon was found significantly lower (LSD = 5.55, $P<0.05$) in SDMDF (172.68 Mg C ha^{-1}). The ECS of PSF (234.67 Mg C ha^{-1}) and MDFWS (242.41 Mg C ha^{-1}) was statistically indifferent (Figure 6.2B).

Table 6.7 Carbon stock (Mg C ha^{-1}) variations in three forest types

Forest type	**Living biomass C stock**		**Non-living biomass C stock**	**SOC stock**	**Ecosystem C stock (ECS)**	**SOC: ECS**
	AGBCS	**BGBCS**				
PSF	94.98^{b} (9.76)	22.51^{b} (2.56)	5.73^{b} (0.16)	111.45^{a} (1.01)	234.67^{a} (12.28)	48.82^{a} (2.32)
SDMDF	77.80^{b} (4.25)	16.89^{b} (1.23)	6.97^{a} (0.17)	71.02^{b} (0.60)	172.68^{b} (5.12)	41.60^{b} (1.47)
MDFWS	147.09^{a} (15.06)	35.34^{a} (3.97)	5.71^{b} (0.15)	54.28^{c} (0.45)	242.41^{a} (18.95)	23.95^{c} (1.90)
Mean	106.62 (7.78)	24.92 (2.05)	6.13 (0.13)	78.92 (4.08)	216.58 (9.16)	38.12 (2.07)
LSD ($P<0.05$)	30.65	8.10	10.46	2.10	38.47	5.55

Values presented in parenthesis are mean ± Standard error, Different alphabetical letters indicate significant differences within the same column at $P<0.05$, AGBCS-Aboveground biomass carbon stock, BGBCS-Belowground biomass carbon stock, SOC- soil organic carbon



A **B**

Figure 6.2 Carbon stock variations in three forest types A. Ecosystem C stock, B. share of different tree diameter classes to the aboveground biomass stock

6.3.4.2 Carbon stocks in different vegetation components

The assessment of carbon stocks (Mg C ha^{-1}) across various vegetation components in three forest types revealed significant variations (Table 6.8). The highest tree carbon stock was observed in the MDFWS (171.24 Mg C ha^{-1}) which was significantly ($P<0.05$) more than that of the PSF (109.11 Mg C ha^{-1}) and SDMDF (81.87 Mg C ha^{-1}). Sapling C stock varied significantly across forest types with PSF having the highest value (1.99 Mg C ha^{-1}) followed by SDMDF (1.57 Mg C ha^{-1}) and MDFWS (1.12 Mg C ha^{-1}). In contrast to this shrub biomass C stock did not differ significantly among the forest types ($P>0.05$) with values ranging between 3.34 Mg C ha^{-1} (PSF) to 4.01 Mg C ha^{-1} (SDMDF). However, liana carbon stocks varied significantly, being highest in SDMDF (6.91 Mg C ha^{-1}) followed by MDFWS (5.86 Mg C ha^{-1}) and lowest in PSF (2.86 Mg C ha^{-1}). Herbaceous vegetation carbon stocks followed a distinct pattern with MDFWS recording the highest value (0.51 Mg C ha^{-1}), while PSF had the lowest (0.18 Mg C ha^{-1}). Deadwood carbon stocks also varied significantly ($P<0.05$), with MDFWS showing the highest value (1.68 Mg C ha^{-1}) and PSF the lowest (0.85 Mg C ha^{-1}).

Aboveground litter carbon stock was significantly higher in SDMDF (5.22 Mg C ha⁻¹) compared to PSF (4.25 Mg C ha⁻¹) and MDFWS (3.56 Mg C ha⁻¹).

Table 6.8 Carbon stocks (Mg C ha^{-1}) in various vegetation components

Vegetation component	PSF	SDMDF	MDFWS	Mean	LSD (P<0.05)
Tree	109.11 [b] (12.42)	81.87 [b] (5.95)	171.24 [a] (19.22)	120.74 (9.92)	39.26
Saplings	1.99 [a] (0.21)	1.57 [b] (0.10)	1.12 [c] (0.12)	1.56 (0.10)	0.43
Shrubs	3.34 [ns] (0.39)	4.01 [ns] (0.44)	3.69 [ns] (0.51)	3.68 (0.26)	1.29
Liana	2.86 [b] (0.15)	6.91 [a] (0.82)	5.86 [a] (0.52)	5.21 (0.43)	1.63
Herbs	0.18 [c] (0.02)	0.32 [b] (0.02	0.51 [a] (0.05)	0.34 (0.03)	0.11
Dead wood	0.85 [c] (0.05)	1.21 [b] (0.07)	1.68 [a] (0.05)	1.25 (0.07)	0.16
Aboveground litter	4.25 [b] (0.13)	5.22 [a] (0.17)	3.56 [c] (0.12)	4.34 (0.14)	0.41
Fine root litter	0.63 [a] (0.06)	0.53 [ab] (0.03)	0.46 [b] (0.04)	0.54 (0.03)	0.13

Values presented as mean ± Standard error, Different alphabetical letters indicate significant differences within the same row at P<0.05

6.3.4.3 Carbon stocks in different ecosystem components

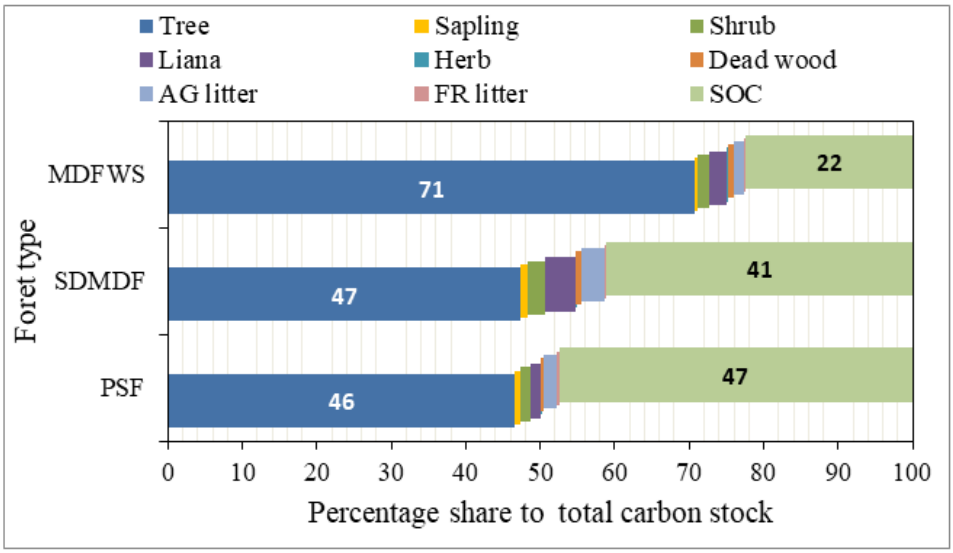
The significant variations were observed in different ecosystem components of PSF, SDMDF and MDFWS forests (Table 6.9). The over-story biomass C stock recorded in MDFWS (135.91 Mg C ha⁻¹) was significantly higher (LSD =95.83, P<0.05) than that of the PSF (86.59 Mg C ha⁻¹) and SDMDF (64.98 Mg C ha⁻¹). The under-story biomass C which includes saplings, shrubs and lianas (dbh ≥10 cm) varied significantly across the forest types with highest value recorded in SDMDF (12.49

Mg C ha⁻¹) followed by MDFWS (10.67 Mg C ha⁻¹) and the lowest in PSF (8.20 Mg C ha⁻¹). Herbaceous layer biomass carbon was significantly different among forest types ($P<0.05$), with the highest value recorded in MDFWS (0.51Mg C ha⁻¹) followed by SDMDF (0.32 Mg C ha⁻¹) and PSF (0.19 Mg C ha⁻¹). Forest floor litter biomass C was highest in SDMDF (6.43 Mg C ha⁻¹), while MDFWS and PSF had similar but lower values (5.24 Mg C ha⁻¹ and 5.09 Mg C ha⁻¹ respectively). Significant differences (LSD=8.13, $P<0.05$) were observed in belowground biomass C with MDFWS showing the highest stock (35.80 Mg C ha⁻¹) followed by PSF (23.15 Mg C ha⁻¹) and SDMDF (17.43 Mg C ha⁻¹).

Table 6.9 Carbon stocks (Mg C ha^{-1}) in various ecosystem components of three forest types

Ecosystem component C	**PSF**	**SDMDF**	**MDFWS**	**Mean**	**LSD (P<0.05)**
Over-story biomass C	86.59±9.84^{b}	64.98±4.72^{b}	135.91±15.26^{a}	95.83±7.88	31.15
Under-story biomass C	8.20±0.39^{b}	12.49±1.14^{a}	10.67±0.91a^{b}	10.45±0.57	2.50
Herbaceous layer biomass C	0.19±0.03^{c}	0.32±0.02^{b}	0.51±0.03^{a}	0.34±0.03	0.11
Forest floor litter biomass C	5.09±0.14^{b}	6.43±0.16^{a}	5.24±0.13^{b}	5.59±0.13	0.43
Belowground biomass C	23.15±2.58^{b}	17.43±1.22^{b}	35.80±3.98^{a}	25.46±2.05	8.13
SOC (0-45 cm depth)	111.45±1.01^{a}	71.02±0.60^{b}	54.28±0.45^{c}	78.92±4.08	2.09

Under-story includes sapling, shrub and liana (diameter ≥ 10 cm), SOC-soil organic carbon



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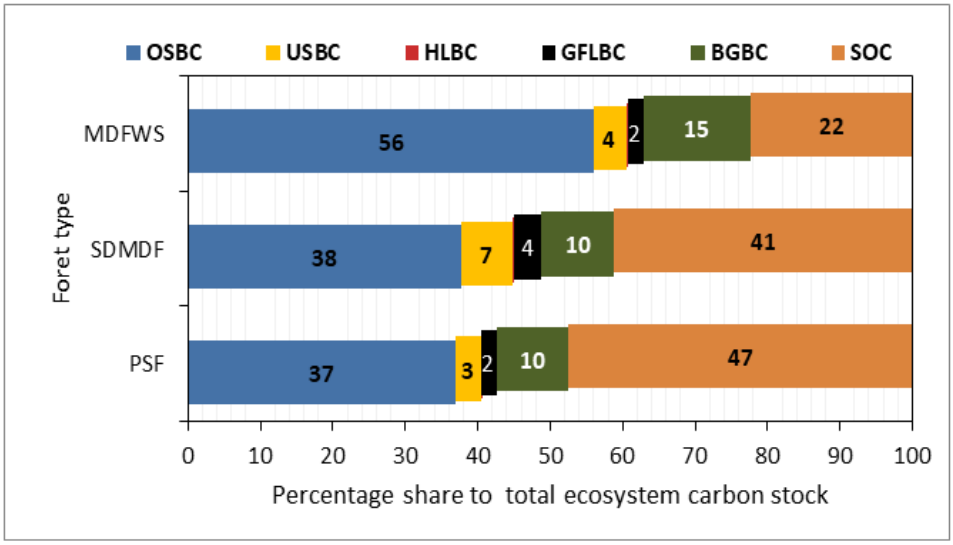


B).

Figure 6.3 Share of different components to total C stock A. vegetation components, B. ecosystem components. Abbreviations: OSBC- over-story biomass carbon, USBC- understory biomass carbon, HLBC- herbaceous layer biomass carbon, GFLBC- ground floor litter biomass carbon, BGBC- belowground biomass carbon, SOC- soil organic carbon

6.3.5. Contribution of major tree species to the biomass and carbon stock

The analysis of aboveground biomass (AGBS) and carbon stock (AGBCS) reveals that *Shorea robusta* dominates the PSF and SFMDF contributing 83.53% and 44.74 % to the total biomass carbon stock (TBCS). In PSF *Semecarpus anacardium* **(**7.43%), *Cleistanthus collinus* (1.45%), *Careya arborea* (1.25%) and all other species (5.29%) make smaller contributions. Similarly, in SDMDF apart from sal other major contributors include *Schleichera oleosa* (5.5%), *Buchanania lanzan* (3.65%) and *Pterocarpus marsupium* (3.32%) while the remaining species collectively contributed 40.45% to the total biomass C stock. MDFWS exhibited highest species diversity with biomass more evenly distributed among the species. Key contributors are *Terminalia alata* (8.00%), *Schleichera oleosa* (7.03%) and *Anogeissus latifolia* (5.38%) while all other species together account for 70.4% of the total biomass C emphasizing the forest's diverse composition.

Table 6.10 Contribution of major tree species to the aboveground biomass (Mg ha^{-1}) and carbon stock (Mg C ha^{-1}) of three forest types

Species	AGBS	BGBS	AGBCS	BGBCS	TBCS	% Share TBCS
Pure sal forest (PSF)						
Shorea robusta	153.9	40.01	72.33	18.81	91.14	83.53
Semecarpus anacardium	13.69	3.56	6.43	1.67	8.11	7.43
Cleistanthus collinus	2.67	0.69	1.26	0.33	1.58	1.45
Careya arborea	2.31	0.6	1.09	0.28	1.37	1.25
Terminalia alata	1.92	0.5	0.9	0.23	1.14	1.05
Rest of the species	9.75	2.54	4.58	1.19	5.78	5.29
Total	184.24	47.90	86.59	22.51	109.12	100
Sal dominated moist deciduous forest (SDMDF)						
Shorea robusta	74.61	19.4	35.07	9.12	44.18	44.74
Schleichera oleosa	9.18	2.39	4.31	1.12	5.43	5.5
Buchanania lanzan	6.09	1.58	2.86	0.74	3.6	3.65
Pterocarpus marsupium	5.53	1.44	2.6	0.68	3.27	3.32
Semecarpus anacardium	3.91	1.02	1.84	0.48	2.31	2.34
Rest of the species	74.9	10.12	35.19	4.75	39.97	40.45
Total	174.22	35.95	81.87	16.89	98.76	100
Moist deciduous forest without sal (MDFWS)						
Terminalia alata	23.12	6.01	10.87	2.83	13.69	8.00
Schleichera oleosa	20.34	5.29	9.56	2.49	12.05	7.03
Anogeissus latifolia	15.55	4.04	7.31	1.9	9.21	5.38
Mitragyna parvifolia	14.00	3.64	6.58	1.71	8.29	4.84
Desmodium oojeinensis	12.58	3.27	5.91	1.54	7.45	4.35
Rest of the species	203.64	52.87	95.71	24.84	120.55	70.4
Total	289.23	75.12	135.94	35.31	171.24	100

6.3.6 Annual biomass increment in different vegetation components

The net annual biomass increment varied significantly ($p<0.05$) across different vegetation components (tree, liana, herb, dead wood and aboveground litter) in the three forest types (Table 6.11). The tree biomass accumulation was highest in MDFWS (41.44 Mg ha^{-1}), followed by SDMDF (22.87 Mg ha^{-1}) and PSF (10.78 Mg ha^{-1}). While sapling and shrub biomass increments show no significant differences, liana and herbaceous biomass were notably higher in MDFWS. Deadwood accumulation was found higher in MDFWS (0.81 Mg ha^{-1}), whereas SDMDF records the highest aboveground litter accumulation (1.59 Mg ha^{-1}). The total annual biomass gain follows a similar pattern with tree biomass, with MDFWS (51.04 Mg ha^{-1}) exhibiting the highest productivity followed by SDMDF (31.73 Mg ha^{-1}) and PSF (17.97 Mg ha^{-1}).

Table 6.11 Net annual biomass (Mg ha^{-1}) increment of different vegetation components in PSF, SDMDF and MDFWS

Vegetation component	**PSF**	**SDMDF**	**MDFWS**	**Mean**	**LSD (P<0.05)**
Tree	10.78±2.64^{c}	22.87±2.48^{b}	41.44±1.74^{a}	25.03±4.61	8.03
Saplings	0.33±0.07^{ns}	0.46±0.05^{ns}	0.57±0.18^{ns}	0.45±0.06	0.39
Shrubs	0.36±0.05^{ns}	0.49±0.03^{ns}	0.48±0.05^{ns}	0.44±0.03	0.15
Liana	0.26±0.04$^{\mathbf{b}}$	0.49±0.10^{b}	0.97±0.08^{a}	0.58±0.11	0.27
Herbs	0.41±0.09^{b}	0.71±0.04^{b}	1.14±0.14^{a}	0.75±0.12	0.34
Dead wood	0.73±0.07^{ns}	0.85±0.10^{ns}	0.81±0.14^{ns}	0.79±0.06	0.37
Aboveground litter	1.61±0.10^{a}	1.59±0.04^{a}	0.46±0.02^{b}	1.22±0.19	0.23
Fine root litter	0.30±0.02^{a}	0.27±0.01^{a}	0.17±0.01^{b}	0.25±0.02	0.05
Total annual biomass gain	17.79±1.97^{c}	31.73±1.84^{b}	51.04±1.04^{a}	33.52±4.89	5.78

Values presented as mean ± Standard error, Different alphabetical letters indicate significant differences within the same row at P<0.05

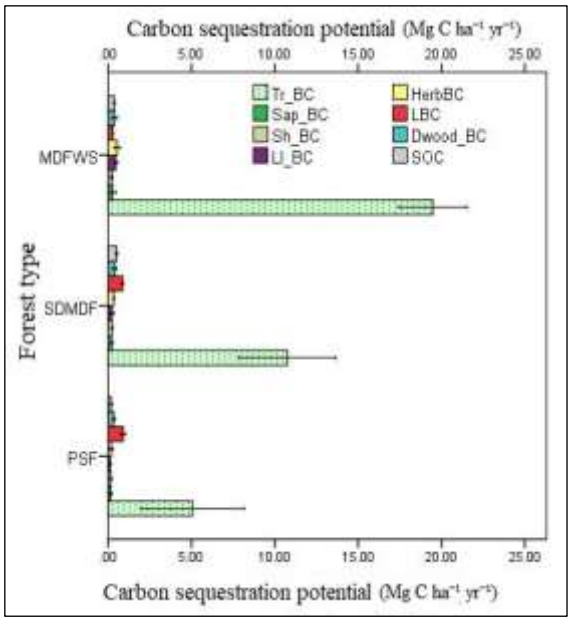
6.3.7 Annual carbon sequestration potential of different vegetation components

The annual carbon sequestration potential of different vegetation components across PSF, SDMDF, and MDFWS was found significant ($P<0.05$, Table 6.12). Among the vegetation components, trees exhibited the highest carbon sequestration capacity, with MDFWS recording the highest value (19.48 Mg C ha^{-1}), followed by SDMDF (10.75 Mg C ha^{-1}) and PSF (5.07 Mg C ha^{-1}). The contribution of saplings, shrubs and dead wood litter to carbon sequestration remained statistically non-significant across all forest types. However, other vegetation components, including lianas, herbs, litter and soil organic carbon (SOC) varied significantly among the forest types with MDFWS consistently exhibiting the highest sequestration values. Aboveground and belowground litter also played a significant role in carbon storage, with aboveground litter being highest in PSF (0.76 Mg C ha^{-1}) and the lowest in MDFWS (0.22 Mg C ha^{-1}). SOC values differed significantly, with SDMDF showing the highest sequestration (0.51 Mg C ha^{-1}), followed by MDFWS (0.37 Mg C ha^{-1}) and PSF (0.19 Mg C ha^{-1}). In terms of total carbon sequestration, MDFWS recorded the highest value (22.01 Mg C ha^{-1}), followed by SDMDF (13.54 Mg C ha^{-1}) and PSF (7.14 Mg C ha^{-1}).

Table 6.12 Annual carbon sequestration potential (Mg C ha^{-1}) of different vegetation components in PSF, SDMDF and MDFWS

Vegetation component	**PSF**	**SDMDF**	**MDFWS**	**Mean**	**LSD (P<0.05)**
Tree	5.07±1.24^{c}	10.75±1.16^{b}	19.48±0.82^{a}	11.76±2.16	3.77
Saplings	0.16±0.03^{ns}	0.22±0.02^{ns}	0.27±0.08^{ns}	0.21±0.03	0.18
Shrubs	0.17±0.02^{ns}	0.23±0.02^{ns}	0.22±0.02^{ns}	0.21±0.01	0.07
Liana	0.12±0.02^{b}	0.23±0.05^{b}	0.46±0.04^{a}	0.27±0.05	0.13
Herbs	0.19±0.04^{b}	0.34±0.02^{b}	0.54±0.06^{a}	0.36±0.05	0.16
Dead wood	0.34±0.03	0.39±0.05^{ns}	0.38±0.07^{ns}	0.37±0.03	0.17
Aboveground litter	0.76±0.05^{a}	0.75±0.02^{a}	0.22±0.01^{b}	0.57±0.09	0.11
Fine root litter	0.14±0.01^{a}	0.13±0.00^{a}	0.08±0.00^{b}	0.12±0.01	0.02
SOC	0.19±0.03c	0.51±0.02a	0.37±0.02b	0.36±0.05	0.07
Total C sequestration	7.14±1.21^{c}	13.54±1.15^{b}	22.01±0.77^{a}	14.23±2.22	3.69

Values presented as mean ± Standard error, Different alphabetical letters indicate significant differences within the same row at P<0.05



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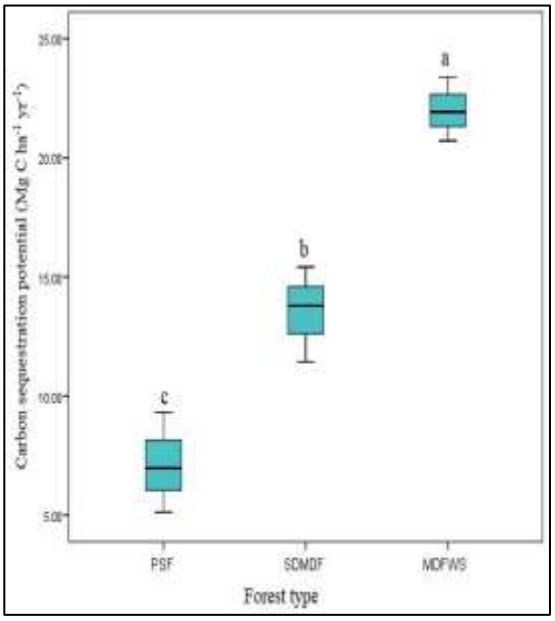


B.

Figure 6.4 Annual carbon sequestrations potential A). different vegetation components, B) three forest types. (Abbreviations: BC-biomass carbon, Tr- tree, SAP-sapling, Li- liana, Sh-shrub, Dwood-dead wood, SOC-soil organic carbon, L-litter biomass carbon, PSF- pure sal forest, SDMDF-sal dominated moist deciduous forest, MDFWS- moist deciduous forest without sal)

6.3.8 Carbon sequestration potential of different ecosystem components

The difference in carbon sequestration potential of different ecosystem components across three forest types was found significant ($P<0.05$, Table 6.13). Among these, MDFWS has significantly higher (LSD = 3.92 at $P < 0.05$) total carbon sequestration potential (27.42 Mg C ha^{-1} yr^{-1}), than SDMDF (19.64 Mg C ha^{-1} yr^{-1}) and PSF (11.94 Mg C ha^{-1} yr^{-1}). This trend was consistent across most biomass components, with MDFWS having the significantly (LSD = 3.00, $P <0.05$) higher over-story biomass carbon (15.46 Mg C ha^{-1} yr^{-1}) than SDMDF (8.53 Mg C ha^{-1} yr^{-1}) and PSF (4.02 Mg C ha^{-1} yr^{-1}). The C contributions from belowground biomass (root), understory vegetation (sapling, shrub and liana) and herbaceous layer plants showed similar pattern (MDFWS > SDMDF > PSF) with mean value 0.78 Mg C ha^{-1} yr^{-1}, 0.55 Mg C ha^{-1} yr^{-1} and 0.36 Mg C ha^{-1} yr^{-1} respectively. However, the carbon

contribution from forest floor litter and soil organic carbon (SOC) to annual carbon sequestration was significantly higher in SDMDF (1.15 and 0.51 Mg C ha^{-1} yr^{-1}) compared to PSF (1.10 and 0.19 Mg C ha^{-1} yr^{-1}) and MDFWS (0.59 and 0.37 Mg C ha^{-1} yr^{-1}) respectively. The Figure 6.5 illustrates the proportional contributions of distinct ecosystem carbon pools to total ecosystem C sequestration. The over-story biomass carbon (OSBC) contributes maximum to annual C sequestration rate followed by belowground biomass carbon (BGBC) and floor litter biomass carbon (FFLBC).

Table 6.13 Carbon sequestration potential (Mg C ha^{-1} yr^{-1}) of different ecosystem components in three forest types

Ecosystem component	**PSF**	**SDMDF**	**MDFWS**	**Mean**	**LSD (P<0.05)**
Over-story biomass	4.02 ± 0.99^{c}	8.53 ± 0.92^{b}	15.46 ± 0.65^{a}	9.34±1.72	3.00
Under story biomass	0.36 ± 0.03^{c}	0.54 ± 0.02^{b}	0.75 ± 0.03^{a}	0.55±0.05	0.08
Herbaceous layer biomass	0.19 ± 0.04^{b}	0.34 ± 0.02^{b}	0.54 ± 0.06^{a}	0.36±0.05	0.16
Forest floor litter biomass	1.10 ± 0.05^{a}	1.15 ± 0.04^{a}	0.59 ± 0.06^{b}	0.95±0.09	0.18
Belowground biomass	1.28 ± 0.26^{c}	2.49 ± 0.24^{b}	4.29 ± 0.17^{a}	2.69±0.45	0.78
Soil organic carbon	0.19 ± 0.03^{c}	0.51 ± 0.02^{a}	0.37 ± 0.02^{b}	0.36±0.04	0.07
Ecosystem C sequestration	7.14 ± 1.22^{c}	13.54 ± 1.16^{b}	22.01 ± 0.77^{a}	14.23±2.22	3.69

Note: Under story biomass carbon sequestration (CS) includes sapling, shrub and liana CS; belowground biomass CS includes coarse root and fine root biomass CS

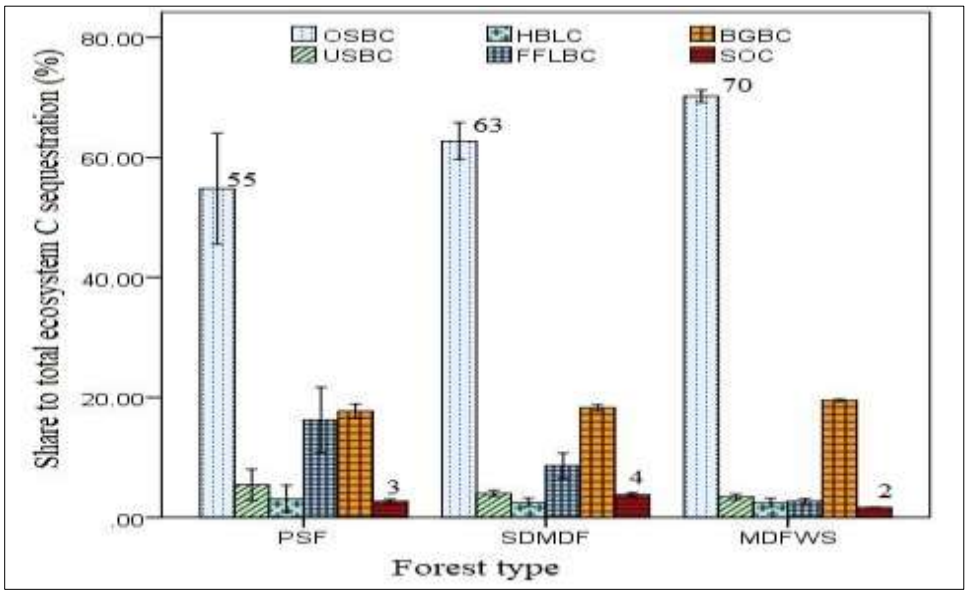


Figure 6.5 Percentage shares of different ecosystem components to total ecosystem C sequestration. Abbreviations: OSBC-over-story biomass carbon, USBC- under-story biomass carbon, HBLC-herbaceous layer biomass carbon, FFLBC-forest floor litter biomass carbon, BGBC- belowground biomass carbon, SOC-soil organic carbon

6.4 Discussion

Studying forest biomass production is crucial for understanding energy flow, primary productivity and nutrient cycling within ecosystem. The biomass estimates across different vegetation components, provides insights into energy transfer, carbon sequestration and nutrient movement, which are crucial for maintaining forest health and function. Biomass data also help to assess forest productivity, resilience and ecological balance, offering key information for sustainable forest management and conservation. Additionally, these studies are vital for understanding the role of forests in climate change mitigation by evaluating their carbon storage capacity and response to environmental stresses (Parresol, 1999).

Biomass production in a forest ecosystem varies with forest types, species composition, stand age and other site-specific factors such as soil fertility, precipitation and altitudinal variations (Khadanga and Jayakumar, 2020; Zhao *et al.*, 2014; Cao *et al.*, 2012). Though various vegetation components contribute to forest biomass production, the influence of tree biomass is substantial. Tree diameter, height and basal area are major attributes considered for determining forest biomass

estimation (Chave *et al.,* 2005). This phenomenon was observed in this study with highest total biomass stock in MDFWS (401.13 Mg ha^{-1}) which was attributed to higher tree density and basal area (Table 6.4 and 5.2). The aboveground biomass production ranged from 165.55 Mg ha^{-1} (PSF) to 313.04 Mg ha^{-1} (MDFWS) which is well within the range of aboveground biomass production reported earlier for tropical forests of Deogarh district of Odisha (13.96 to 514.50 Mg ha^{-1}, Pradhan *et al.,* 2019), Mahendragiri hill ranges of the Eastern Ghats (102.04 to 202.85 Mg ha^{-1}, Khadanga and Jayakumar, 2019), Santhapur reserve forests of Tamil Nadu (64.81 to 624.95 Mg ha^{-1}, Gandhi and Sundarpandian, 2017), sal forests of Sonebhadra, Uttar Pradesh (247 to 392 Mg ha^{-1}, Chaturvedi and Raghubanshi, 2015). The variations in tree AGB of three forest types was ascribed to differences in stand structural attributes *viz.* density and basal distribution among various diameter classes (Behera *et al.,* 2017). The aboveground biomass of lianas ranged from 6.09 Mg ha^{-1} in PSF to 14.70 Mg ha^{-1} in SDMDF, aligning with the reported liana biomass of 0.74 to 18.5 Mg ha^{-1} in the tropical dry evergreen forests of peninsular India (Pandian and Parthasarathy, 2016). Likewise, the herbaceous layer contributed between 0.41 and 1.14 Mg ha^{-1} to the total forest biomass, which was comparable to the herb biomass of 1.0 to 1.54 Mg ha^{-1} recorded in the tropical forests of Satpura, Madhya Pradesh (Pande, 2005).

Trees contribute the most to forest biomass due to their large size, higher wood density, longevity and structural dominance. Compared to other vegetation elements such as shrubs, lianas and herbs, trees have much higher wood density and volume, allowing them to sequester and store significantly higher amounts of carbon over long periods. Their strong influence within forest ecosystems makes them the primary contributor to total biomass carbon (Chave *et al.,* 2005; Brown *et al* 1989). In this study, the contribution of tree AGB to forest biomass carbon ranged from 46% in PSF to 71% in MDFWS and that of SOC from 22% in MDFWS to 47% in PSF, respectively. The higher SOC percentage in PSF was due to the accumulation of a thick forest floor litter layer, resulting from a slower decay rate and extensive root biomass. In contrast, MDFWS had a species mixture matrix characterized by rapidly decomposing litter, resulting in lower SOC storage (Chaturvedi *et al.,* 2011). The total carbon stock of three forests observed in this study ranged from 242.41 Mg

C ha^{-1} (MDFWS) to 172.68 Mg C ha^{-1} (SDMDF) was comparable with the C stock of 224.80 to 373.90 Mg C ha^{-1} in sal forests of Kumaun Himalaya (Siddiqui *et al.,* 2024), 189.29 to 230.81 Mg C ha^{-1} in Siwalik sal forests (Kongkham *et al.*, 2021).

The significant difference ($P < 0.05$) in carbon sequestration potential among the three forest types can be attributed to variations in tree density, species composition, productivity and litter decomposition rate. MDFWS exhibited the highest sequestration potential (22.01 Mg C ha^{-1} yr^{-1}), likely due to higher species diversity, tree density, basal area leading to increased biomass accumulation that enhanced both aboveground and belowground carbon storage (Chave *et al.,* 2005; Malhi and Grace, 2000). Pure sal forest had the lowest sequestration (7.14 Mg C ha^{-1} yr^{-1}) due to lower species diversity, reduced litter decomposition and lower biomass accumulation by sal tree (Brown, 1989). Jana *et al.* (2009) reported a carbon sequestration potential of 11.97 Mg C ha^{-1} yr^{-1} for sal saplings in the Chadra forest of West Bengal. The observed sequestration rate of 13.54 Mg C ha^{-1} yr^{-1} in SDMDF is comparable to this estimate. Similarly, Lasco and Pulhin (2003) documented a sequestration rate of approximately 15.0 Mg C ha^{-1} yr^{-1} in tropical forest ecosystems. The higher carbon sequestration observed in MDFWS (22.01 Mg C ha^{-1} yr^{-1}) can be attributed to a greater proportion of young trees, which contribute significantly to total annual biomass increment. Additionally, this elevated rate results from the inclusion of all biomass sources such as shrubs, lianas, herbs and deadwood that are frequently overlooked in carbon sequestration assessments.

CHAPTER-7

LITTER FALL AND ITS DYNAMISM

7.1 Introduction

Litter fall in forests is a crucial ecological process that significantly contributes to nutrient cycling, soil formation and overall ecosystem functioning (Giweta, 2020). In a forest ecosystem, litter can originate from both plant and animal populations. Plant litter includes all kind of organic material *viz*. leaves, branches, barks and reproductive parts that fall to the forest floor after senescence or detachment from mother plant for some reason. Litterfall from senescent leaf accounts for two-third of above-ground litter mass in forests (Krishna and Mohan, 2017). Once the litter reaches to the forest floor, it undergoes into complex decay process which is influenced by various intrinsic (substrate quality, litter composition, nutrient content, size and surface area of litter) and exogenic (climatic and edaphic variable; fauna and microbial activity) factors of the forest (Bohara *et al.,* 2020; Paudel *et al.,* 2015; Lalnunzira and Tripathi 2018). Apart from this species composition also influences forest floor standing litter on at a particular time (Olson, 1963). Once decomposition process starts complex organic compounds present in litter are mineralised releasing inorganic nutrients that support plant productivity and soil fertility building through accumulation of soil organic matter. The recycling pathway consisting photosynthesis, litter fall and decay regulates the nutrient budget of forests. This is crucial in natural terrestrial ecosystems where vegetation depends on recycling of nutrients from plant detritus.

For understanding litter dynamics, it is essential to consider the different types of forests, their geographical locations, involved littering species and the environmental conditions that govern the processes (Aponte *et al.,* 2012). Tree species significantly contribute to litter pool in a forest through leaf drop and the shedding of other plant parts which can be either a seasonal or continuous process. Anthropogenic activities such as logging, lopping, NTFP collection, fire, grazing, mining and quarrying directly or indirectly alter structure and composition of forest

(Richards *et al.,* 2022; Singh and Borthakur 2015). These can affect the microclimate (air temperature and relative humidity), canopy density as well as litter quality due to alteration in species composition and traits. Since climatic factors and litter quality regulate litter decay, forest management and disturbances can also affect the nutrient cycling process. It is well established that microbial activity in disturbed tropical forest is quite low and thus a slower decomposition process (Leal *et al.,* 2023). Sal forests occur in tropical to subtropical climates and accounts nearly 14% of the total forest area of India. These forests are much exploited for multifarious produce they generate. The moist deciduous forest of Kandhamal district dominated by sal is also much exploited by tribals for timber, fuel wood and much other forest produces. Forest soils within this track of the Eastern Ghats are highly weathered and leached by heavy annual rainfall (~1500 mm). However, these soils support dense forest cover with climax species sal having higher girth classes. Hence it is essential to have an understanding on the nutrient recycling process mediated by litter decomposition and dynamics in forests of this region.

7.2 Material and methods

7.2.1 Quantification of litter input to soil

Litter production in the studied forest type *viz*. PSF, SDMDF and MDFWS) was determined by litter trap technique. Ten numbers of litter traps of size 1 m x 1 m x 30 cm were constructed within the vegetation sample plots using locally available stones to capture floral litter (senescent leaf, reproductive parts and small branches <2.5cm diameter). The fine root litter (<2.0 cm diameter) was collected adopting sequential soil core method using a steel auger (inner dia 7.5 cm x length 60 cm) at four random places within the canopy layer up to the depth of 45 cm (Pandey *et al.,* 2023). The above-ground litter and fine root litter were collected seasonally (Winter-January, Summer-May and Rainy-September) and summed up to estimate the annual litter production. Litter thus collected were segregated plant part wise, oven-dried at 60 ^{0}C for 72 hours for estimating annual litter input to soil and further analysis.

7.3 Chemical analysis of litter samples

7.3.1 Sample preparation

Freshly collected and recovered litters (after cleaning soils and other debris on the nylon-net bags with a hair brush) were oven dried at 60 ^{0}C for 72 hours, grinded to fine powder and stored in glass jars for further chemical analysis *viz*. estimation of phosphorus (P), Potash (P), calcium (Ca), Magnesium (Mg), lignin (L), cellulose, hemicellulose and total phenol content.

7.3.2. Determination of total organic carbon and Nitrogen

The total organic carbon (C) and total nitrogen (N) was estimated by combusting 0.2 mg of oven dried samples in CHNS analyzer (Elementar UNICUBE, with accuracy; 99.7 ± 0.3 %).

7.3.3 Determination of phosphorus (P), Potash (K), Calcium (Ca), Magnesium (Mg)

7.3.3.1 Digestion of litter samples

Powdered litter samples were digested with a 3:2 di-acid mixture of Nitric Acid (HNO_3) and Perchloric Acid ($HClO_4$) (Bockheim *et al.*, 1991). A 0.5 g powdered litter sample was digested with 15 ml of concentrated HNO_3 in a conical flask, left at room temperature overnight. The mixture was then heated on a hot plate until brown fumes appeared, followed by the addition of 5-10 ml of di-acid mixture. The flask was heated until white fumes appeared, then cooled. After adding 1 ml of 6N HCl, it was gently heated for one minute. The mixture was transferred to a volumetric flask, diluted to 50 ml and filtered through a 0.22-micron syringe filter.

7.3.3.1 Estimation of P, K, Ca and Mg

Digested litter samples were analyzed for key nutrients phosphorus (P), potash (K), calcium (Ca) and magnesium (Mg) using inductively coupled plasma optical emission spectrometry (ICP-OES) with a Perkin Elmer-Avio 200 dual view analyzer. [Perkin Elmer- Avio 200 with dual view analyzer controlled by Syngistix software with analysis set up: 1500 W RF power, Replicates-3, 8 L/m in gas flow, 0.3 L/min auxiliary gas flow, and 0.8 L/min nebulizer gas flow].

7.3.4 Estimation of cellulose, hemicellulose and lignin content

The cellulose, hemicellulose, and lignin content of the litter sample were determined using a modified direct estimation method of Moubasher *et al.,* (1982). The powdered litter sample (3.0 g) was subjected to extraction in a Soxhlet apparatus with 75 ml of a Methanol-Toluene (2:1) mixture to remove oils, gums and other polar solvents. The residual mass was thoroughly washed with distilled water, oven-dried at 40 °C overnight, weighed and designated as fraction A. It was then treated with a 24% KOH solution (100 ml/g of biomass) for 4 hours at 25 °C, washed five times with distilled water, dried overnight at 80 °C and the dry weight was recorded as fraction B. The same sample again treated with 72% H_2SO_4 for 4 hrs to hydrolyze the cellulose, then refluxed with 5% H_2SO_4 for 2hrs. After thorough washing with distilled water to remove H_2SO_4, the sample was dried overnight at 80 °C and the dry weight was recorded as fraction C. Lignin, cellulose and hemicellulose was calculated as follows:

Lignin (%) = $(C/W_0]$ x 100

Cellulose (%) = $[(B-C)/ W_0]$ x 100

Hemicellulose (%) = $[(A-B)/ W_0]$ x 100

Where W_0 – Initial dry weight of powdered litter mass

7.3.5 Estimation of total phenol content

The total phenol content in litter samples was determined through Folin-Ciocalteu method (Sánchez-Rangel *et al*., 2013).

7.3.5.1 Preparation of crude extract of litters

To obtain the aqueous methanolic extract, 3 g each of the powdered samples of leaf, small bark-reproductive parts and root litter were refluxed for 90 minutes using 30 milliliters of a methanol-distilled water mixture (4:1) as the solvent. After extraction, the aqueous methanolic plant extract was filtered into a beaker and concentrated on a water bath. The extract was air-dried for 3 to 5 days until solid encrustation formed.

After drying, the flakes were scraped, crushed into a fine powder and mixed thoroughly. The crude extract yield was then calculated using the following formula.

Crude extract yield (%) = (Wt. of the extract /Wt. of dried sample) × 100

7.3.5.2 Preparation of standard curve of Gallic Acid

A solution of gallic acid was prepared by dissolving 1g in 1 liter of distilled water, followed by a 1:50 dilution to create stock solution. From this stock solution, 1.0 to 5.0 ml aliquots were pipetted to separate test tubes, mixed with 0.5 ml of Folin-Ciocalteu reagent followed by varying volumes (7.0 to 3.0ml respectively) of distilled water. After 10 minutes, 1.5 ml of a 20% sodium carbonate solution (w/v) was added to each tube. The solutions were covered with silver foil and incubated in the dark for 4 hours at room temperature. The absorbance of each solution was then measured using a UV-double beam spectrophotometer at 755 nm and graph was generated to know the relationship between Gallic acid concentration (X) and absorbance values (Y). The linear equation was found as

$Y = 50.143X-0.0014$ $(R^2 = 0.9956)$

7.3.5.3 Estimation of total phenol content (TPC) in litter samples

Ten milligrams of dried plant extract was taken in a test tube, added with 3 to 4 drops of methanol, 50 ml of distilled water and thoroughly mixed. One milliliter of this solution was pipetted into another test tube, mixed with 0.5 ml of Folin-Ciocalteu reagent and 7 ml of distilled water, allowed to react for 10 minutes following which 1.5 ml of 20% Na_2CO_3 (w/v) was added, resulting in a total volume of 10 ml. A blank solution was prepared in the same manner using only distilled water, Folin-Ciocalteu reagent, and sodium carbonate. All solutions were covered with silver foil and stored in the dark for 4 hours at room temperature. Absorbance was measured at 755 nm with a UV spectrophotometer, and total phenolic content (mg GAE/g sample) was calculated as per the following equation.

$$TPC\ \frac{Absorbance\ of\ sample}{Absorbance\ of\ standard} \times\ Conc.of\ standard\ \times \frac{1}{Sample\ wt.(g)}$$

7.3.6 Quantification of litter decomposition kinetics, mass loss and nutrient release

The litter decomposition rate was studied by nylon net bag technique (Bocock *et al.,* 1960). The collected above-ground litters (senescent leaves, reproductive parts, small branches, cleaned fine roots) were shade dried till constant weight is achieved. Litters were categories into three group *viz*. leaf litter, small branch and reproductive parts litter and fine root litter. Five grams of well mixed litter (each sample plot) from each category were placed in nylon-net bags of size 15 cm × 15 cm and 1 mm mesh. 360 numbers of such bags were prepared (120 for each category leaf, small branch and root litter) and buried at 10-15 cm depth in different locations of study site in each forest types (Figure 7.1). Ten bags containing decomposing litter recovered at monthly intervals from the ground until 95% decomposition occurred. The recovered litter bags were cleaned with a small brush carefully, oven dried for 36 hours at 60 ^{0}C and weighed. The annual decay rate (k) was calculated as per the mathematical equation as follows:

$$k = -\text{Ln}\,(M_t/M_0)/t$$ **(**Olson, 1963)

Where:

M_0 - Initial dry weight of litter at the time of incubation in top soil

M_t -Dry weight remaining at time t of collection

t - time of collection

The time required for 50 % (t_{50}) and 99 % (t_{99}) decay were calculated from the decay rate coefficient (k) using following equation.

t_{50} =0.693/k and t_{99}=5/k (Olson, 1963)

Weight loss was determined by subtracting the initial mass from the sampled mass at each sampling point and then dividing the difference by the initial mass.

Weight loss (%) = [(Initial weight – Final weight)/ Initial weight] x 100

(Rai *et al.,* 2016)

The nutrient content of litter at the end of the experiment was determined adopting standard procedure and nutrient release (NR) was determined using following equation.

$$NR\ (\%) = \frac{M_0N_0 - M_tN_t}{M_0N_0} \times 100 \qquad \text{(Guo and Sims, 1999)}$$

Where NR represents the nutrient release percentage, N_0 is the initial nutrient concentration of the litter, and N_t is the nutrient concentration at time t.

7.3.7 Statistical analysis of data

The variation in initial litter fall, nutrient content, and litter mass loss across different forest types and litter categories was evaluated using one-way analysis of variance (ANOVA), after testing for normality and outliers. The litter decay constant was calculated using Microsoft Excel 2011. Post hoc analysis was performed using Duncan's test to determine the significance of litter components. Pearson correlation analysis was conducted to examine the relationships between different litter components. All statistical analyses were done using SPSS-20 (Statistical Package for the Social Sciences).

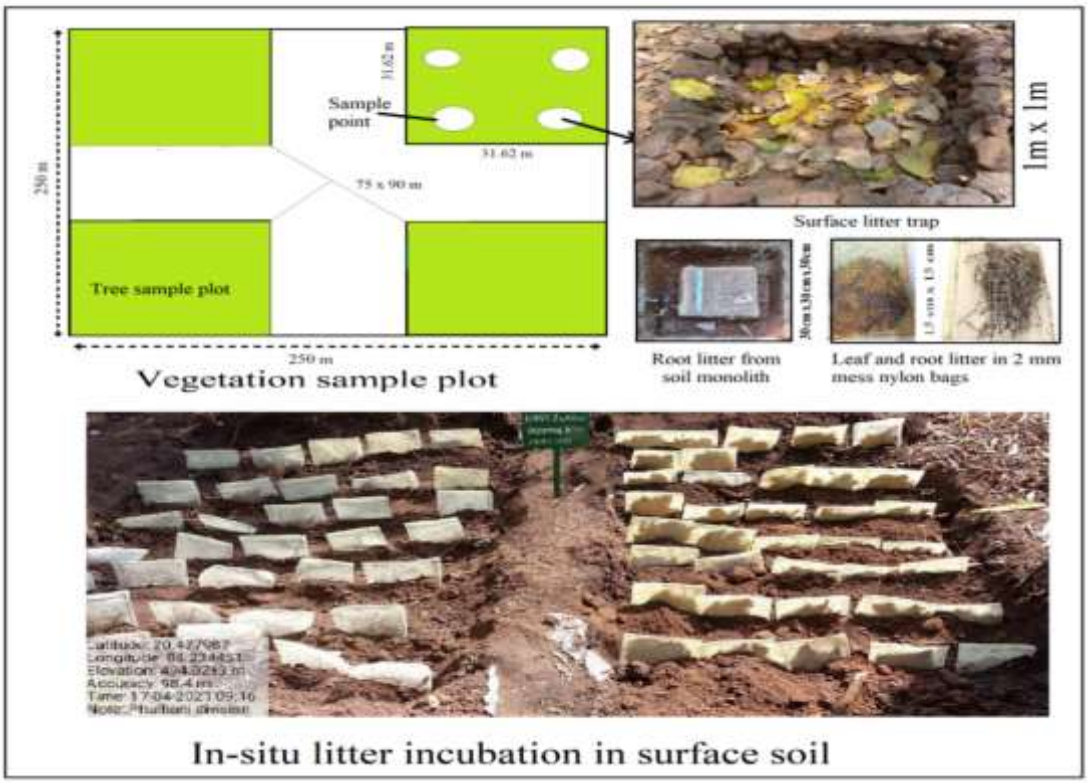


Figure 7.1 Litter collection and *in-situ* incubation in surface soil

7.4 Results

7.4.1 Seasonal variations in litter fall in three forest types

The seasonal and annual variation in litter fall was presented in Table 7.1. The total annual litter fall was significantly ($p<0.05$) highest for SDMDF (12.77 Mg ha^{-1} yr^{-1}) followed by PSF (10.58 Mg ha^{-1} yr^{-1}) and MDFWS (8.93 Mg ha^{-1} yr^{-1}). The share of above-ground litter (leaf, small branch and reproductive parts) to annual litter pool ranged from 90.60 % in SDMDF to 88.47 % in MDFWS (Figure 7.2). Among the different plant parts that make up the above-ground litter mass, senescent leaves (foliage) contributed 70.88 % to 75.33 % (Figure 7.3). The annual litter fall of leaves, small branches, and reproductive parts showed significant differences among the three forest types, whereas the variation in root litter was not statistically significant. Litter fall followed a unimodal distribution pattern in all forest types with a distinct peak litter fall during winter months (December-February). Total litter fall during winter season was significantly high ($P<0.05$) in SDMDF (7.57 Mg ha^{-1} yr^{-1}) followed by PSF (5.82 Mg ha^{-1} yr^{-1}) and MDFWS (4.49 Mg ha^{-1} yr^{-1}). Equal quantity of litter (1.37 Mg ha^{-1} yr^{-1}) was generated in SDMDF and PSF. The variation in litter fall among forest types during summer months was not statistically significant ($P = 0.47$). There were significant seasonal variations in fine root biomass ($P < 0.001$) across different forest types except summer season. The annual litter fall in three forest types was positively and significantly ($P<0.05$) correlated with tree density (0.733) and tree basal area (0.997) (Table 7.2).

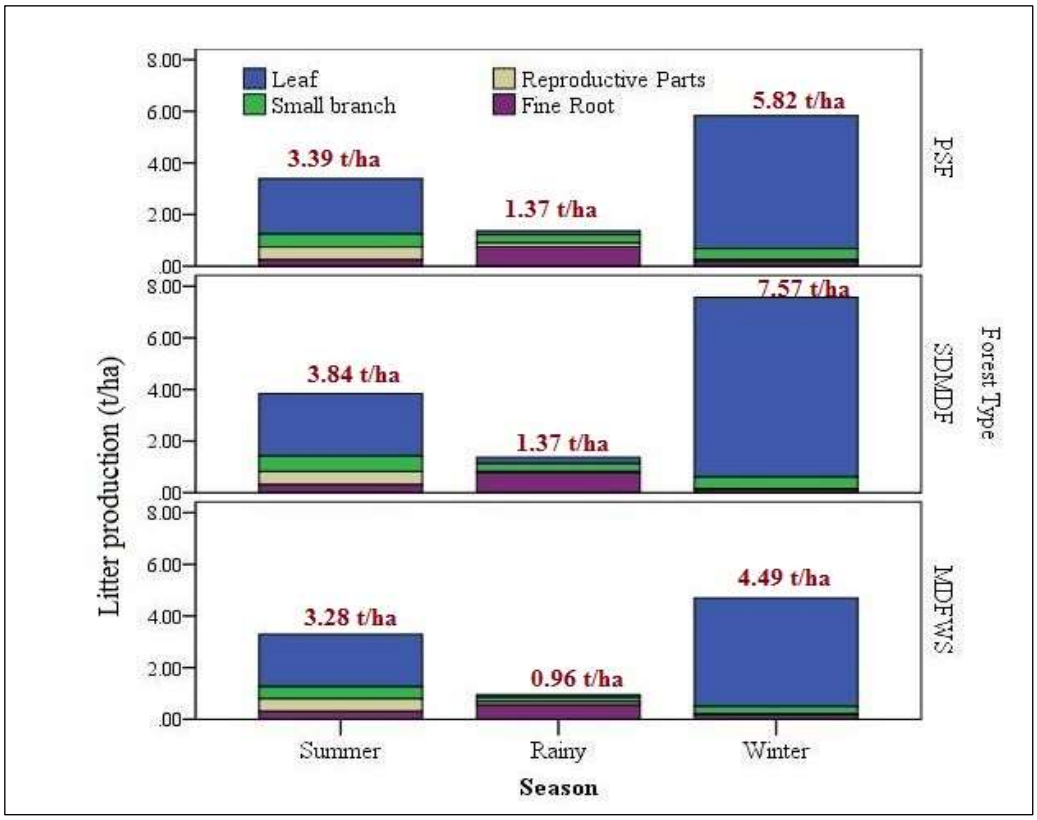


Figure 7.2 Seasonal variations in litter fall in three forest types

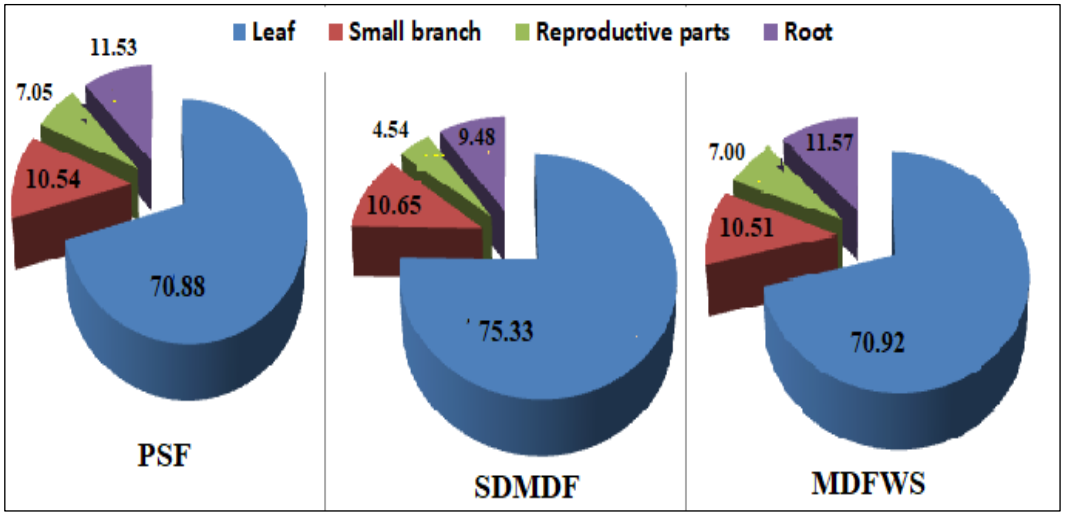


Figure 7.3 Constituents of litter pool in three forest types

Table 7.1 Seasonal variation in litter fall (Mg ha^{-1}) in three forest types

Forest Type	Season	Leaf litter	Small branch litter	Rep. parts	Total AG litter (4+5+6)	Fine root litter	Total annual litter (6+7)
1	2	3	4	5	6	7	8
PSF	Summer	2.14^{ns} (0.06)	0.51^{A} (0.03)	0.50^{ns} (0.03)	3.15^{ns} (0.09)	0.24^{ns} (0.05)	3.39^{ns} (0.17)
	Rainy	0.16^{A} (0.02)	0.32^{B} (0.01)	0.15^{B} (0.02)	0.63^{C} (0.002)	0.75^{B} (0.06)	1.37^{B} (0.11)
	Winter	5.15^{B} (0.27)	0.42^{B} (0.03)	0.07^{B} (0.02)	5.64^{B} (0.13)	0.19^{B} (0.01)	5.82^{B} (0.30)
	Total	**7.45a (0.28)**	**1.24b (0.15)**	**0.72c (0.08)**	**9.41b (0.21)**	**1.17^{ns} (0.06)**	**10.58b (0.39)**
SDMDF	Summer	2.41^{ns} (0.26)	0.60^{B} (0.04)	0.51^{ns} (0.04)	3.53^{ns} (0.11)	0.31^{ns} (0.02)	3.84^{ns} (0.35)
	Rainy	0.24^{B} (0.04)	0.30^{B} (0.31)	0.05^{A} (0.000)	0.59^{B} (0.05)	0.78^{B} (0.04)	1.37^{B} (0.05)
	Winter	6.96^{C} (0.21)	0.47^{B} (0.01)	0.02^{A} (0.00)	7.44^{C} (0.20)	0.12^{A} (0.01)	7.57^{C} (0.23)
	Total	**9.62b (0.44)**	**1.37c (0.12)**	**0.58a (0.04)**	**11.57c (0.11)**	**1.21^{ns} (0.04)**	**12.77c (0.51)**
MDFWS	Summer	2.03^{ns} (0.24)	0.47^{A} (0.02)	0.48^{ns} (0.02)	2.98^{ns} (0.22)	0.30^{ns} (0.02)	3.28^{ns} (0.31)
	Rainy	0.11^{B} (0.01)	0.17^{A} (0.01)	0.13^{B} (0.02)	0.41^{A} (0.02)	0.55^{A} (0.02)	0.96^{A} (0.05)
	Winter	4.19^{A} (0.32)	0.31^{A} (0.03)	0.01^{A} (0.00)	4.51^{A} (0.34)	0.18^{B} (0.01)	4.49^{A} (0.29)
	Total	**6.33^{a} (0.57)**	**0.94^{a} (0.14)**	**0.63^{b} (0.09)**	**7.90^{a} (0.11)**	**1.03^{ns} (0.06)**	**8.93^{a} (0.64)**
P value (season)	Summer	0.291	0.01	0.540	0.311	0.785	0.470
	Rainy	0.02	<0.001	0.001	0.03	0.005	0.006
	Winter	<0.001	0.006	<0.001	<0.001	0.007	<0.001
P value (Forest type)		0.005	<0.001	<0.001	0.003	0.158	0.003

Values in parenthesis () are standard error of means, Total litter values accompanying same alphabet in lower case (a, b) are not statistically different for the specific litter type in the Duncan's multiple range test (DMRT). Season wise litter fall mean values superscript with same alphabet in upper case (A, B) is not statistically different in DMRT for the corresponding season and litter type among forest types (same column).

Table 7.2 Pearson's correlation coefficient between vegetation attributes and total annual litter fall in three forest types

Vegetation attributes	SR	TD	TBA	SDI
Tree density (TD)	0.456			
Total basal area of trees (TBA)	-0.269	0.734		
Shannon diversity index (SDI)	0.730	0.941	0.462	
Total annual litter fall (TALF)	-0.271	0.733*	0.997**	0.460

*. Correlation is significant at the 0.05 level, **. Correlation is significant at the 0.01 level; Sr-species richness,

7.4.2 Quality of various types of litter

The initial concentrations of nutrients and secondary compounds in the oven dried leaf, small branch and root litter varied significantly except carbon (Table 7.2). The concentration of all nutrients (N, P, K) was low in all litter categories across the three forest types. The carbon concentration varied from 373.57 mg g^{-1} in small branch (SB) litter to 457.87 mg g^{-1} in root litter. Although the variation in carbon concentration of small branch litter among the three forest types was statistically significant, the differences were not substantial. In contrast, the variation in the other two categories of litter (leaf and root) was not statistically significant. In different litter components the concentration of hemicellulose ranged from 233.22 mg g^{-1} to 466.67 mg g^{-1}, cellulose ranged from 143.02 mg g^{-1} to 579.60 mg g^{-1}, lignin ranged from 116.89 mg g^{-1} to 293.33 mg g^{-1} and total phenol content ranged from 134.52 mg g^{-1} to 220.45 mg g^{-1}. Maximum hemicellulose content was found in PSF root litter, cellulose content in MDFWS root litter, lignin content in PSF small branch litter and total phenol content in MDFWS leaf litter. The nitrogen content ranged from 5.00 mg g^{-1} to 8.30 mg g^{-1}, phosphorus content ranged from 1.07 mg g^{-1} to 2.91 mg g^{-1} and potash content ranged from 0.99 to 2.81 mg g^{-1} in different litter categories of three forest communities. The carbon to nitrogen ratio (C/N) ratio and lignin to nitrogen ratio (L/N) ranged from 53.70 mg g^{-1} to 79.10 mg g^{-1} and 16.78 mg g^{-1} to 58.67 mg g^{-1} across various categories of litter and forest types respectively. Significantly highest C/N ratio was observed in all litter components of PSF

community. A similar pattern was also noted for the L/N ratio. Overall, the nutrient content (N, P and K) in leaf litter was higher compared to small branch and root litter.

Table 7.3 Initial concentrations of nutrients and secondary compounds in leaf, small branch and root litter (mg g^{-1}) of three forest types

Litter type and attribute	**PSF**	**SDMDF**	**MDFWS**	**P-value (0.05)**
Leaf litter				
Carbon (C)	439.80±6.03^{ns}	447.70±5.69 ^{ns}	445.40±8.64 ^{ns}	0.850
Nitrogen (N)	7.17±0.21^{a}	7.60±0.12^{a}	8.30±0.25^{b}	0.014
Phosphorus	2.64±0.06^{ab}	2.91±0.15^{b}	2.42±0.17^{a}	0.048
Potash	2.31±0.12^{a}	2.07±0.06^{a}	2.81±0.04^{b}	0.001
Hemicellulose	336.11±15.28^{a}	427.44±27.69^{b}	407.89±32.67^{b}	0.044
Cellulose	279.63±36.85^{ns}	277.50±11.86^{ns}	279.70±29.12^{ns}	0.997
Lignin (L)	271.00±8.59^{c}	192.11±7.54^{b}	157.0±21.40^{a}	<0.001
TPC-GAE	220.45±11.73^{b}	183.01±12.20^{a}	157.80±7.31^{a}	0.012
C/N ratio	61.37±1.75^{b}	58.92±0.81^{b}	53.70±0.62^{a}	0.003
L/N ratio	32.65C0.28^{c}	25.30±1.16^{b}	21.91±1.98^{a}	0.002
TPC/N ratio	30.78±2.14^{c}	24.18±2.18^{b}	19.06±1.36^{a}	0.015
Small branch and reproductive parts				
Litter type and attribute	**PSF**	**SDMDF**	**MDFWS**	**P-value (0.05)**
Carbon	373.57±7.57^{a}	413.53±9.98^{b}	421.57±21.37^{b}	0.007
Nitrogen	5.00±0.06^{a}	5.70±0.12^{b}	6.03±0.31^{b}	0.001
Phosphorus	1.54±0.06^{b}	1.37±0.07^{b}	1.14±0.11^{a}	0.005
Potash	1.11±0.12^{ns}	0.99±0.08^{ns}	1.06±0.11^{ns}	0.066
Hemicellulose	357.89±49.42^{ns}	382.11±27.31^{ns}	348.00±14.16^{ns}	0.775
Cellulose	216.02±21.63^{a}	202.95±18.62^{a}	338.91±16.24^{b}	0.011
Lignin	293.33±11.95^{c}	249.42±10.62^{b}	191.44±12.13^{a}	<0.001
TPC-GAE	196.71±4.39^{b}	174.32±6.37^{ab}	138.55±8.93^{a}	0.40
C/N ratio	74.71±1.21^{b}	72.54±1.35^{ab}	69.93±1.18^{a}	0.050
L/N ratio	58.67±2.30^{c}	43.76±1.66^{b}	31.75±5.10^{a}	<0.001
TPC/N ratio	39.42±1.85^{c}	30.53±1.42^{b}	22.98±1.67^{a}	0.02

Root litter				
Litter type and attribute	**PSF**	**SDMDF**	**MDFWS**	**P-value (0.05)**
Carbon	440.23±8.06^{ns}	457.87±2.90 ^{ns}	444.53±9.13 ^{ns}	0.49
Nitrogen	5.57±0.09^{a}	6.33±0.13^{b}	6.97±0.35^{c}	<0.001
Phosphorus	1.08±0.06^{a}	1.32±0.03^{b}	1.07±0.11^{a}	0.003
Potash	1.32±0.04^{a}	1.23±0.04^{a}	1.87±0.05^{b}	<0.001
Hemicellulose	466.67±17.67^{b}	404.33±19.35^{b}	233.22±20.26^{a}	0.02
Cellulose	143.02±14.70^{a}	233.59±23.74^{a}	579.60±20.95^{c}	<0.001
Lignin	255.22±6.40^{c}	200.11±2.08^{b}	116.89±13.50^{a}	<0.001
TPC-GAE	184.18±8.82^{b}	192.74±2.16^{b}	134.52±4.79^{a}	0.013
C/N ratio	79.10±1.35^{c}	72.37±1.88^{b}	63.78±3.07^{a}	0.001
L/N ratio	45.84±2.45^{c}	31.62±2.62^{b}	16.78±4.78^{a}	<0.001
TPC/N ratio	33.21±1.05^{b}	30.45±2.38^{b}	19.37±1.14^{a}	0.011

Values in parenthesis () are standard error of means, Nutrient concentration values accompanying same alphabet in lower case (a, b) are not statistically different for the specific litter type in the Duncan's multiple range test (DMRT). TPC-GAE: Total phenol

7.4.3 Mass loss during decomposition of litter

In time-course study of litter mass remaining revealed significant variations ($P < 0.01$) in the decay rate across all litter categories in the three forest types (Table 7.4). Three distinct phases of mass loss were observed in this study. In all categories of litter, the first phase was marked by a slow decay rate during summer season. This was followed by a rapid phase of mass loss during rainy season. The third phase, which took place in winter, the mass loss continued at a relatively constant rate (Figure 7.4). Maximum mass loss occurred in leaf litter followed by root litter and small branch litter. As far as impact of litter generation source (forest type) is concerned maximum litter decay was noticed in MDFWS forest for all categories of litter. Mass loss in PSF litter was slowest with 12.70% of leaf litter, 35.80% of small branch litter and 25.83% of root litter remaining after 270 days of incubation. Rapid mass loss occurred between days 60 and 120 of incubation in all forest types and litter categories, coinciding with the rainy season, followed by a gradual mass loss phase for the remaining days. The decay

rate constant for leaf litter ranged from 2.82 a^{-1} to 4.75 a^{-1}, small branch litter 1.39 a^{-1} to 2.32 a^{-1} and root litter 1.83 a^{-1} to 2.69 a^{-1}. The time required for 50% mass decay (t_{50}) was significantly highest for all types of litter generated from PSF (leaf 0.25 a^{-1}, small branch 0.50 a^{-1}, root 0.38 a^{-1}). A similar pattern was also noted for the 99% mass decay (t_{99}). The mean residence time (1/k) was also significantly highest for each litter components of PSF (leaf 0.35 a^{-1}, small branch 0.72 a^{-1}, root 0.55 a^{-1}) and lowest for MDFWS community (leaf 0.21 a^{-1}, small branch 0.42 a^{-1}, root 0.41 a^{-1}).

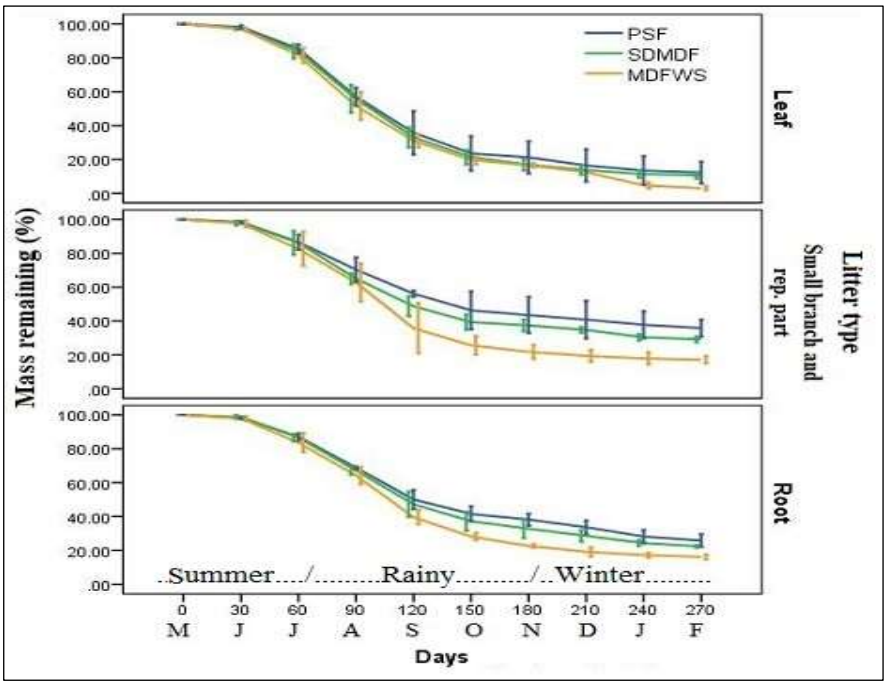


Figure 7.4 Mass remaining at different days of litter incubation in soil

Table 7.4 Decomposition parameters (decay rate) and time required for various level of decay (t_{50} 50% and t_{99} 99%) of different categories of litter in three forest types

Litter type	Forest type	Annual decay rate (k)	t_{50} (Year)	t_{99} (Year)	Residence time (1/k) (a^{-1})	Mass remaining (% initial)
Leaf	PSF	2.82 ± 0.02^{a}	0.25 ± 0.02^{b}	1.79 ± 0.14^{b}	0.35 ± 0.02^{c}	12.70 ± 1.91^{b}
	SDMDF	3.03 ± 0.06^{a}	0.23 ± 0.004^{b}	1.65 ± 0.03^{b}	0.33 ± 0.03^{b}	10.63 ± 0.45^{b}
	MDFWS	4.75 ± 0.13^{b}	0.15 ± 0.02^{a}	1.05 ± 0.03^{a}	0.21 ± 0.01^{a}	3.00 ± 0.29^{a}
Small branch and rep.	PSF	1.39 ± 0.04^{a}	0.50 ± 0.02^{c}	3.60 ± 0.12^{c}	0.72 ± 0.02^{c}	35.80 ± 1.17^{c}
	SDMDF	1.66 ± 0.02^{b}	0.42 ± 0.008^{b}	3.01 ± 0.04^{b}	0.60 ± 0.05^{b}	29.23 ± 0.41^{b}
	MDFWS	2.32 ± 0.11^{c}	0.30 ± 0.01^{a}	2.17 ± 0.10^{a}	0.42 ± 0.01^{a}	18.10 ± 1.46^{a}
Root	PSF	1.83 ± 0.05^{a}	0.38 ± 0.04^{c}	2.73 ± 0.07^{c}	0.55 ± 0.05^{c}	25.83 ± 0.88^{c}
	SDMDF	2.03 ± 0.01^{a}	0.34 ± 0.002^{b}	2.47 ± 0.02^{b}	0.49 ± 0.01^{b}	22.33 ± 0.20^{b}
	MDFWS	2.69 ± 0.15^{b}	0.26 ± 0.02^{a}	1.87 ± 0.11^{a}	0.41 ± 0.04^{a}	13.87 ± 1.44^{a}
P value	Leaf	0.001	0.001	0.001	0.003	0.002
	Small	<0.001	<0.001	<0.001	0.002	<0.001
	Root	0.002	<0.001	<0.001	0.001	<0.001

Mean values followed by ± are standard error of means. Decay constant values accompanying same alphabets are not statistically different for the specific litter type (column) in the DMRT test.

7.4.4 Relationship between locality factors and litter quality on mass loss

Irrespective of litter types, various locality factors that significantly ($P<0.05$) influenced the mass decomposition were air temperature, relative humidity (RH), soil moisture, soil nitrogen and organic matter content. Among these factors air temperature, relative humidity and soil nitrogen concentration were best predictors of mass decomposition explaining 54 % to 56 % of mass loss ($r = 0.544$ to 0.562). Climatic variables air temperature and RH positively influenced the mass loss. Among edaphic variables soil moisture content ($r = 0.426$) and nitrogen content ($r = 0.562$) positively regulated the

mass reduction but soil organic matter content negatively influenced the process (r = -0.395). Lignin content and the lignin to nitrogen ratio were negatively correlated with the decay rate, with correlation coefficients of -0.664 and -0.864, respectively. In contrast, carbon, nitrogen, cellulose, total phenol content and the C/N ratio exhibited positive correlations, with r values of 0.586, 0.767, 0.426, 0.556 and 0.766 respectively (Table 7.5). The most significant predictors of annual mass loss were the L/N ratio, C/N ratio, and nitrogen content of the litter, which accounted for 76% to 86% of the variability.

Table 7.5 Relationship between mass loss (Y) with locality factors and litter quality (X) (Y= a+bX)

Locality factor				**Litter attribute (mg g^{-1} except C/N and L/N ratio)**			
Factor	**Intercept (a)**	**Slope (b)**	**r**	**Factor**	**Intercept (a)**	**Slope (b)**	**r**
Air temp. (^{0}C)	24.192	2.09	0.544**	Carbon	-8.982	0.208	0.586**
RH	14.41	1.134	0.548**	Lignin	106.21	-0.118	-0.664**
SMC	67.65	0.404	0.426*	Nitrogen	35.063	7.111	0.767**
Soil pH	78.92	0.330	0.210 ns	Cellulose	71.43	0.034	0.426*
Soil N (%)	124.01	-0.378	0.562**	Hemi-cellulose	85.05	0.011	0.663*
SOC (%)	92.33	-6.465	-0.395*	TPC	50.74	0.171	-0.556**
				C/N ratio	143.538	-0.929	0.766**
				L/N ratio	104.313	-0.675	-0.864**

TPC-total phenol content, SMC- soil moisture content, SOM-soil organic matter, RH-relative humidity, N-nitrogen, r- Pearson's correlation coefficient, ** Correlation is significant at the 0.01 level, *. Correlation is significant at the 0.05 level.

7.4.5 Nutrient return to soil by different litter types

The annual input of carbon, nitrogen and phosphorous to soil through litter fall differed significantly ($P<0.05$) in three forest types. Significantly higher quantities of carbon (5876.71 kg ha^{-1} yr^{-1}), nitrogen (88.91 kg ha^{-1} yr^{-1}) and phosphorus (33.48 kg ha^{-1} yr^{-1}) were recycled in SDMDF through 12.77 Mg ha^{-1} yr^{-1} litter fall. Amongst different litter categories, leaf litter contributed more than two-thirds to the nutrient pool of the forest soil.

The total annual carbon input was significantly highest in SDMDF (5876.71 kg ha^{-1} yr^{-1}) with the largest share contributed by leaf litter (78%). SDMDF also showed the highest inputs of nitrogen (88.91 kg ha^{-1} yr^{-1}) and phosphorus (33.48 kg ha^{-1} yr^{-1}). The input of carbon and nitrogen in PSF and MDFWS were not differing significantly from each other. The annual phosphorous return by litter fall was significantly higher in MDFWS (33.48 kg ha^{-1} yr^{-1}) followed by PSF (24.55 kg ha^{-1} yr^{-1}) and MDFWS (19.49 kg ha^{-1} yr^{-1}). The annual potash returns to soil ranged from 21.54 kg ha^{-1} yr^{-1} to 24.21 kg ha^{-1} yr^{-1} and the variation was not significant. A mixed trend was observed in the variation of nutrient return to the soil across different litter categories. For instance, the return of phosphorus to the soil through leaf litter fall varied significantly ($P<0.001$) among the three forest types, while the variation in potash return was not significant. The return of carbon (4594.25 kg ha^{-1} yr^{-1}) and nitrogen (71.36 kg ha^{-1} yr^{-1}) through litter fall was significantly higher in SDMDF but the variation between PSF and MDFWS was not significant (Table 7.6).

Table 7.6 Nutrient return (kg ha^{-1} yr^{-1}) to the soil after 270 day of *in-situ* litter incubation

Litter type	Forest type	Carbon	Nitrogen	Phosphorus	Potash
Leaf (LL)	PSF	3513.59±91.74^{a}	58.39±0.84^{a}	20.73±0.24^{b}	18.07±0.35^{ns}
	SDMDF	4594.25±220.62^{b}	71.36±4.29^{b}	29.48±0.15^{c}	20.89±1.44^{ns}
	MDFWS	3196.82±318.05^{a}	48.70±3.87^{a}	16.77±0.07^{a}	19.84±1.58^{ns}
Small branch and Rep. parts (SBL)	PSF	623.72±12.58^{a}	7.94±0.18^{a}	2.63±0.11^{b}	1.92±0.04^{b}
	SDMDF	767.23±18.41^{b}	10.69±0.23^{c}	2.57±0.13^{b}	1.90±0.05^{b}
	MDFWS	658.16±3.73^{a}	8.81±0.22^{b}	1.64±0.05^{a}	1.60±0.06^{a}
Root (RL)	PSF	490.38±11.41^{b}	5.59±0.09^{a}	1.19±0.04^{a}	1.56±0.03^{b}
	SDMDF	515.22±2.36^{b}	6.86±0.15^{b}	1.43±0.05^{b}	1.42±0.05^{a}
	MDFWS	446.83±15.51^{a}	6.84±0.13^{b}	1.08±0.04^{a}	1.91±0.03^{c}
Total (LL+SBL+RL)	PSF	4627.69±72.14^{a}	71.92±0.96^{a}	24.55±0.31^{b}	21.54±0.34^{ns}
	SDMDF	5876.71±203.71^{b}	88.91±3.99^{b}	33.48±0.06^{c}	24.21±1.53^{ns}
	MDFWS	4301.81±330.74^{a}	64.35±4.16^{a}	19.49±0.11^{a}	23.36±1.65^{ns}
P value	LL	0.012	0.009	<0.001	0.338
	SBL	0.001	0.001	0.002	0.007
	RL	0.014	0.001	0.002	<0.001
	Total	0.006	0.006	<0.001	0.397

7.4.6 Alterations in nutrient stock during litter decay

The Figure 7.5 illustrates that nitrogen (N) and phosphorus (P) decay followed a tri-phasic pattern across all litter categories and forest types. In the first 60 days of incubation, nutrient decomposition occurred along with litter mass reduction. The subsequent phase (days 61-150) was marked by net accumulation of N and P, followed by a rapid release phase that continued until the end of the experiment (270 days). After 270 days of *in-situ* litter incubation, the remaining nitrogen (N) concentrations in leaf litter ranged from 6.85% (MDFWS) to 18.75% (PSF), in small branch litter from 7.45% (SDMDF) to 16.86% (PSF), and in root litter from 7.41% (MDFWS) to 23.36% (PSF). The concentration of carbon (C) stock consistently decreased throughout the decomposition period, with the most significant loss occurring between 30 and 150 days. The remaining C stock ranged from a low of 0.71% in MDFWS leaf litter to a high of

14.98% in PSF root litter. Amongst three litter categories the C stock loss was in the order of leaf litter > small branch litter > root litter across all forest types. Similarly, as far as forest types is concerned C stock loss was in the order MDFWS > SDMDF > PSF across three categories of litter. The loss of potash follows a tri-phasic pattern, similar to nitrogen (N) and phosphorus (P), where the magnitude of mineralization and accumulation varies significantly across different litter types and forest types. A rapid loss of potassium (K) was observed during the first 60 days of litter incubation, followed by a phase of slow immobilization until day 150 and then a gradual release thereafter (Table 7.7).

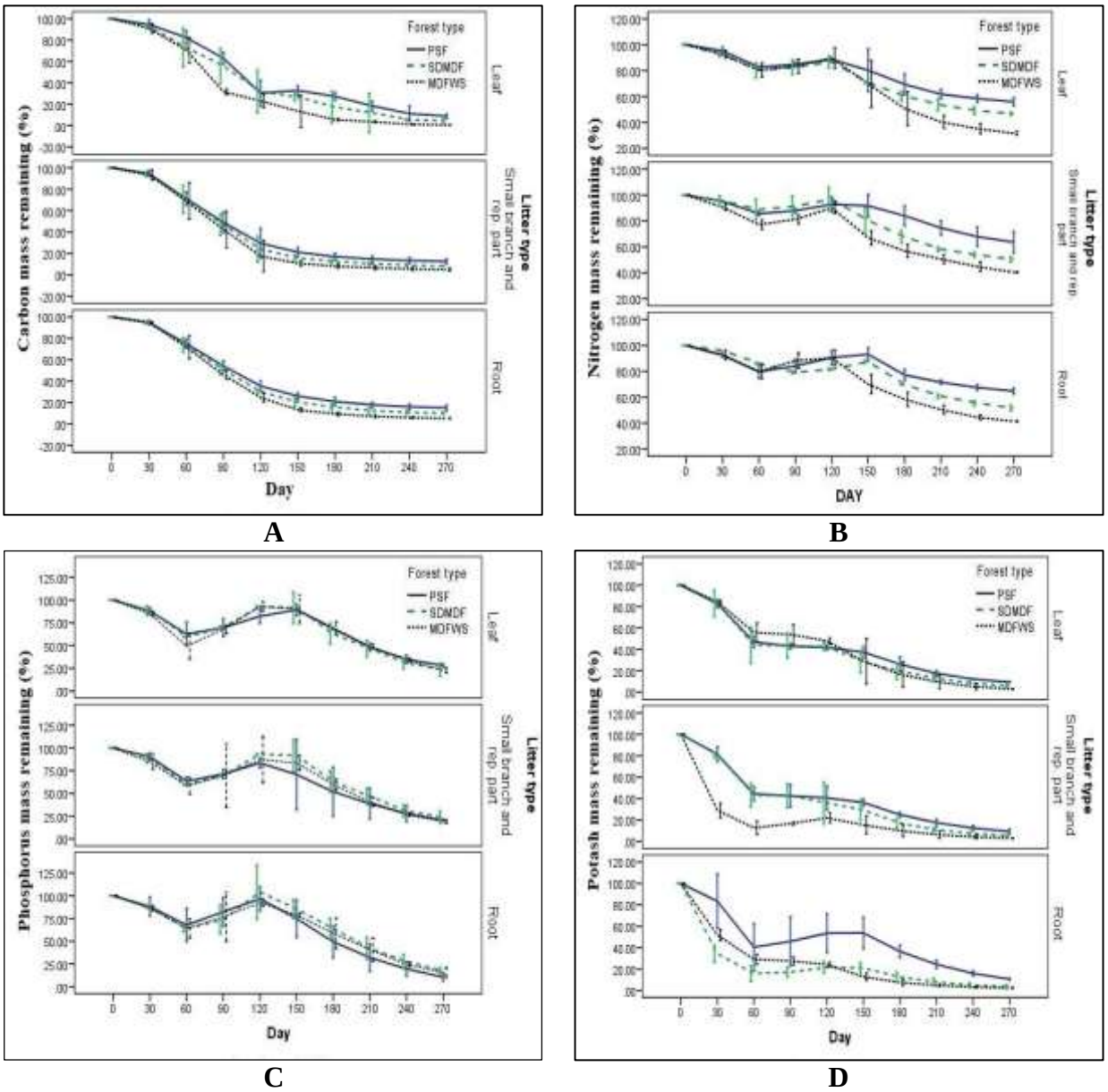


Figure 7.5 Temporal changes in carbon (A), nitrogen (B), phosphorus (C) and potassium (D) stock in different litter types during decay study (mean ± SE).

Table 7.7 Decay parameters: residual stock remaining (%), annual decay kinetics (a^{-1}) and time required (a^{-1}) for 50% release (t_{50}) for carbon (C), Nitrogen (N), Phosphorus (P), Potassium (K) from different types of litter in three forest types

Litter type	**Forest type**	**Residual stock (%)**				**Decay kinetics (k)**				**Time required for 50% release (t_{50})**			
		C	**N**	**P**	**K**	**k_C**	**k_N**	**k_P**	**k_K**	**t_{50}-C**	**t_{50}-N**	**t_{50}-P**	**t_{50}-K**
Leaf (LL)	PSF	8.89^{c} (0.36)	18.75^{c} (0.43)	9.38^{c} (0.14)	9.58^{c} (0.13)	1.05^{a} (0.02)	0.79^{a} (0.02)	1.72^{a} (0.08)	1.69^{a} (0.03)	0.66^{c} (0.04)	0.88^{c} (0.02)	0.40^{c} (0.01)	0.41^{c} (0.002)
	SDMDF	4.59^{b} (0.32)	12.78^{b} (0.97)	5.59^{b} (0.46)	6.14^{b} (0.42)	1.32^{b} (0.04)	1.03^{b} (0.01)	2.05^{b} (0.06)	2.02^{a} (0.04)	0.52^{b} (0.01)	0.67^{b} (0.02)	0.32^{b} (0.02)	0.34^{b} (0.01)
	MDFWS	0.71^{a} (0.06)	6.85^{a} (0.18)	2.28^{a} (0.26)	3.06^{a} (0.15)	1.95^{c} (0.03)	1.56^{c} (0.02)	3.06^{c} (0.15)	2.65^{b} (0.02)	0.36^{a} (0.01)	0.45^{a} (0.01)	0.23^{a} (0.01)	0.26^{a} (0.001)
	p-value	**	**	**	**	**	**	*	*	**	**	*	*
Small branch and rep. part (SBRL)	PSF	12.58^{c} (0.41)	16.86^{b} (1.46)	7.33^{b} (1.22)	9.23^{c} (0.64)	0.90^{a} (0.01)	0.61^{a} (0.05)	1.77^{a} (0.17)	1.42^{a} (0.03)	0.77^{c} (0.02)	1.15^{b} (0.09)	0.39^{ns} (0.01)	0.49^{c} (0.01)
	SDMDF	8.15^{b} (0.08)	7.45^{a} (0.75)	2.65^{a} (0.86)	5.08^{b} (0.23)	1.03^{a} (0.04)	0.94^{b} (0.02)	2.15^{b} (0.11)	1.69^{b} (0.03)	0.67^{b} (0.02)	0.74^{a} (0.02)	0.35^{ns} (0.01)	0.41^{b} (0.001)
	MDFWS	4.80^{a} (0.26)	10.39^{a} (.56)	3.06^{a} (0.14)	2.92^{a} (0.05)	1.75^{b} (0.08)	1.23^{c} (0.01)	2.33^{b} (0.06)	1.90^{c} (0.04)	0.40^{a} (0.02)	0.57^{a} (0.01)	0.30^{ns} (0.01)	0.36^{a} (0.01)
	p-value	**	**	*	**	**	*	*	*	**	*	NS	*

Litter type	Forest type	Residual stock (%)				Decay kinetics (k)				Time required for 50% release (t_{50})			
		C	N	P	K	k_C	k_N	k_P	k_K	t_{50}-C	t_{50}-N	t_{50}-P	t_{50}-K
Root (RL)	PSF	14.98^{c} (0.49)	23.36^{c} (1.13)	8.49^{c} (0.25)	10.50^{b} (0.23)	0.85^{a} (0.01)	0.59^{a} (0.03)	1.99^{a} (0.05)	1.69a (0.06)	0.84^{b} (0.03)	1.18^{c} (0.04)	0.41^{b} (0.03)	0.41^{c} (0.001)
	SDMDF	9.98^{b} (0.18)	13.35^{b} (0.82)	2.93^{b} (0.13)	3.38^{a} (0.53)	0.87^{a} (0.02)	0.89^{b} (0.01)	2.23^{b} (0.04)	1.95b (0.02)	0.80^{b} (0.05)	0.78^{b} (0.01)	0.33^{a} (0.01)	0.36^{b} (0.03)
	MDFWS	5.17^{a} (0.16)	7.41^{a} (0.58)	1.48^{a} (0.17)	2.28^{a} (0.14)	1.60^{b} (0.09)	1.19^{c} (0.02)	2.52^{c} (0.13)	2.25c (0.02)	0.43^{a} (0.01)	0.58^{a} (0.04)	0.28^{a} (0.05)	0.31^{a} (0.002)
	p-value	**	**	*	**	**	**	*	*	**	**	*	*
Total (LL+ SBRL+ RL) pooled	PSF	12.18^{c} (2.69)	19.66^{b} (1.10)	8.46^{c} (0.47)	9.77^{c} (0.27)	0.94^{a} (0.03)	0.66^{a} (0.04)	1.83^{c} (0.06)	1.60^{a} (0.04)	0.74^{c} (0.02)	1.07^{c} (0.05)	0.38^{c} (0.01)	0.44^{c} (0.01)
	SDMDF	7.57^{b} (2.39)	11.09^{a} (1.09)	3.72^{b} (0.55)	4.87^{b} (0.45)	1.07^{b} (0.07)	0.95^{b} (0.02)	2.13^{b} (0.05)	1.89^{b} (0.05)	0.66^{b} (0.04)	0.73^{b} (0.02)	0.32^{b} (0.01)	0.37^{b} (0.02)
	MDFWS	3.56^{a} (2.16)	8.42^{a} (0.69)	2.27^{a} (0.25)	2.76^{a} (0.13)	1.76^{c} (0.06)	1.32^{c} (0.06)	2.64^{a} (0.12)	2.27^{c} (0.01)	0.39^{a} (0.01)	0.53^{a} (0.02)	0.26^{a} (0.01)	0.31^{a} (0.02)
	p-value	**	**	**	**	**	**	**	**	**	**	**	**

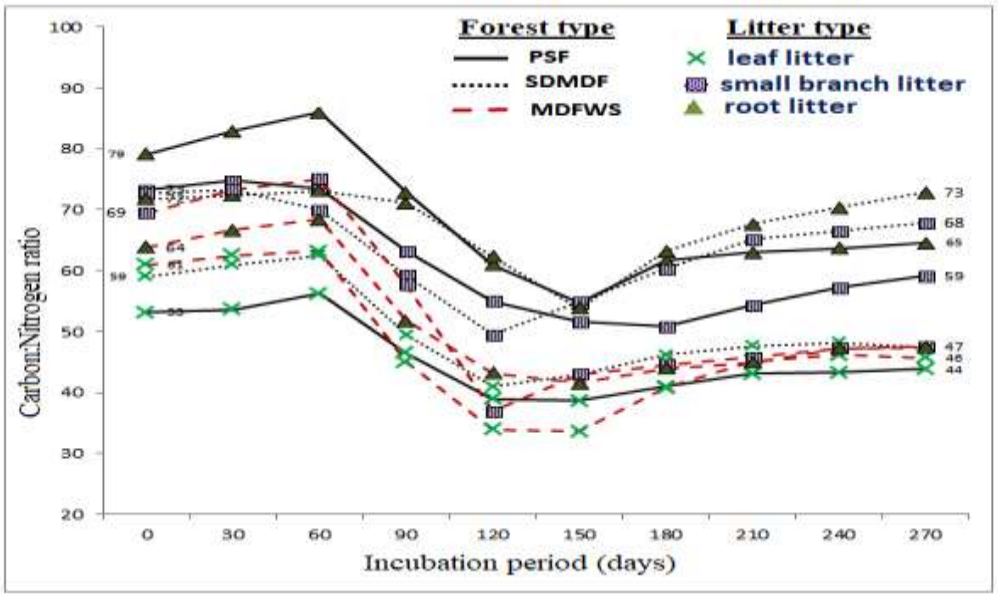
Mean values followed by ± are standard error of means. Decomposition parameter values accompanying same alphabets are not statistically different for the specific litter type in the DMRT test. ** Significant at 0.01 level, *. Significant at the 0.05 level.

7.5 Discussion

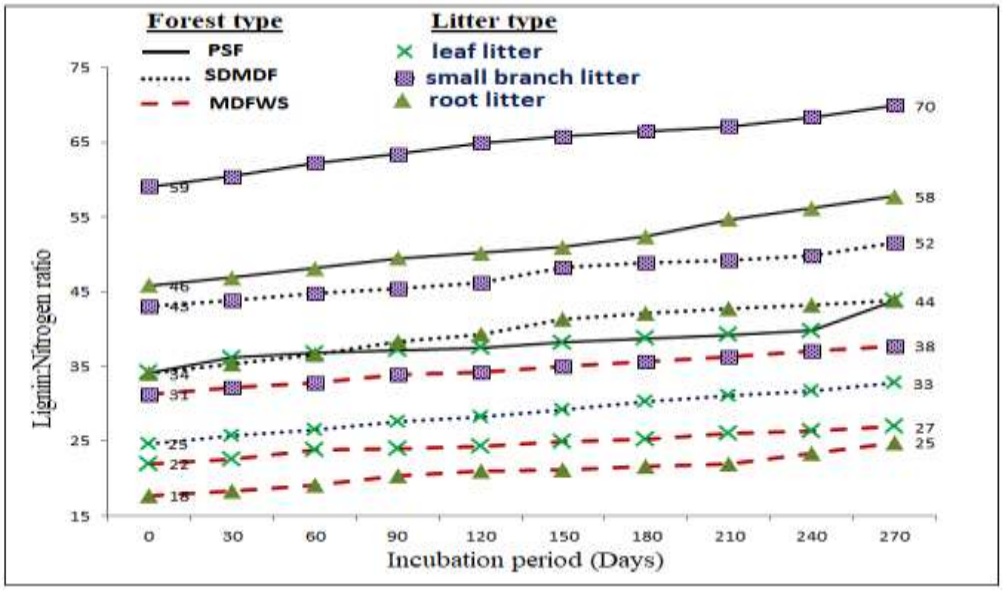
7.5.1 Pattern of litter fall

Quantity and duration of litter fall in a forest ecosystem is influenced by site quality, air temperature, soil moisture availability and sudden stress induced by fire or other metrological events (Giweta, 2020). The present investigation in moist deciduous forest of Kandhamal showed significant seasonal variation in litter fall in all forest types. Heavy leaf shedding (55% to 69% of total leaf litter fall) was observed during winter months (November to February) which are the dry period for this part of the Eastern Ghats. Water stress is the cardinal of dry period where moisture availability is limited. During the dry period trees enter to a phase of dormancy or reduced metabolic activity. This is primarily due to hormonal changes that help the trees to cease certain activities. During the dry season, when water availability decreases, abscisic acid levels increase in the plant (Alves and Setter, 2004). Abscisic acid promotes the closing of stomata to reduce water loss, induces the breakdown of chlorophyll and cell wall components, leading to leaf yellowing and abscission. As abscisic acid levels rise, it triggers an increase in ethylene production, which weakens the cell walls in the abscission zone of the leaf stalks, leading to leaf senescence **(**Socias *et al.*, 1997). Leaf senescence during the dry winter months helps the trees to conserve resources for forthcoming growth season. Post winter temperature rise stimulates the production of gibberellins and auxins that promote leaf flushing, flowering and fruiting (Bhattacharya, 2022)**.** The leaf flushing and mass blooming among trees are often synchronized with the increased pollinator activity. Whether trees re-flush and bloom in response to increased pollinators activity or pollinators multiply rapidly in response to availability of food is immaterial but it is a sophisticated ecological interaction that ensures maximum reproductive success in trees. Higher leaf litter production during dry winter months in tropical forests of this part of the Eastern Ghats is in accordance with the seasonal litter fall pattern of moist tropical forests of the Western Ghats (Kumar. and Deepu, 1992), sub-tropical oak forests of N-E India (Pandey *et al.*, 2007) and sub-tropical sal forests of West Bengal (Das and Mondal, 2016). However significantly higher root litter was produced during rainy season which was primarily driven by the increased

root growth and root turnover triggered by abundant moisture. The rainy season provides the optimal conditions for vegetative growth, which includes the shedding of older roots and the production of new roots (Pandey *et al.*, 2023). Seasonality in root biomass production in tropical forest was reported earlier (Lalnunzira and Tripathi, 2018). The total mean annual litter fall recorded in this study (8.93 Mg ha^{-1} yr^{-1} – 12.77 Mg ha^{-1} yr^{-1}) were within the range of litter fall reported for tropical moist deciduous forests of the Western Ghats (Ramachandra and Proctor, 1994), tropical dry evergreen forest of Coromandel coast (Pragasan and Parthasarathy, 2005) and humid sub-tropical forests of N-E India (Arunachalam *et al.*, 1998; Devi and Yadava, 2010)



[A]



[B]

Figure 7.6 Change in carbon: nitrogen ratio (A) and Lignin to nitrogen ratio (B) in different litter types of three forest types

7.5.2 Litter decay pattern and rate

In this study, litter decomposition followed a tri-phasic pattern initially slow followed by a phase of rapid mass loss (90-150 days) and then at slower pace. This pattern is quite common in tropical forest ecosystems which are influenced by factors

like litter quality, high humidity, temperature and the diversity of decomposers (Barbhuiya *et al.,* 2008). Sluggish colonization of decomposer community in high temperature and dry conditions during initial periods (first 60 days of incubation coincides with summer months) led to slower mass loss rate. After 150 days, the slower decay is attributed to the buildup of more recalcitrant materials in the litter with lignin becoming more prominent compared to carbon and nitrogen (Figure 7.5). This is also supported by the reduced activity of microbes in low winter temperature and soil moisture stress (Austin and Vitousek, 2000). At the end of the study maximum weight loss was observed in MDFWS (each litter category) and leaf litter decomposed faster than root and small branch. The variation in decomposition rates across different litter and forest types is ascribed to differences in litter chemistry as well as litter structure such as morphometric characteristics of leaf and other components (Songwe *et al.,* 1995). Sal being the dominant species contributes maximum to the annual litter pool of PSF (57%) and SDMDF (29%). The sal leaf's prominent dense venation pattern with thick midrib, tough petiole, low nitrogen and high lignin-to-nitrogen ratio influence colonization of decomposers and decompose much slowly than other leaf litter, resulting in significantly slower mass loss rate in PSF (Rai *et al.,* 2016; Paudel *et al.,* 2015). In MDFWS community Fabaceae being the dominant family (FIV 51.71), litters are rich in fall out leaves and other plants parts from nitrogen fixing species belonging to genera *Dalbergia, Pterocarpus, Albizia, Desmodium, Cassia and Bauhinia*. The presence of nitrogen rich plant parts in MDFWS litter mixture amplify microbial abundance, growth and colonization including other enzymatic processes involved in decomposition (Getaneh *et al*., 2022). This hastens the decomposition process and comparatively faster mass loss rate than other two forest types. The annual decay rate for mass loss (k_m) observed in PSF (1.39 small branch to 2.82 leaf) and SDMDF (1.69 SBRL to 3.03 leaf) having higher percentage of sal plant component was within the litter decay rate of sal leaves having k_m value 2.48 in sub-tropical forests of West Bengal (Das and Mondal, 2016) and 3.00 in tropical dry forests of Utter Pradesh (Pandey *et al.,* 2014). In the initial phase of decaying, the C:N ratio of decomposing litter increased steadily up to 60 days then declined sharply and again increased till the end of the study period. However, a constant increase in L:N ratio was noticed in the entire decaying process.

Such change pattern of C: N and L:N ratio in decaying litter in tropical sal forest ecosystem was reported earlier (Rai *et al.*, 2016). Lignin is a complex structured compound, decomposes slowly and resistant to microbial breakdown, whereas nitrogen is more easily utilized by decomposers or lost through leaching which led to elevated L:N ratio as the decay process continues (Taylor *et al*., 1989).

7.5.3 Nutrient dynamics and return to soil

Nutrient variation in decomposition studies arises due to the nature of each nutrient, microbial activity, and contributions from other sources such as atmospheric fixation or the release of nutrients through parent material weathering (Pandey *et al.,* 2007; Tripathi and Singh, 1992). In our current study, nitrogen and phosphorus immobilization occurs during the rainy months (July–October), followed by a rapid release phase. With the onset of the rainy season, favorable conditions on the forest floor promote the rapid multiplication of the microbial community on the litter, leading to the consumption of significant amounts of labile nitrogen and phosphorus for their growth and reproduction. This incorporation of nitrogen and phosphorus into microbial biomass results in the immobilization of these nutrients. Immobilization of nitrogen and phosphorus during the rainy season (peak decay period in tropical climate) has been reported previously (Melillo *et al.,* 1989). In contrast, carbon and potassium are continuously released across all litter categories and forest types. Similar patterns of C, N, P and K dynamics have also been reported earlier (Devi and Yadava, 2010; Das and Mondal, 2016). After 270 days of the litter decay study, the return of nitrogen (64.35 kg ha^{-1} yr^{-1} to 88.91 kg ha^{-1} yr^{-1}), phosphorus (19.49 kg ha^{-1} yr^{-1} to 24.55 kg ha^{-1} yr^{-1}) and potassium (21.54 kg ha^{-1} yr^{-1} to 24.21 kg ha^{-1} yr^{-1}) to the soil through litter fall was found to be comparable to nutrient release from litter fall in other tropical forest ecosystems in India (Das and Mondal, 2016; Pandey *et al.,* 2007). The variation in nutrient return across different forest types was attributed to differences in litter composition which arise from the species composition within each forest type.

SOIL RESPIRATION DYNAMISM IN THREE FOREST TYPES

8.1 Introduction

Soil respiration refers to the release of carbon dioxide (CO_2) from the soil due to the metabolic activity of soil biota which includes microorganisms, plant roots and soil fauna (Singh and Gupta, 1977). Forest soil respiration is a valuable ecophysiological parameter that offers insights into carbon metabolism within the forest floor and underlying soil. The release of CO_2 from soil carbon metabolism governs the exchange of C between the soil and the atmosphere, thus it plays a significant role in the global C cycle (Schlesinger and Andrews, 2000). The rate of CO_2 release per unit soil surface at particular time period is a reliable indicator of the abundance and activity of soil inhabiting organisms. It reflects nutrient mineralization rates and helps to estimate C allocation below ground. The microbial communities in the soil play a pivotal role in maintaining soil fertility, nutrient mineralization activities and ecosystem productivity. Hence knowledge on soil respiration is key requisite in understanding soil health, plant growth and ecosystem productivity. Moreover, it provides insights into the impact of land-use changes, agricultural practices and climate variations on soil carbon dynamics. With growing concerns about global warming and carbon sequestration, soil respiration has received significant attention now a day (Lal *et al.,* 2007; Anderson, 2011; Suseela and Dukes, 2013). The rapid rise in temperatures caused by global warming along with human activities has accelerated soil respiration and CO_2 emissions, further intensifying climate change (Nissan *et al.,* 2023). Monitoring soil respiration is as essential as climate change mitigation strategies for sustainable land management, greenhouse gas reduction and improving C flux modeling (Makipaa *et al.,* 2023).

Soil respiration in forest ecosystems results from microbial, faunal and underground root respiration. Microorganisms, particularly bacterial and fungal communities, account for approximately 99% of forest floor respiration and CO_2 emissions (Meena *et al.,* 2023). Therefore, estimating soil respiration is one of the

most effective methods for assessing soil biological activity in relation to carbon and energy flow within forest ecosystems. Forest soil respiration can be measured *in-situ* beneath tree canopies or in laboratory settings using imported soil samples. Laboratory incubations help to evaluate the effects of specific controlling factors, such as moisture and temperature under controlled conditions. Conversely, *in-situ* measurements are designed to assess total respiration, encompassing both autotrophic and heterotrophic components within a natural environment. *In-situ* methods are often preferred for their ecological relevance; however, they are subject to spatial and temporal variability due to fluctuations in substrate quality, microbial communities, root activity and environmental factors, particularly temperature and moisture (Mohanty and Panda, 2011). Alkali absorbents and infrared gas analysis (IGA) are two techniques widely used for on field soil respiration measurement. The key distinction between these methods lies in airflow, with alkali absorbents functioning in a static setup without airflow, while IGA operates dynamically with airflow (Pongracic *et al.,* 1997; King and Harrison, 2002).

Kandhamal district being a part of the Eastern Ghats, abode of vast tract of sal forests. These forests play a crucial role in carbon sequestration, soil fertility maintenance and overall ecosystem stability (Kaul *et al.,* 2010; Kumar *et al.,* 2022). However, temperature fluctuations, irruptive rainfall and changing land use patterns increase CO_2 emissions by altering soil respiration rates. Apart from this, anthropogenic activities such as logging, shifting cultivation, NTFP collection, encroached agriculture and forest degradation disrupt the soil ecosystem balance. Studying soil respiration in these forests is essential for understanding the impacts of climate change and human pressures on C cycling. It is also vital for developing sustainable forest management practices that enhance carbon sequestration and mitigate greenhouse gas emissions in Odisha's forest ecosystems. Extensive research has been conducted to assess soil respiration rates in various ecosystems of Odisha, including tropical dry deciduous forests (Mohanty and Panda, 2011; Basu *et al*., 1991), grasslands (Behera and Pati, 1986), plantations (Panda, 2010) and coastal sand dunes (Panda, 2009). However, studies on soil respiration in the tropical moist deciduous forests of Kandhamal remain limited. Therefore, this study aims to

estimate the annual soil respiration rate and CO_2 emissions to the atmosphere in this region.

8.2.1 Material and methods

The soda lime method was employed to measure soil respiration (RT) by estimating CO_2 absorption (Raich *et al.,* 1990; Keith and Wong, 2006). This technique involved using soda lime (NaOH) granules within a sealed chamber to absorb CO_2 released from the soil over a specified duration. At each study site, five sampling points were randomly chosen within the primary vegetation sample plots (31.62 m × 31.62 m). All sorts of herbaceous vegetation were clipped to ground level with a sharp knife with minimal disturbance to the soil. An equal number of chambers (transparent plastic tumblers with an internal diameter of 24 cm, height of 24 cm, surface area of 0.045 m^2 and closed on one end) were installed at these selected points in a manner that the open end penetrating ~2.0 cm to the soil with minimal soil disturbance. Before proceeding to the field, soda lime pellets were oven-dried at 105°C for 24 hours, cooled in a desiccator and 50 g were sealed in petri dishes for transport. In the field petri dishes were unsealed, moistened using fine spray (8–10 ml water) and placed on metallic stands inside the chambers **(Figure 8.1)**. A stone was placed above the chamber to minimize any loss of gas through chamber side. After 24 hours of exposure, the petri dishes containing soda lime granules were collected, sealed and transported to the laboratory. They were then oven-dried at 105°C for 24 hours, cooled in desiccators and weighed. A blank chamber was also used in the field to account for CO_2 absorption by the soda lime during the experimental process (Pathak *et al.,* 2018). The soil CO_2 efflux (g C m^{-1} day^{-1}) was calculated as per the given formula (Keith and Wong, 2006).

$$\text{Total soil respiration (g C m}^{-2}\text{ day}^{-1}) = \left\{\frac{W_2 - W_1 \times 1.69}{\text{Chamber area (m}^2)}\right\} \times \left\{\frac{24\text{ h}}{\text{eposure time (h)}}\right\} \times \frac{12}{44}$$

Where: W_2 – Dry weight of soda lime after exposure (g)

W_1- Dry weight of soda lime before exposure (g)

During the course of experiment, soil temperature was measured using soil thermometer, while soil moisture was recorded with a digital soil moisture meter (SM-HH150T) directly in the field. The measured CO_2 efflux accounts for respiration from both coarse roots (>2 mm in diameter) and fine roots, as well as microbial respiration. In the tropical moist deciduous forests of Odisha**,** roots contribute 50.5% to total soil respiration **(**Behera *et al.,* 1990**).** This proportion was applied in the present study to estimate soil heterotrophic (microbial) respiration which was calculated using the following equation:

$SR_h = SR_T - SR_{A\ root}$ (O'Connell *et al.,* 2003)

Where SR_T - total soil respiration

$SR_{A\ root}$- soil respiration attributable to roots (fine and coarse root)

8.2.2 Statistical analysis of data

Soil CO_2 respiration (SR_T), soil temperature (ST) and soil moisture (SM) data from three forest types were analyzed using SPSS and MS Excel. Analysis of variance (ANOVA) was conducted to compare mean values and assess statistical significance at $P<0.05$. Multiple regression analysis was used to determine the relationship between SR_T, ST and SM and linear models were developed to predict SR_T rates under specific edaphic conditions

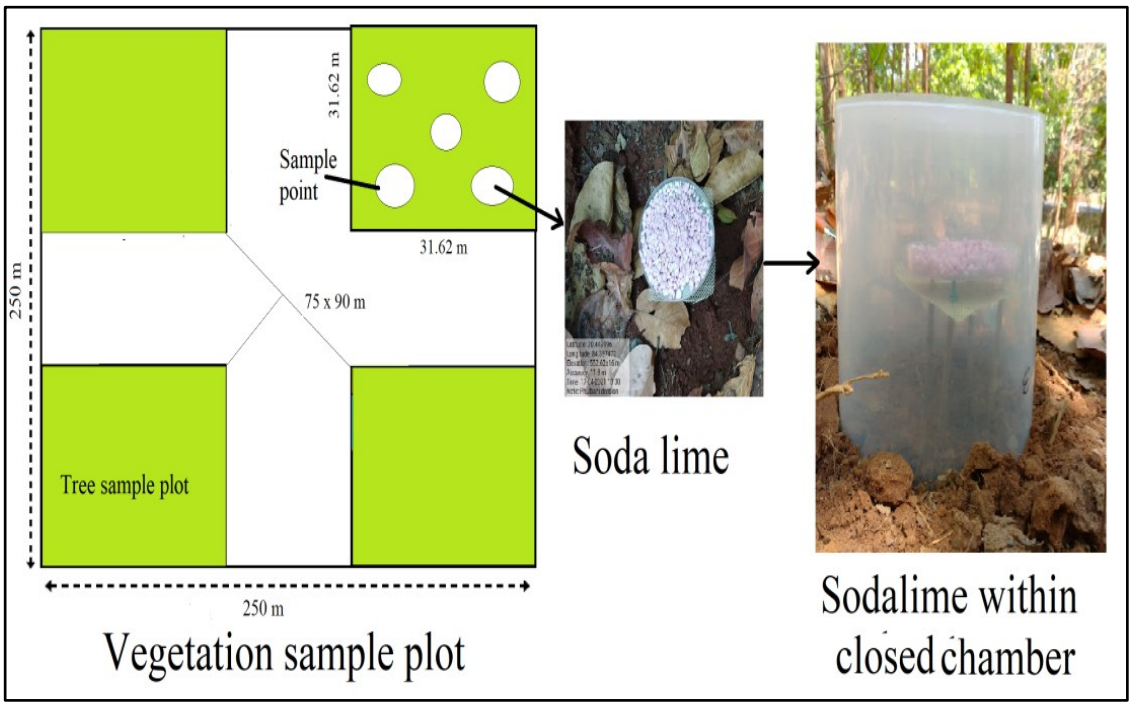


Figure 8.1 *In-situ* total soil respiration (SR_T) absorption by soda lime in closed chamber

8.3 Results

8.3.1 Monthly variations in soil temperature, moisture and respiration

The monthly variation in soil temperature, soil moisture and soil respiration within each forest types was statistically significant at $P<0.05$ (Table 8.1). The highest soil temperature was recorded during the summer months (April to May) and the lowest during the winter months (December to February) across all forest types. Among the three forest types, PSF recorded the highest mean soil temperature (27.72 °C), followed by SDMDF (26.42 °C) and MDFWS (23.43 °C). The peak soil temperatures were observed in May, reaching 39.48 °C in PSF, 34.50 °C in SDMDF and 30.18 °C in MDFWS, reflecting intense summer heating. Conversely, the lowest temperatures occurred in February with mercury dropping to 13.27 °C (PSF), 12.72 °C (SDMDF) and 12.02 °C (MDFWS) due to cooler winter conditions (Figure 8.2 A).

The significant seasonal fluctuations in soil moisture was noticed across all forest types with the highest levels recorded during the monsoon months (July to September) and the lowest levels during the dry months (March to May). Among the three forest types, MDFWS exhibits the highest mean soil moisture (20.92 %), followed by SDMDF (17.13 %) and PSF (15.61 %)**.** The peak soil moisture values were recorded in September**,** reaching 26.78 % in PSF, 26.98 % in SDMDF and 32.32 % in MDFWS, coinciding with the period of maximum rainfall. In contrast, the lowest soil moisture levels were observed in May, dropping to 3.82 % in PSF, 7.25 % in SDMDF and 9.72 % in MDFWS, reflecting the effects of seasonal drought conditions (Figure 8.2 B).

The results indicate that soil respiration fluctuates significantly ($P<0.05$) throughout the year, with peak values observed during the monsoon months (July to September) and lower values recorded during the dry winter months (December to February) (Table 8.1)**.** Among the three forest types, MDFWS exhibits the highest mean soil respiration rate (0.99 g C m^{-2} d^{-1}), followed by SDMDF (0.92 g C m^{-2} d^{-1}) and PSF (0.62 g C m^{-2} d^{-1})**.** The highest soil respiration rates were recorded in September in SDMDF and MDFWS with a peak rate of 2.98 g C m^{-2} d^{-1} and 2.75 g C m^{-2} d^{-1} respectively. The peak respiration rate was noticed during October in PSF (1.67 g C m^{-2} d^{-1}). In contrast, the lowest respiration rates were observed in February**,** with values dropping to 0.16 g C m^{-2} d^{-1} in SDMDF, 0.18 g C m^{-2} d^{-1} in PSF and 0.19 g C m^{-2} d^{-1} in MDFWS (Figure 8.2 C).

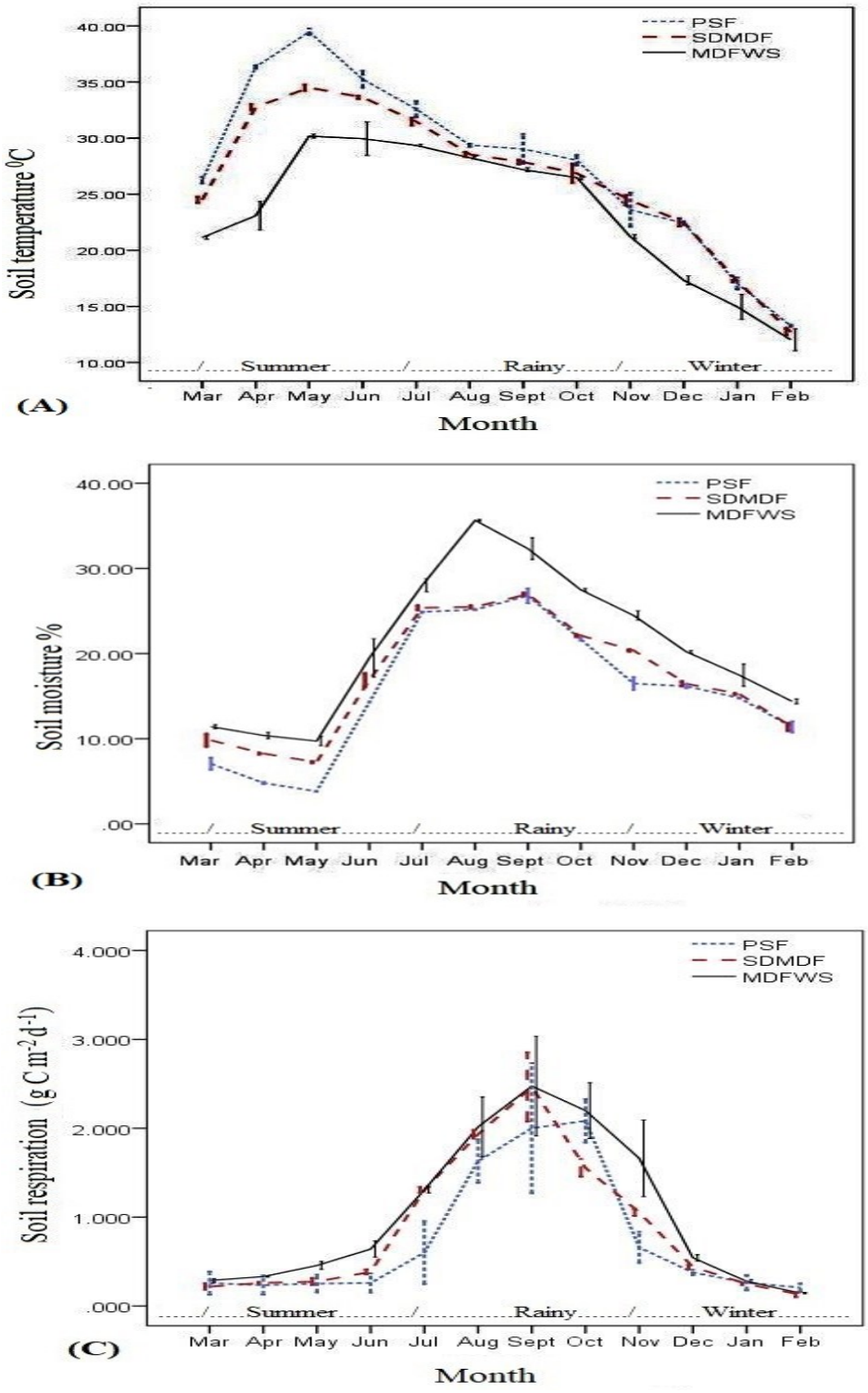


Figure 8.2 Seasonal variations in soil temperature (A), soil moisture (B) and soil respiration (C) in three forest types.

Table 8.1 Monthly variations in soil temperature, moisture and respiration in three forest types

Month	Soil temperature ^{0}C			Soil moisture %			Soil respiration (g C m^{-2} d^{-1})		
	PSF	SDMDF	MDFWS	PSF	SDMDF	MDFWS	PSF	SDMDF	MDFWS
Mar.	26.25±0.14^{f}	24.50±0.14^{h}	21.13±0.07^{e}	7.06±0.36^{f}	9.82±0.38^{h}	11.42±0.12^{hi}	0.24±0.07^{b}	0.24±0.02^{e}	0.31±0.01^{d}
Apr.	36.35±0.08^{b}	32.77±0.14^{c}	23.08±0.64^{d}	4.79±0.07^{g}	8.25±0.06^{i}	10.38±0.19^{ij}	0.23±0.06	0.29±0.01^{e}	0.37±0.01^{d}
May	39.48±0.15^{a}	34.50±0.15^{a}	30.18±0.09^{a}	3.82±0.04^{h}	7.25±0.07^{j}	9.72±0.27^{j}	0.24±0.05	0.31±0.02^{e}	0.51±0.02^{d}
Jun.	35.25±0.38^{c}	33.63±0.08^{b}	29.95±0.75^{a}	14.30±0.03^{d}	16.88±0.40^{e}	19.48±1.12^{e}	0.25±0.06	0.43±0.02^{e}	0.71±0.05^{d}
Jul.	32.58±0.36^{d}	31.47±0.17^{d}	29.35±0.06^{a}	24.90±0.03^{b}	25.38±0.15^{b}	28.02±0.38^{c}	0.61±0.11	1.53±0.05^{c}	1.14±0.14^{c}
Aug.	29.37±0.07^{d}	28.55±0.11^{e}	28.25±0.05^{b}	25.16±0.04^{b}	25.48±0.09^{b}	35.65±0.06^{a}	1.30±0.09^{a}	1.93±0.12^{b}	1.86±0.03^{b}
Sept.	29.03±0.66d^{e}	27.87±0.11^{f}	27.18±0.09^{bc}	26.78±0.44^{a}	26.98±0.08^{a}	32.32±0.64^{b}	1.60±0.29^{a}	2.98±0.21^{a}	2.75±0.31^{a}
Oct.	28.03±0.24^{e}	26.87±0.43^{g}	26.48±0.07^{c}	21.68±0.09^{b}	22.12±0.06^{c}	27.48±0.09^{c}	1.67±0.08^{a}	1.47±0.03^{c}	1.55±0.07^{b}
Nov.	23.62±0.76^{g}	24.47±0.24^{h}	21.22±0.05^{e}	16.48±0.38^{c}	20.37±0.07^{d}	24.48±0.27^{d}	0.53±0.07	1.03±0.08^{d}	1.87±0.27^{b}
Dec.	22.42±0.08^{h}	22.48±0.19^{i}	17.32±0.22^{f}	16.16±0.44^{c}	16.45±0.15^{e}	20.20±0.08^{e}	0.35±0.01	0.45±0.04^{e}	0.33±0.12^{d}
Jan.	17.03±0.27^{i}	17.25±.06^{j}	14.95±0.56^{g}	14.79±0.03^{d}	15.25±0.06^{f}	17.47±0.66^{f}	0.25±0.05	0.28±0.01^{e}	0.35±0.01^{d}
Feb.	13.27±0.04^{j}	12.72±0.15^{k}	12.02±.49^{h}	11.38±0.33^{e}	11.38±0.24^{g}	14.38±0.15^{g}	0.18±0.01c	0.16±0.02^{f}	0.19±0.01^{e}
Mean	27.72±1.26	26.42±1.07	23.43±1.00	15.61±1.28	17.13±1.13	20.92±1.42	0.62±0.09	0.92±0.14	0.99±0.14
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: Mean values followed by ± are standard error of mean, Soil temperature, moisture and respiration values accompanying same alphabet in lower case (a, b) are not statistically different for the specific attribute in the Duncan's multiple range test (DMRT)

8.3.2 Variations in soil respiration, root respiration and microbial respiration

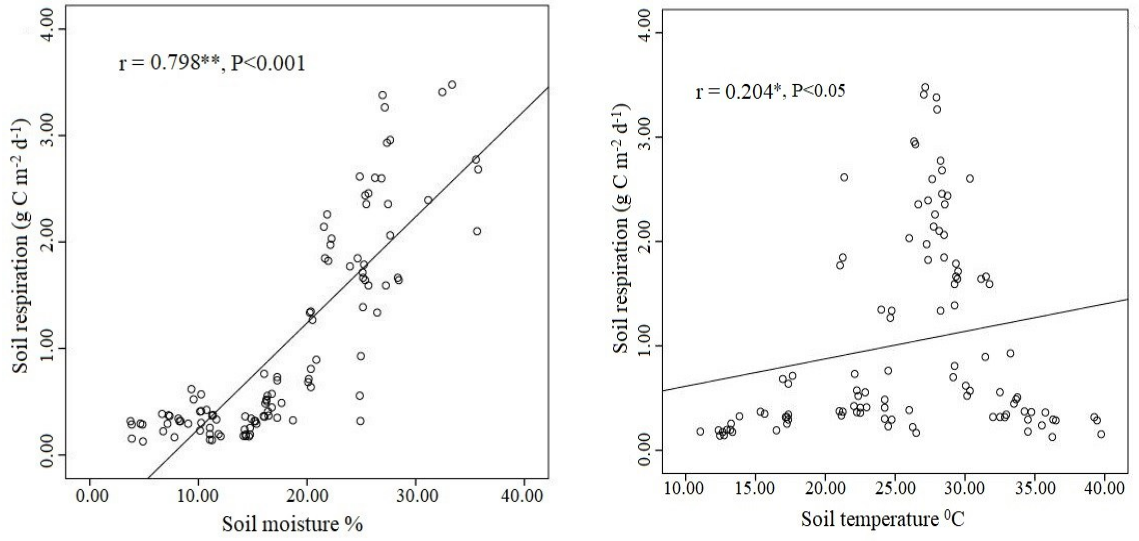
The comparative analysis of average monthly soil temperature, moisture and respiration dynamics across three forest types is represented in Table 8.2. The data reveal significant variations in these parameters, highlighting the influence of forest type on soil biogeochemical processes. Among the three forest types, PSF exhibited the highest average monthly soil temperature (27.72 °C), followed by SDMDF (26.42 °C), while MDFWS recorded the lowest soil temperature (23.43 °C). Conversely, soil moisture was highest in MDFWS (20.92 %), indicating greater water retention capacity, whereas PSF had the lowest soil moisture (15.61 %). The total annual soil respiration (ASR_T) was found significantly (LSD = 8.48, $P<0.05$) higher in MDFWS (43.61 Mg C ha^{-1} yr^{-1}), followed by SDMDF (40.51Mg C ha^{-1} yr^{-1}), while PSF had the lowest annual soil respiration (27.21 Mg C ha^{-1} yr^{-1}). Similar trend in root respiration ($SR_{A\ root}$) and microbial respiration (SR_h) were also observed with highest value in MDFWS (23.76 Mg C ha^{-1} yr^{-1} and 19.84 Mg C ha^{-1} yr^{-1} respectively) and lowest value in PSF (14.83 Mg C ha^{-1} yr^{-1} and 12.38 Mg C ha^{-1} yr^{-1} respectively). The observed differences were statistically significant, as indicated by the least significant difference (LSD) at a 0.05 confidence level.

Table 8.2 Variations in soil temperature (^{0}C), moisture (%), respiration rate (g C m^{-2} d^{-1}), root respiration (g C m^{-2} yr^{-1}) and microbial respiration (g C $m^{-2}yr^{-1}$) across three forest types

Forest type	Monthly average		Soil respiration rate (SR_T)	Total annual respiration		
	soil temperature	soil moisture		Soil (ASR_T)	Root ($SR_{A.\ root}$)	Microbial (SR_h)
PSF	27.72±1.26^a	15.61±1.28^b	0.62±0.09^{ns}	27.21±3.92^b	14.83±2.15^b	12.38±1.79^b
SDMDF	26.42±1.07^{ab}	17.13±1.13^b	0.92±0.14^{ns}	40.51±0.57^a	22.08±0.31^a	18.43±0.26^a
MDFWS	23.43±1.00^b	20.92±1.42^a	0.99±0.14^{ns}	43.61±1.50^a	23.76±0.82^a	19.84±0.68^a
Mean	25.86±0.66	17.88±0.77	0.85±0.07	37.11±2.79	20.22±1.52	16.88±1.27
LSD (0.05)	3.14	3.59	0.44	8.48	4.63	3.87

8.3.3 Pearson correlation coefficient between soil respiration rate, soil moisture and temperature

Pearson correlation revealed that both soil moisture and temperature have a significant ($P<0.05$) association with soil respiration rate. However soil moisture have a strong positive association with soil respiration rate ($r = 0.798$, $P < 0.01$), while soil temperature showed a weaker correlation ($r = 0.204$, $P < 0.05$). This highlights soil moisture as a primary driver of soil respiration (Figure 8.3).



A B

Figure 8.3 Pearson's correlation coefficient between soil respiration rate, soil moisture and temperature A) between soil moisture and soil respiration, B) between soil temperature and soil respiration.

8.3.4 Multicollinearity between soil temperature, moisture and respiration rate

The multiple regression analysis for soil respiration (SR_T) with soil moisture (SM) and soil temperature (ST) across the three forest types (PSF, SDMDF and MDFWS) reveals that SM is the dominant predictor, while ST has a comparatively smaller influence (Table 8.3).

In PSF, the regression equation $SR_T = -0.866 + 0.071SM + 0.018ST$ shows that SM (b = 0.071) has a stronger effect on SR_T than ST (b = 0.018), with a strong correlation (r = 0.749) and 53.4% of the variation in SR_T explained by the model (adjusted r^2=0.534).

In SDMDF, the equation $SR_T = -1.718 + 0.013SM + 0.025ST$ highlights a greater influence of ST (b = 0.025) compared to SM (b = 0.013), with 79.4% of SR_T variation explained (adjusted $r^2 = 0.794$ r = 0.898).

Similarly in MDFWS, the equation $SR_T = -1.337 + 0.082SM + 0.032ST$ indicates SM remains the primary driver (b = 0.082), while ST (b = 0.032) has a relatively greater effect than in the other forest types (r = 0.854, adjusted $r^2 = 0.713$).

Overall, the findings indicate that soil moisture is the most significant factor influencing SR_T across all forest types, with the highest impact observed in MDFWS (b = 0.082). Though soil temperature has a weaker influence, its effect is relatively more pronounced in MDFWS (b = 0.032). The models for SDMDF and MDFWS exhibit the highest predictive accuracy, with high adjusted r^2 values (0.763 and 0.713, respectively).

Table 8.3 Relationship between soil respiration (Y) with soil temperature and soil moisture (X) (Y= a+bX)

Forest type	**Intercept (a)**	**Slope (b)**		**r**	**Adjusted r^2**	***P value* (0.05)**
		Soil temperature	**Soil moisture**			
PSF	-0.866	0.018	0.071	0.749	0.534	0.000
SDMDF	-1.718	0.025	0.013	0.881	0.763	0.000
MDFWS	-1.337	0.032	0.082	0.854	0.713	0.000
Over all	-1.10	0.078	0.021	0.821	0.674	0.000

8.4 Discussion

Soil respiration is a vital process in terrestrial ecosystems driving CO_2 flux through microbial decomposition, root respiration and soil fauna activity. It regulate soil carbon storage and determine whether an ecosystem functions as a carbon sink or source (Khatoon *et al.*, 2017). High soil respiration is an indicative of rapid microbial decomposition of organic matter, improving soil fertility, while low rates may signal degradation or environmental stress (Powlson *et al.*, 2001). Vegetation cover and type influence belowground processes in terrestrial ecosystems by affecting soil organic matter inputs, root activity, soil moisture dynamics and microbial communities (Han *et al.,* 2014). The mean daily soil respiration values estimated in this study (0.62 g C m^{-2} d^{-1} in PSF to 0.99 g C m^{-2} d^{-1} in MDFWS) are comparable to the SR_T range of 0.36 to 2.36 g C m^{-2} d^{-1} observed in tropical dry deciduous forests of Odisha (Mohanty and Pand, 2011, Basu *et al.,* 1991), 1.82 to 2.07 g C m^{-2} d^{-1} under canopies of various forest tree species in semi-arid regions of north-west India (Jha and Mohapatra, 2011), 0.104 to 26.25 g C m^{-2} d^{-1} under the tree canopies in Himalayan temperate forests of Uttarakhand (Rawat *et al.,* 2021). The observed variation in soil respiration rates is driven by differences in soil physicochemical properties, temperature and moisture which significantly impact microbial population as well as their activity.

Monthly variations in soil respiration were found significant ($P<0.05$) across all forest types with peak during monsoon rainy months (September to October), while the lowest in the dry winter months (December to February)**.** Seasonal variations in soil respiration rate in forest ecosystems were reported earlier (Kumar *et al.,* 2023; Singh and Parida, 2019; Jha and Mohapatra, 2011**).** The respiration rate fluctuated significantly across months, reaching its peak during September-October and lowest in February-March (Figure 8.2). While the seasonal pattern of soil respiration remained consistent across all forest types, its magnitude varied significantly between months (Table 8.1). The significant monthly variations in soil respiration ($P < 0.05$) across all forest types can be attributed to seasonal changes in soil temperature, moisture and microbial activity. The peak respiration rates recorded during the monsoon months (September to

October) are likely attributed to increased microbial decomposition and root respiration, driven by elevated soil moisture and temperatures combined with warm, humid air circulation (Davidson and Janssens, 2006). Heavy rainfall during peak monsoon months leaches phenols and other secondary metabolites from the litter, facilitating rapid microbial decomposition. Additionally, the warm and humid climate accelerates organic matter breakdown resulting in a higher CO_2 flux from the soil. Conversely, the lowest respiration rates in the dry winter months (February to March) can be explained by low temperatures and reduced soil moisture, which limit microbial activity and slow down decomposition processes (Jha and Mohapatra, 2011). Cold conditions also suppress root respiration, further decreasing CO_2 emissions. These findings align with previous studies that highlight temperature and moisture as primary regulators of soil respiration in forest ecosystems (Sivaranjani *et al.,* 2025; Singh and Parida, 2019). Although similar pattern in respiration seasonality was there, the rate of respiration was high in MDFWS followed by SDMDF and PSF (Figure 8.2 C). The difference was mainly due to variations in litter quality and their decomposition rate (Ngao *et al.,* 2005). However soil moisture alone accounted for greater variability in soil respiration than soil temperature.

CHAPTER-9

NET PRIMARY PRODUCTION, NET ECOSYSTEM PRODUCTION AND CARBON FLUX IN THREE FOREST TYPES

9.1 Introduction

Net primary production (NPP) and net ecosystem production (NEP) are fundamental ecological indicators that quantify carbon (C) dynamics within forest ecosystems. NPP represents the total amount of C fixed by autotrophic organisms through photosynthesis, minus the C lost through plant respiration (Chapin *et al.,* 2011). It serves as a key measure of ecosystem productivity, influencing biomass accumulation and energy transfer within trophic levels (Clark *et al.,* 2001). NPP directly influences carbon fluxes within an ecosystem by determining the amount of carbon that enters the food web and soil organic matter pools. Higher NPP indicates greater C sequestration, whereas lower NPP suggests reduced carbon uptake and potential vulnerability to disturbances (Ciais *et al.,* 2014). NEP, on the other hand accounts for the balance between gross primary production (GPP) and total ecosystem respiration, including both autotrophic and heterotrophic respiration, thereby indicating whether an ecosystem functions as a carbon source or sink (Luyssaert *et al*., 2008). NEP can also be estimated by subtracting heterotrophic respiration (Rh) from NPP, were Rh accounts for carbon loss through microbial decomposition and respiration by herbivores and decomposers. A positive NEP suggests carbon sequestration, while a negative NEP implies carbon emission to the atmosphere. This balance is critical in understanding forest contributions to atmospheric CO_2 levels and climate regulation.

Forests store carbon in multiple pools, including living biomass (trunks, branches, leaves and roots), dead organic matter (fallen leaves, decomposing logs and stumps) and SOC. While trees can store carbon for decades to centuries in their woody tissues, forest soils act as long-term reservoir by storing carbon for thousands of years in organic matter (Pan *et al.,* 2011). Tropical forests store carbon mostly in living biomass, whereas temperate and boreal forests have significant carbon

reserves in their soils because of slow decomposition rates in cold climates (Luyssaert *et al.,* 2008). Photosynthesis is the primary pathway for capturing atmospheric carbon, facilitating its conversion into organic matter within plant biomass. However, this captured carbon is continuously released back into the atmosphere through plant and animal metabolism, microbial respiration and disturbance linked emissions such as draught, fire, deforestation and land-use changes (Chapin *et al.,* 2011; Houghton *et al.,* 2015). Apart from this, temperature driven C fluxes such as increased soil respiration, direct CO_2 exchange between terrestrial ecosystems and atmosphere, further influence the balance of carbon sequestration and release, impacting overall ecosystem carbon dynamism (Ciais *et al.,* 2014; Friedlingstein *et al*., 2022).

Carbon flux in a forest ecosystem represents the dynamic exchange of carbon between the atmosphere, vegetation, soil and decomposers. NPP and NEP are central to understanding carbon fluxes in forest ecosystems. NPP determines how much carbon is fixed and stored in biomass, while NEP indicates whether a forest functions as a carbon sink or source. These metrics influence global carbon flux patterns and play a key role in climate change mitigation, Strategies such as reforestation, afforestation, reduced deforestation and sustainable forest can enhance NPP and maintain positive NEP (Griscom *et al.,* 2017; Angelsen *et al.,* 2018). Understanding the dynamics of NPP and NEP in the tropical moist deciduous forests of Odisha is crucial for evaluating the effects of climate change and land-use changes on forest carbon balance.

9.2 Material and methods

9.2.1 Vegetation composition and biomass determination

The vegetation composition of three forest types (pure sal forest-PSF, sal dominated moist deciduous forest-SDMDF and moist deciduous forest without sal-MDFWS) was analyzed as per the procedure described in section 6.2.2. The biomass of woody species, including trees, saplings, shrubs and lianas, was assessed using a non-destructive approach based on allometric equations, while herbaceous biomass (both shoot and root) was estimated through oven-dry weight measurement. Measurements

for deadwood (standing and fallen) was taken at three places (top, middle and bottom) along with other parameters such as species name and physical condition (freshly cut or decomposed). Roots and stumps with a dbh of 10 cm or more were also classified as dead wood. Herbs present in 1 m x 1 m plot were uprooted, washed to remove adhered soil at root and oven-dried at 80 ^{0}C to constant weight. The litter input was measured from randomly placed stone-block lined quadrats (3 forest types x 3 sites x 8 numbers per site) following the procedures of Pragasan and Parthsarthy (2005). The fine root (2.0 mm diameter) litter production was determined by digging soil monoliths (30 cm x 30 cm x 30 cm) on seasonal basis (rainy, winter and summer). The monoliths were washed in fine jet of water using 2 mm mesh screen. Live and dead fine roots were separated through visual observations (colour, texture and feel), oven-dried at 80 ^{0}C to constant weight and weighed. The dry weight of dead fine root mass was reported as fine root litter (detailed procedure described in section 6.2.7.). The quantity of small timber, firewood and non-timber forest products (NTFPs) harvested by fringe villagers for domestic consumption was estimated through verbal interviews. Ground fire was observed in some isolated areas within the study site and the biomass lost due to wildfire was determined by multiplying the area affected by the surface fire with the standing floor litter.

9.2.2 Biomass carbon stock determination

The carbon content of woody components (tree, saplings, shrubs, liana and un-decomposed dead wood) was estimated by multiplying the biomass with 0.47 (default value for carbon content in woody species as per IPCC, 2006). The carbon percentage of carbon content in herbaceous vegetation and litter mass (aboveground litter and fine root) was analyzed by combusting 0.2 g of oven-dried sample in CHNS auto- analyzer (Elementar UNICUBE) and then the value was multiplied with the corresponding dry biomass amount (Campbell and Plank, 1998). The above and belowground biomass carbon stock of each component was summed up to determine the ecosystem carbon content of each forest.

9.2.3 Determination litter production and decay

The litter production in three forest types was estimated through litter trap technique (Pandey *et al.,* 2023). The monthly pattern of aboveground litter (AGL) production was measured using traps of size 1 m x 1 m x 30 cm. The belowground litter production (BGL) was measured adopting sequential soil core method and digging soil monolith (30 cm x 30 cm x 30 cm) at four months intervals (section 7.2.1). The nylon net bag technique of Bocock *et al.,* (1960) was used to study the litter decay rate (section 7.3.6)

9.2.4 Determination of net primary production

The net primary production (NPP) was calculated conventionally by estimating the biomass dynamics (Δ biomass) over a period of one year (Δt).

NPP = Δ (standing biomass) + Losses (Waring *et al.,* 1998).

= Δ AGB (tree + sapling + shrub + lianas) +

Δ BGB (tree + sapling + shrub + lianas) + herb biomass (root and shoot) +

Litter (aboveground + belowground) + Dead wood

9.2.5 Determination of heterotrophic respiration

The total soil respiration (root respiration and heterotrophic respiration, SR_T) was measured at monthly intervals adopting the soda lime method of Keith and Wong, (2006) as described in section 8.2.1. This measured CO_2 efflux accounts for respiration from both coarse root (>2 mm diameter), fine as well as microbial respiration. Soil heterotrophic respiration was calculated indirectly by adopting the ratio of root respiration (fine and coarser) to microbial respiration for tropical forest ecosystems of the state. In the tropical moist deciduous forests of Odisha, roots contribute 50.5% to total soil respiration (Behera *et al.,* 1990). This proportion was applied in the present study to estimate soil heterotrophic (microbial) respiration which was calculated using the following equation:

$SR_h = SR_T - SR_{A\ root}$ (O'Connell *et al.,* 2003)

Where SR_T - total soil respiration

$SR_{A\ root}$ - soil respiration attributable to roots (fine and coarse root)

9.2.6 Determination of net ecosystem production (NEP)

Net ecosystem production in a forest ecosystem denotes the net accumulation of biomass and it is nothing but the difference between rate of production of living organic matter (net primary production) and the heterotrophic respiration (R_h).

NEP (Mg C ha^{-1} yr^{-1}) = Input - Output

= NPP - R_h (Sierra *et al.,* 2007)

9.2.7 Statistical analysis of inventoried data

Descriptive statistical tools were used to calculate replicated sample mean and standard error of means. The mean values of various attributes were compared using one-way analysis of variance (ANOVA) at 95% confidence level. Turkey honest significance difference (HSD) post hoc test was performed to indicate significant differences ($P<0.05$). All the statistical analysis was carried out using MS EXCEL and SPSS statistical package SPSS-20 (SPSS Inc. Chicago, USA).

9.3 Results

9.3.1 Net Primary Production (NPP) in Different Forest Types

The carbon accumulated in biomass of trees, lianas, aboveground litter mass and harvested wood showed significant variations ($P<0.05$) across three forest types (Table 9.1).The tree aboveground biomass carbon (AGBC) varied significantly among forest types, with MDFWS recording the highest value (15.46 Mg C ha^{-1} yr^{-1}), followed by SDMDF (8.53 Mg C ha^{-1} yr^{-1}) and the lowest in PSF (4.02 Mg C ha^{-1} yr^{-1}). Saplings and shrubs contributed relatively small amounts to AGBC, with no significant differences among the forest types. However, lianas displayed a notable variation, with MDFWS (0.36 Mg C ha^{-1} yr^{-1}) accumulating significantly more carbon than SDMDF (0.18 Mg C ha^{-1} yr^{-1}) and PSF (0.10 Mg C ha^{-1} yr^{-1}). The belowground biomass carbon (BGBC) of trees followed a similar trend as AGBC,

with MDFWS showing the highest value (4.02 Mg C ha^{-1} yr^{-1}), followed by SDMDF (2.22 Mg C ha^{-1} yr^{-1}) and PSF (1.05 Mg C ha^{-1} yr^{-1}). Similar pattern in BGBC allocation was observed for lianas. The deadwood carbon ranged from 0.34 Mg C ha^{-1} yr^{-1} (PSF) to 0.40 Mg C ha^{-1} yr^{-1} (SDMDF). The aboveground litter carbon in PSF and SDMDF was almost same (0.76 and 0.75 Mg C ha^{-1} yr^{-1}respectively) and significantly differed for MDFWS (0.22 Mg C ha^{-1} yr^{-1}). The variations of harvested biomass carbon (small timber, fuel wood and NTFP) from three forest types was statistically insignificant and ranged from 3.53 Mg C ha^{-1} yr^{-1} (SDMDF) to 2.51 Mg C ha^{-1} yr^{-1} (MDFWS). The three forest types differed significantly with respect to net primary productivity (NPP) which was higher in MDFWS (24.55 Mg C ha^{-1} yr^{-1}) followed by SDMDF (17.50 Mg C ha^{-1} yr^{-1}) and PSF (10.75 Mg C ha^{-1} yr^{-1}).

Table 9.1 Net primary production (NPP) during the period 2021-22 (Mg C ha^{-1} yr^{-1}) in different vegetation components

Vegetation component	PSF	SDMDF	MDFWS	Mean	LSD (P<0.05)
Aboveground biomass carbon (AGBC)					
Tree	4.02±0.98^{c}	8.53±0.92^{b}	15.46±0.65^{a}	9.34±1.72	3.00
Sapling	0.12±0.03^{ns}	0.17±0.02^{ns}	0.21±0.07^{ns}	0.17±0.02	0.15
Shrub	0.14±0.02^{ns}	0.18±0.01^{ns}	0.18±0.02^{ns}	0.17±0.01	0.05
Liana	0.10±0.01^{b}	0.18±0.04^{b}	0.36±0.03^{a}	0.22±0.04	0.10
Belowground biomass carbon (BGBC)					
Tree	1.05±0.26^{c}	2.22±0.24^{b}	4.02±0.17^{a}	2.42±0.45	0.78
Saplings	0.03±0.005^{ns}	0.04±0.00^{ns}	0.05±0.02^{ns}	0.04±0.006	0.04
Shrubs	0.03±0.002^{ns}	0.05±0.00^{ns}	0.05±0.00^{ns}	0.04±0.002	0.01
Liana	0.03±0.003^{b}	0.05±0.008^{b}	0.10±0.01^{a}	0.06±0.01	0.03
Herbaceous plants C	0.19±0.04^{b}	0.34±0.02^{b}	0.54±0.06^{a}	0.36±0.05	0.16
Biomass carbon loss (BCL)					
Dead wood C	0.34±0.03^{ns}	0.40±0.05^{ns}	0.38±0.07^{ns}	0.37±0.02	0.17
Aboveground litter C	0.76±0.05^{a}	0.75±0.02^{a}	0.22±0.01^{b}	0.57±0.09	0.11
Fine root litter C	0.14±0.01^{a}	0.12±0.01^{a}	0.08±0.00^{b}	0.11±0.001	0.03
Biomass C loss by fire**	0.70±0.04^{ns}	0.65±0.22^{ns}	0.41±0.17^{ns}	0.59±0.09	0.57
Harvested biomass C***	3.11±1.04^{ns}	3.53±0.60^{ns}	2.51±0.09^{ns}	3.05±0.38	2.41
Net primary production	10.75±0.12^{c}	17.21±0.35^{b}	24.55±0.56^{a}	17.50±2.00	1.34

Note: *Herbaceous plants include tree seedlings, **Biomass loss by fire includes only surface standing litter, ***Harvested biomass includes small timber, fuel wood and collected NTFPs for domestic consumption only.

9.3.2 Litter production and decomposition across forest types

The total litter production (aboveground + belowground) varied significantly ($P<0.05$) across the three forest types (Table 9.2). The sal dominated moist deciduous Forest (SDMDF) exhibited the highest aboveground litter (AGL) production at 11.57 Mg ha^{-1} yr^{-1} which was significantly higher than both PSF (9.41 Mg ha^{-1} yr^{-1}) and MDFWS (7.89 Mg ha^{-1} yr^{-1}). The belowground litter (BGL) production showed less variability, with values ranging from 1.03 Mg ha^{-1} yr^{-1} (MDFWS) to 1.21 Mg ha^{-1} yr^{-1} (SDMDF) and the differences were not statistically significant. The decay constant (k) for litter also varied significantly. For AGL, SDMDF (0.0098 day^{-1}) had the highest decay rate followed by MDFWS (0.0064 day^{-1}) and PSF (0.0058 day^{-1}). Similar trend in decomposition rate for BGL was also noticed. The quantity of AGL mass decomposed was highest in SDMDF (9.97 Mg ha^{-1} yr^{-1}), followed by PSF (7.80 Mg ha^{-1} yr^{-1}) and MDFWS (7.44 Mg ha^{-1} yr^{-1}). The residual un-decomposed AGL mass was also higher in SDMDF (1.59 Mg ha^{-1} yr^{-1}) and PSF (1.61 Mg ha^{-1} yr^{-1}) compared to MDFWS. A similar pattern was observed in the BGL, both in terms of the decomposed mass and the un-decomposed residue, with SDMDF and PSF showing greater values than MDFWS. The litter fall in PSF and SDMDF followed a bimodal pattern with peak during January-February and May but it was unimodal in MDFWS with peak during April to May (Figure 9.1). The total quantity of litter decayed was found high during September-October and January-February in all three forest types.

Table 9.2 Variations in total litter production (Mg ha^{-1} yr^{-1}), decay rate (day^{-1}), quantity decayed and amount remain un-decomposed in three forest types

Forest type	Litter production		Decay rate		Litter decayed		Un-decomposed litter	
	AGL	BGL	AGL	BGL	AGL	BGL	AGL	BGL
PSF	9.41^{c} (0.14)	1.17^{a} (0.06)	0.0058^{c} (0.0003)	0.0050^{c} (0.0001)	7.80^{b} (0.18)	0.87^{ns} (0.04)	1.61^{a} (0.10)	0.30^{a} (0.02)
SDMDF	11.57^{a} (0.13)	1.21^{a} (0.03)	0.0098^{a} (0.0001)	0.0067^{a} (0.00003)	9.97^{a} (0.09)	0.94^{ns} (0.02)	1.59^{a} (0.04)	0.27^{a} (0.01)
MDFWS	7.89^{b} (0.44)	1.03^{b} (0.02)	0.0064^{b} (0.0002)	0.0055^{b} (0.00008)	7.44^{b} (0.43)	0.87^{ns} (0.01)	0.46^{b} (0.02)	0.17^{b} (0.01)
Mean	9.63 (0.55)	1.14 (0.03)	0.0073 (0.0018)	0.0058 (0.0003)	8.40 (0.42)	0.89 (0.02)	1.22 (0.19)	0.25 (0.02)
LSD	0.94	0.14	0.0005	0.0003	0.96	0.09	0.23	0.05

Note: Values in parenthesis are ± standard error of mean. Mean values accompanied with different alphabets are statistically differ from each other at $P<0.05$ in DMRT test.

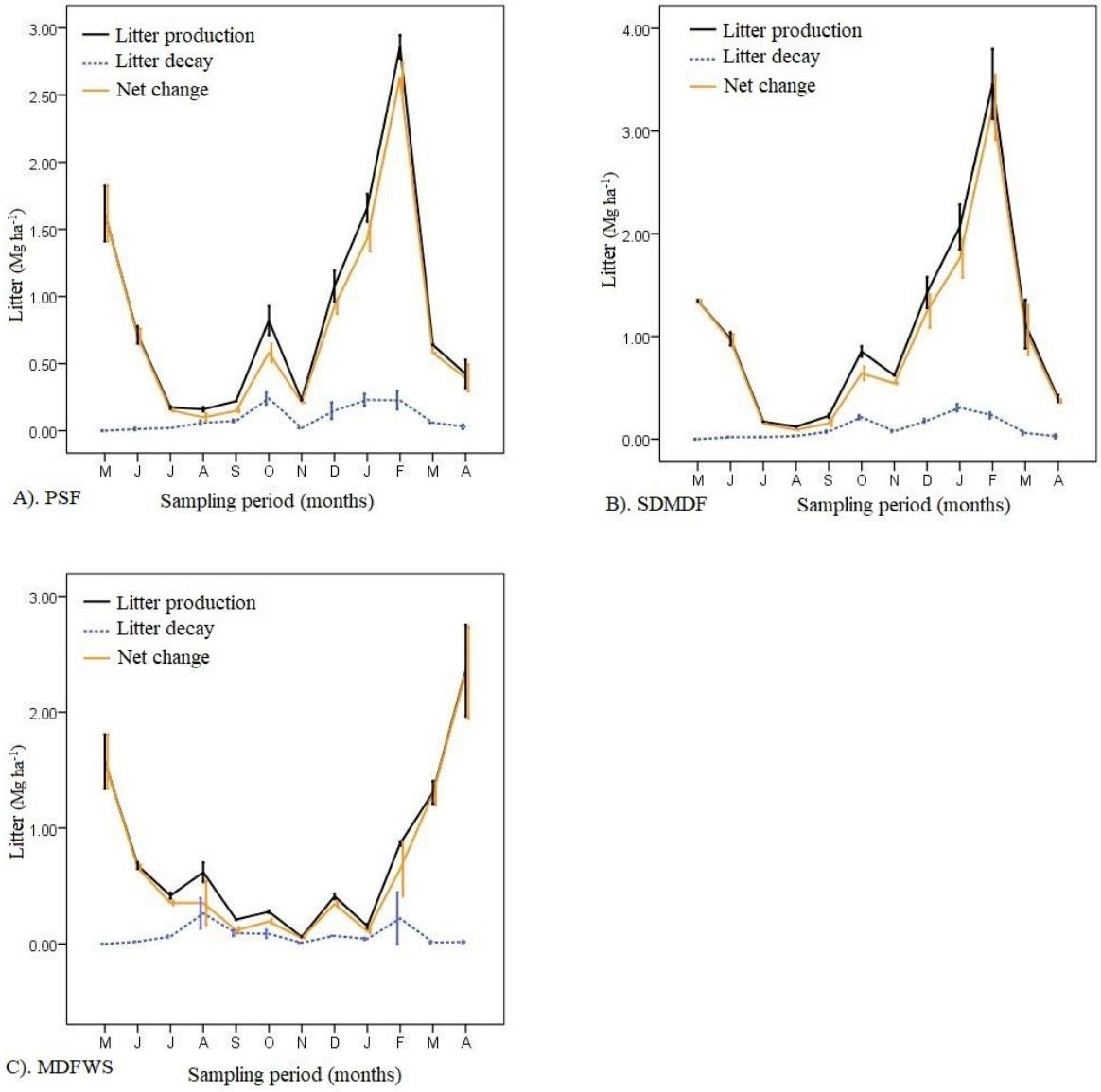


Figure 9.1 Monthly variations in total litter production, decay and net change A) pure sal forest (PSF), B) sal dominated moist deciduous forest (SDMDF) and C) moist deciduous forest without sal (MDFWS). Error bar represents standard error of the mean.

9.3.3 Heterotrophic respiration (Rh), net ecosystem production (NPP) and carbon flux pathways

The significant ($P<0.05$) variation in total biomass stock, carbon stock, net primary production (NPP), heterotrophic respiration (Rh) and net ecosystem production (NEP) among three forest types was observed (Table 9.3). The total biomass stock and carbon stock were highest in MDFWS (401.13 Mg ha^{-1} and 188.53 Mg C ha^{-1} respectively), than the values observed in PSF and SDMDF. The difference in total biomass stock and carbon stock of PSF (262.86 Mg ha^{-1} and 123.55 Mg C ha^{-1} respectively) and SDMDF (217.16 Mg ha^{-1} and 102.07 Mg C ha^{-1} respectively) were statistically insignificant at $P<0.05$. The net primary production (NPP) varied significantly among the three forest types, with MDFWS exhibiting the highest NPP (28.46 Mg C ha^{-1} yr^{-1}), followed by SDMDF (20.07 Mg C ha^{-1} yr^{-1}) and PSF (12.26 Mg C ha^{-1} yr^{-1}). The soil microbial decomposition (Rh), followed a similar trend as NPP. The MDFWS had the highest Rh value (22.11 Mg C ha^{-1} yr^{-1}), while SDMDF and PSF exhibited moderate (20.69 Mg C ha^{-1} yr^{-1}) and lower (14.66 Mg C ha^{-1} yr^{-1}) values, respectively. The net ecosystem production (NEP) also followed a similar pattern as total carbon stock production with highest value in MDFWS (4.71 Mg C ha^{-1} yr^{-1}) followed by SDMDF (-1.22 Mg C ha^{-1} yr^{-1}) and PSF (-1.64 Mg C ha^{-1} yr^{-1}). The NEP of PSF and SDMDF were negative indicating carbon source whereas MDFWS showed a positive indicating carbon sink (Figure 9.2). Overall the three forest types showed a positive value with NEP 0.62 Mg C ha^{-1} yr^{-1}. The contribution of aboveground biomass carbon (AGBC) and harvested wood biomass (HWBC) to the total NEP was substantial (Figure 9.3). The pathways for carbon flux in three forest types are given in Figure 9.4 -9.6.

Table 9.3 Total biomass stock (Mg ha^{-1} yr^{-1}), total C stock, net primary production (NPP), heterotrophic respiration (Rh) and net ecosystem production (NEP) in three forest types (Mg C ha^{-1} yr^{-1})

Forest type	Total biomass stock	Total carbon stock	NPP	Rh	NEP
PSF	262.86±26.31^{b}	123.55±12.36^{b}	10.75±0.12^{b}	12.38±1.79^{b}	-1.64±1.90^{b}
SDMDF	217.16±11.56^{b}	102.07±5.43^{b}	17.21±0.35^{a}	18.43±0.26^{a}	-1.22±0.58^{b}
MDFWS	401.13±40.52^{a}	188.53±19.04^{a}	24.55±0.56^{a}	19.84±0.68^{a}	4.71±1.09^{a}
MEAN	293.72±20.81	138.05±9.78	17.50±2.00	16.88±1.27	0.62±1.21
LSD (P<0.05)	82.54	38.77	1.34	3.87	4.54

Note: ± standard error of mean. Mean values accompanied with different alphabets are statistically differ from each other at P<0.05 in DMRT test

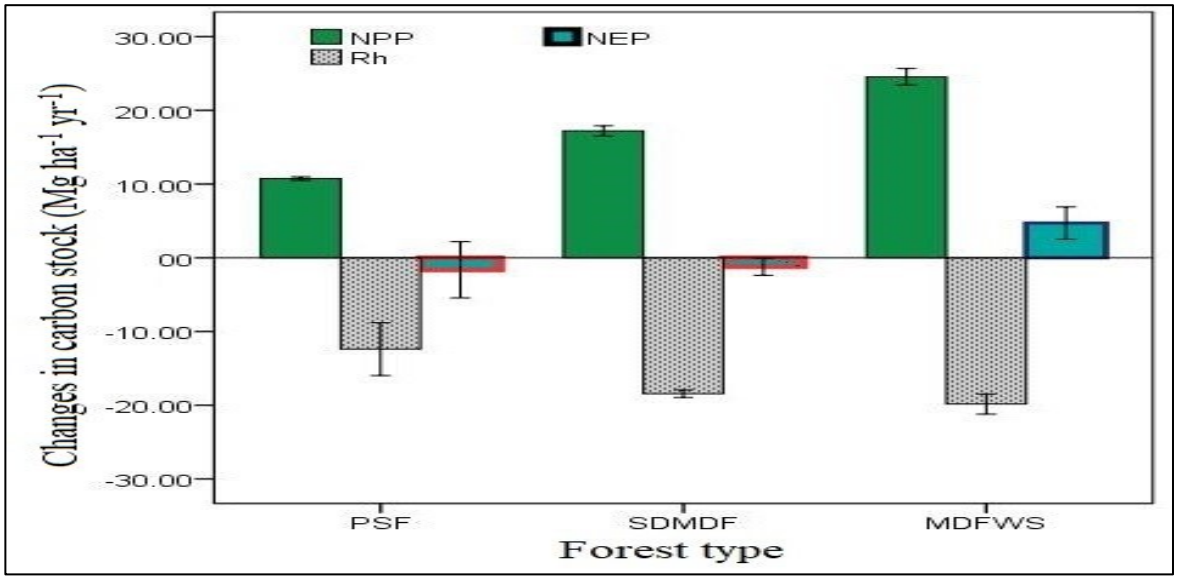


Figure 9.2 Net primary production (NPP), heterotrophic respiration (Rh) and net ecosystem production (NEP) in three forest types. Error bar represents standard error of the mean.

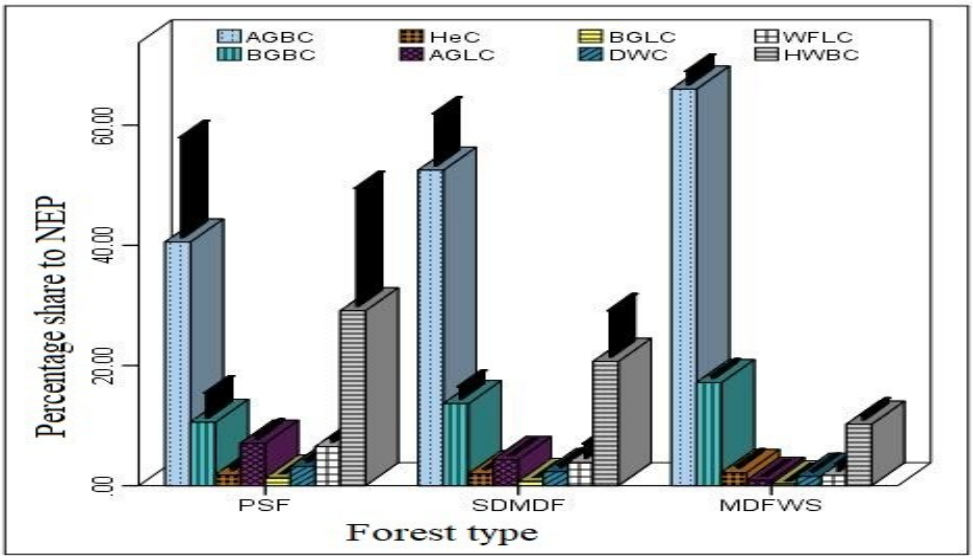


Figure 9.3 Share of various vegetation components to net ecosystem production (NEP) in three forest types. AGBC- aboveground biomass carbon, BGBC- belowground biomass carbon, HeC- herbaceous plats biomass carbon, AGLC- aboveground litter carbon, BGLC-belowground litter carbon, DWC-dead wood carbon, WLFC-wildfire lost carbon, HWBC-harvested wood biomass carbon. Error bar represents standard error of the mean.

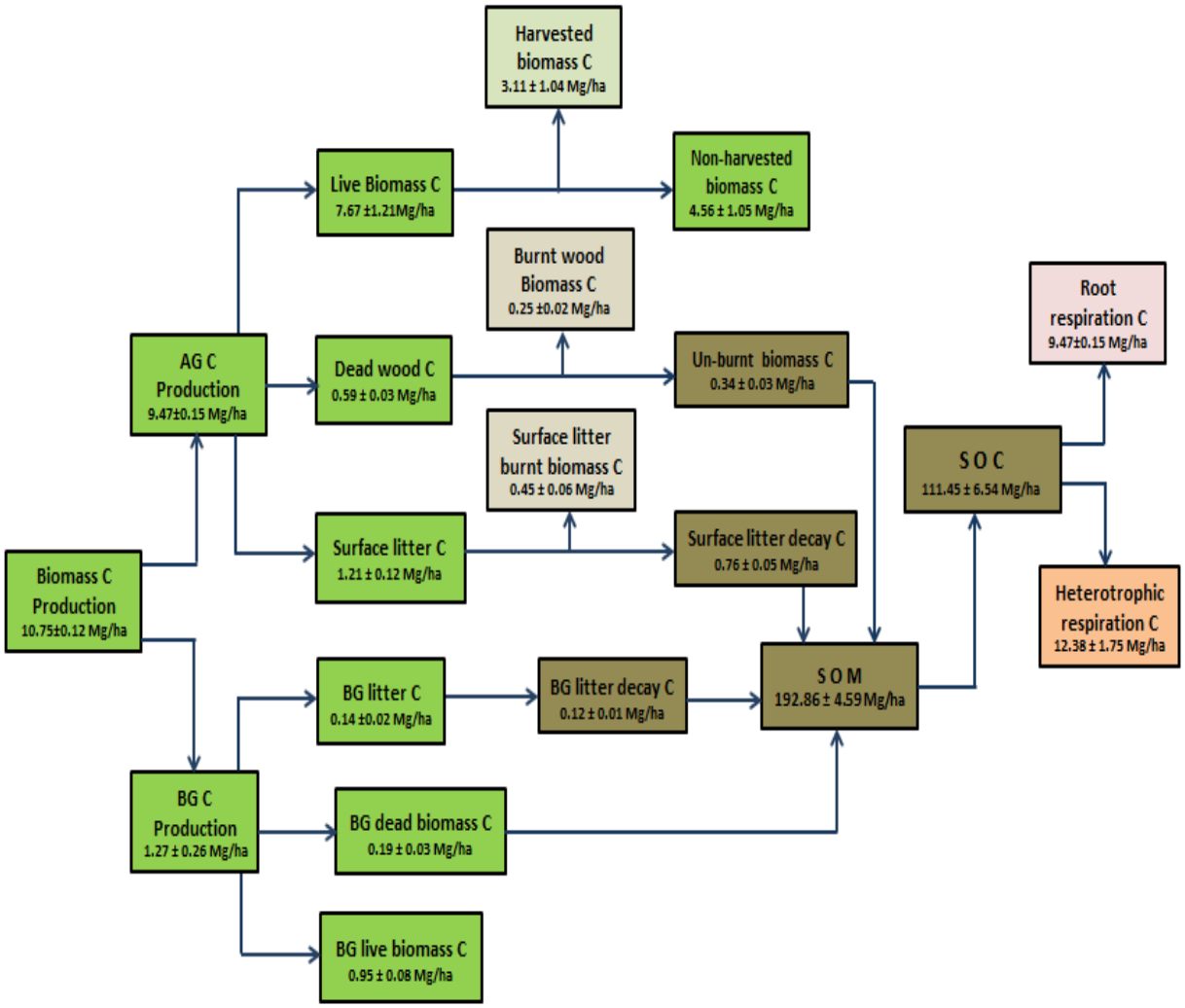


Figure 9.4 Annual carbon budget and flux pathways in pure sal forest (PSF). Values presented as mean ± standard error.

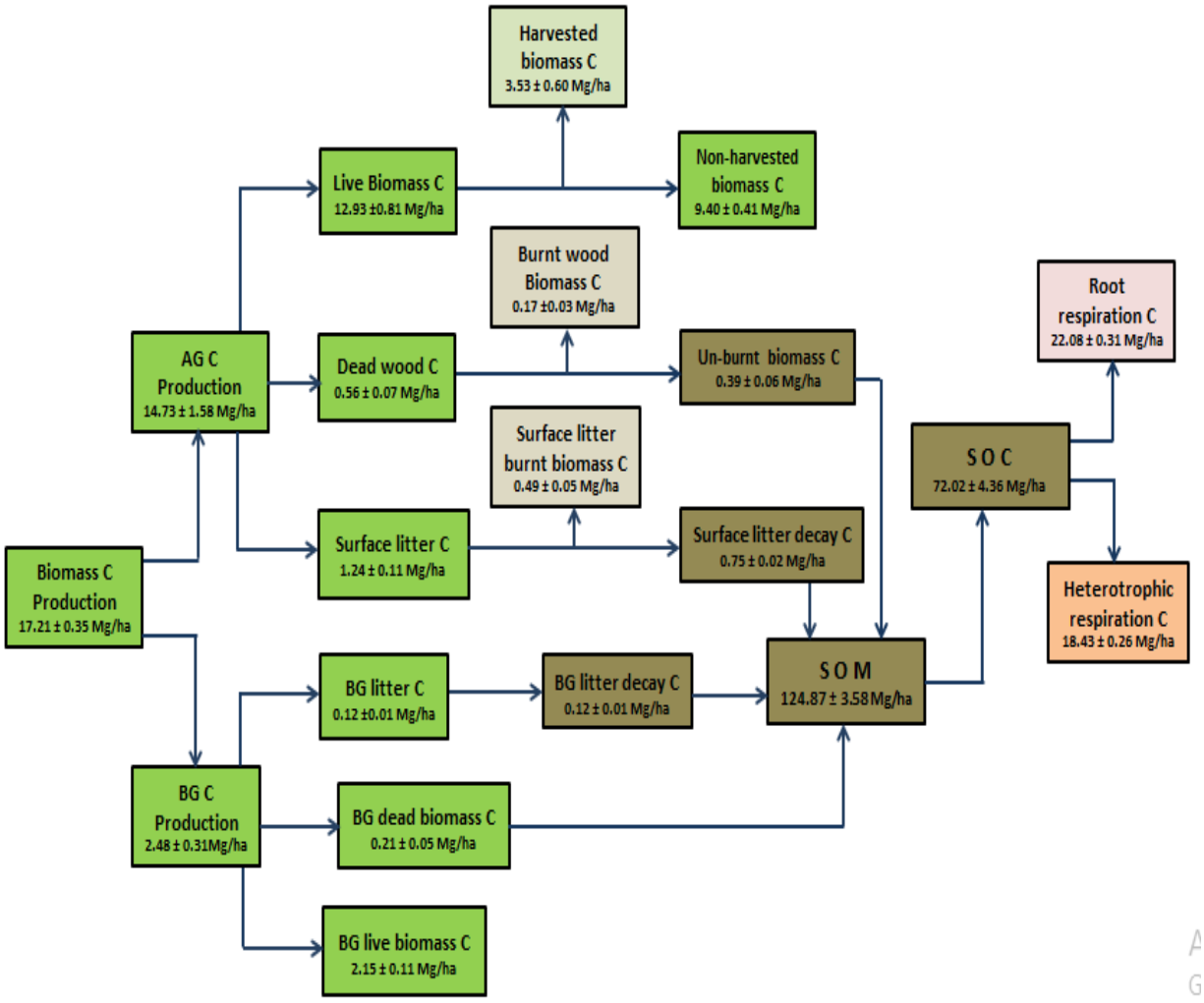


Figure 9.5 Annual carbon budget and flux pathways in sal dominated moist deciduous forest (SDMDF).Values presented as mean ± standard error.

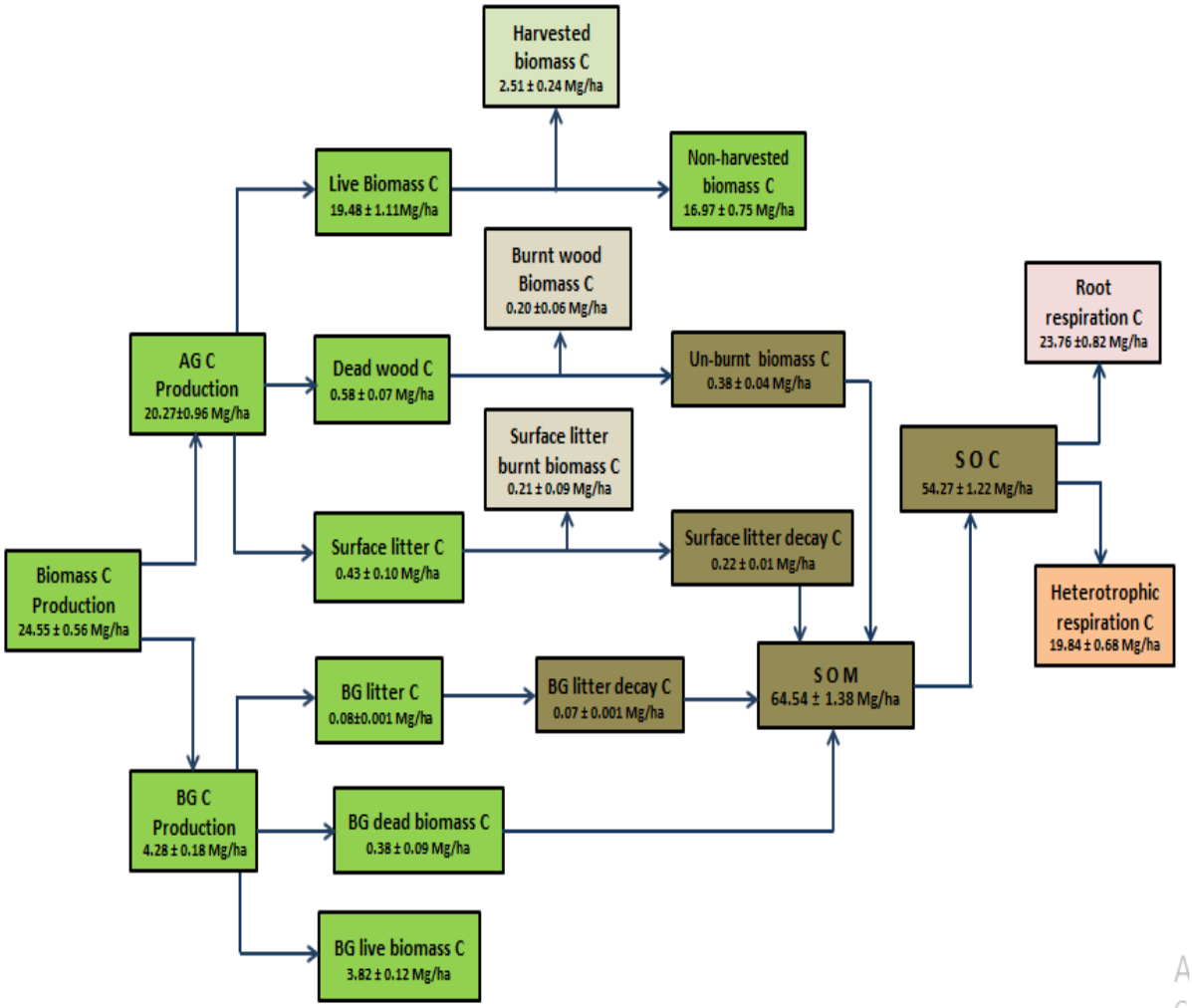


Figure 9.6 Annual carbon budget and flux pathways in moist deciduous forest without sal (MDFWS).Values presented as mean ± standard error.

9.4 Discussion

Net primary production (NPP) is considered as a vital indicator for judging the ecological status and relative significance of an ecosystem. Climate change and various perturbations routed either from nature or human actions influences the NPP in forests. It is mediated through the direct vegetation response to change driven by these factors (Jhariya, 2017). These responses may further be altered by age class distribution and

composition (Boisvenue and Running, 2006). Clark *et al.* (2001) after an extensive analysis of literature, reported that variations in climate, soil, stand age and species composition in tropical forests result in NPP ranging from 3.1 Mg C ha^{-1} yr^{-1} to 31.5 Mg C ha^{-1} yr^{-1}**.** The NPP observed in the present study ranged from 10.75 Mg ha^{-1} in PSF to 24.55 Mg ha^{-1} in MDFWS**.** These values are comparable to previously reported NPP estimates for tropical forests of the Western Ghats (22.40 to 27.70 Mg ha^{-1}, Swamy *et al.,* 2010) and tropical forests in China (12.0 to 20.0 Mg ha^{-1}, Linger *et al.,* 2020), but higher than the NPP reported for tropical forests of Malaysia (6.01–8.37 Mg ha^{-1}, Jeyanny *et al.,* 2021). These differences in NPP can largely be attributed to variations in edaphic and climatic conditions as well as differences in species composition and forest structure across sites. The NPP value varied significantly among three forest types, with the order > SDMDF > PSF (Table 9.3). The significantly higher NPP in MDFWS can be attributed to higher stand density and greater biomass stock by from young trees (Malhi, 2012).

The net ecosystem productivity (NEP) represents the overall accumulation of carbon in a forest ecosystem balancing carbon inputs via photosynthesis against losses through respiration (Sierra *et al.,* 2007). Although quantifying the exact amount of carbon released through respiration remains challenging, it is well recognized that forest stand structure**,** long-term disturbances and year-to-year climatic variability significantly influence this process (Chambers et *al.,* 2004). Zhao *et al.* (2019), using the tree-based model FORCCHN and remote sensing data, estimated NEP for forest ecosystems across globe. They reported that NEP in tropical forests range from 0.678 to 0.875 kg C m^{-2} yr^{-1} which is equivalent to 6.78 to 8.75 Mg C ha^{-1} yr^{-1}. The NEP values obtained in the present study ranging from a low of -1.64 Mg C ha^{-1} yr^{-1} in PSF to a high of 4.71 Mg C ha^{-1} yr^{-1} in MDFWS, fall below the reported range, which may be attributed to the methodological approach in measurement as well as differences in site conditions, forest structure and disturbance regimes**.**

The carbon dynamics of forest ecosystems encompass both the storage and movement of C within vegetation components and soils. These processes involve the uptake of atmospheric carbon through photosynthetic assimilation, its incorporation into biomass and soils and subsequent losses through mechanisms such as respiration, decomposition and leaching (Raj and Jhariya, 2021). The interaction between soil and plants influence carbon transfer pathways and flux across forest ecosystems. In turn, these interactions regulate terrestrial carbon reservoirs and drive nutrient cycling essential for forest health and productivity (Salunkhe *et al.,* 2018). However, variations in vegetation structure and biodiversity lead to significant differences in carbon flux movement and storage within different forest types. In the present study the carbon dynamism among aboveground (AGBC) and belowground biomass (BGBC) varied from 88.09% in PSF to 82.57% in MDFWS (Figure 9.3). These values are comparable with the aboveground biomass C stock in sal forests of Chattishgarh (Raj and Jhariya, 2021) and tropical mixed dry forests of Uttar Pradesh (Singh and Singh, 1991). The results highlight the critical role of forest type in determining carbon dynamics. MDFWS serves as a significant carbon sink, while PSF and SDMDF exhibit near-neutral or negative carbon balance. Understanding these patterns is essential for developing conservation strategies and mitigating climate change impacts.

CHAPTER-10

GENERAL DISCUSSION

Forests are integral to the regulation of the global carbon (C) cycle, functioning simultaneously as carbon sinks and sources. They store vast quantities of C within living biomass, soil and dead organic matter, thereby exerting a significant influence on atmospheric CO_2 concentrations and global climate dynamics. Among the various global forest ecosystems, tropical forests hold particular importance, accounting for approximately 55% of the total forest carbon stock. Within these, tropical moist deciduous forests play a key role in carbon sequestration and ecosystem stability. Beyond their capacity to store carbon, these forests deliver a range of critical ecosystem services, including biodiversity conservation, soil stabilization, hydrological regulation and climate moderation. Forests act as a dynamic system for regulating atmospheric CO_2, making it essential to evaluate their functionality not only in terms of net primary production (NPP) but also through net ecosystem production (NEP)

Odisha has rich forest resources, covering about 33.67% of the state's total area (Indian State of Forest Report 2023). Among the different forest types found in the state, tropical moist deciduous forests stand out for their diverse structure and the valuable benefits they offer. These forests are not only vital for ecological balance but also significantly support the livelihoods of local communities. However, due to increasing pressures from deforestation, logging and agricultural expansion tropical moist deciduous forests are highly vulnerable to degradation. Deforestation, livelihood dependence on forests, agricultural expansion, stone quarrying and climate change are altering carbon dynamics and affecting the NEP of these forests.

The plant community composition in a given forest is nevertheless influenced by abiotic soil physicochemical properties, as well as topographic factors such as slope and aspect, climate, disturbances etc.) and biotic (competition, predation, mutualism etc.). In the tropical moist deciduous forests of Odisha, three distinct forest community types were identified: pure sal forest (PSF), sal dominated moist

deciduous forest (SDMDF) and moist deciduous forest without sal (MDFWS). These communities were differentiated based on the relative abundance and importance value index (IVI) of dominant tree species, as discussed in **Chapter 4**. The IVI of sal (*Shorea robusta*) was recorded at 170.43 in PSF, indicating strong dominance. However, in SDMDF, the IVI of sal declined to 87.65, reflecting reduced dominance. In the MDFWS community, sal presence was negligible and dominance shifted to other species such as *Terminalia alata* (IVI 19.39) and *Anogeissus latifolia* (IVI 14.47), indicating a substantial change in community structure and species composition across forest types. The common associates sharing upper canopy strata with sal in PSF include *Schleichera oleosa*, *Careya arborea*, *Pterocarpus marsupium* and *Syzygium cumini* in moist areas, while *Diospyros melanoxylon*, *Madhuca latifolia* and *Buchanania lanzan* are common in drier sites. In SDMDF, species like *Buchanania lanzan*, *Anogeissus latifolia*, *Careya arborea* and *Lagerstroemia parviflora* dominate the upper canopy. *Cleistanthus collinus* is consistently abundant across all forest types, contributing significantly to forest density and basal area. As expected, the MDFWS community exhibits higher species richness (130 species) across tree, shrub, liana and herb layers compared to SDMDF (98) and PSF (78), likely due to the reduced dominance of Sal. Notable variations were also observed in other quantitative phytosociological attributes, including Margalef's species richness index, Shannon–Weiner diversity index, Simpson's dominance index, and Pielou's evenness index. The tree density (≥10 cm dbh) and basal area (BA) recorded in this study i.e. 490-625 stems ha^{-1} with a BA of 16.66-30.12 m^2 ha^{-1} in PSF, 473-756 stems ha^{-1} with a BA of 11.69-21.70 m^2 ha^{-1} in SDMDF and 663-831 stems ha^{-1} with a BA of 22.25-32.05 m^2 ha^{-1} in MDFWS are well consistent with stocking densities reported from other tropical forests within the state as well as across the country. The variation in stand basal area (11.69-32.05 m^2 ha^{-1}) across forest types is primarily due to anthropogenic disturbances such as selective logging, tree girdling for fuelwood and unsustainable pollarding for NTFP collection. The density-based population structure exhibited a reverse J-shaped curve, marked by a higher proportion of juvenile individuals. This pattern suggests active regeneration, likely facilitated by abundant seed production and the creation of suitable light conditions through seasonal canopy opening in moist deciduous forests. The proportion of

species exhibiting good regeneration was higher in MDFWS (26.2%) and lowest in PSF (9.1%), likely due to thick litter accumulation, recurrent fires and high biotic pressure from grazing and NTFP extraction.

Forest biomass production is influenced by factors such as forest type, species composition, and stand age. Although various vegetation strata contribute to overall biomass, tree biomass constitutes the most significant component. Parameters such as diameter at breast height (DBH), tree height and basal area are commonly used in biomass estimation. In the present study, total biomass stock was found to be highest in MDFWS (401.13 Mg ha^{-1}), followed by SDMDF (262.86 Mg ha^{-1}) and PSF (217.16 Mg ha^{-1}), which can be attributed to the comparatively greater tree density and basal area observed in MDFWS (**Chapter 5**). Aboveground biomass (AGB) constituted the major portion of total biomass across all forest types, reflecting a pattern consistent with total biomass distribution. The aboveground biomass (AGB) observed in this study aligns closely with previously reported values for sal forests from various regions of the state (Table 10.1).

Table 10.1 Comparison of tree AGB in different sal forests Odisha

Forest type	**Place**	**Density (trer ha^{-1})**	**Basal area (m^2 ha^{-1})**	**AGB (Mg ha^{-1})**	**Ref.**
Sal-dominated MDF	Similipal BR	765	29.8	410.70	[1]
Xylia-dominated MDF	Similipal BR	712	26.26	338.0	
DDF with pure sal	Chandaka WLS	835	13.70	74.30	[2]
DDF in Eastern Ghats	Deogarh district	479	15.20	13.96 to 514.50	[3]
Pure sal forest	Phulbani	545.00	21.82	202.95	Present study
Sal dominated moist dec. forest	Phulbani	609.67	17.87	165.55	
Moist dec. for without sal	Phulbani	746.75	27.15	313.04	

Note: MDF-moist deciduous forest, DDF-dry deciduous forest; References; [1] Mohanta *et al.,* 2020, [2] Pattnayak *et al.,* 2020, [3] Sahu *et al.,* 2016

The contribution of shrubs and lianas to the total biomass stock was highest in SDMDF, with values of 8.53 Mg ha^{-1} and 14.70 Mg ha^{-1} respectively. This elevated contribution can be attributed to their higher density and abundance in this forest type, likely driven by increased light availability in canopy gaps, moderate disturbance levels and favorable microsite conditions that promote their proliferation. In SDMDF, the contribution of non-living biomass was also comparatively higher, likely due to increased litterfall and a greater accumulation of deadwood, attributable to the structural characteristics of the forest stand.

In forest ecosystems, the main carbon pools are tree biomass especially aboveground biomass (AGB) and soil organic carbon (SOC), with their relative contributions varying by forest type. Tropical forests store more carbon in AGB due to dense, fast-growing vegetation, while boreal and littoral-swamp forests often have higher SOC due to slower decomposition and biomass turnover. In this study, the contribution of tree aboveground biomass (AGB) to total forest carbon ranged from 46% in PSF to 71% in MDFWS, while SOC contributed between 22% in MDFWS and 47% in PSF. The higher SOC proportion in PSF can be attributed to the slow decomposition of organic matter and the accumulation of a thick litter layer. In contrast, the lower SOC levels in MDFWS reflect a diverse species composition with litter that decomposes more rapidly, limiting long-term carbon buildup in the soil. The total carbon stock across the three studied forests ranged from 172.68 Mg C ha^{-1} (SDMDF) to 242.41 Mg C ha^{-1} (MDFWS), aligning with values reported for sal forests in the Kumaun Himalaya (224.80–373.90 Mg C ha^{-1}) by Siddiqui *et al.* (2024) and Siwalik region (189.29–230.81 Mg C ha^{-1}) by Kongkham *et al.* (2021). The observed variation may be attributed to differences in site conditions, forest structure, species composition and the degree of anthropogenic disturbance, all of which influence biomass accumulation and soil carbon storage (Chapter 6). *Shorea robusta* was the dominant contributor to total biomass carbon stock (TBCS) in PSF (83.53%) and SDMDF (44.74%), with smaller shares from species like *Semecarpus anacardium* and *Schleichera oleosa*. On the other hand, MDFWS with the highest species diversity, shows a more even biomass distribution, led by *Terminalia alata* (8.00%), *Schleichera oleosa* (7.03%) and *Anogeissus latifolia* (5.38%). These

patterns likely result from variations in species dominance, growth dynamics and carbon allocation across forest types.

The significant variation in carbon sequestration ($P < 0.05$) among the three forest types was linked to differences in tree density, species composition, productivity, and litter decomposition rates. Annual carbon sequestration was highest in MDFWS (22.01 Mg C ha^{-1}), followed by SDMDF (13.54 Mg C ha^{-1}) and PSF (7.14 Mg C ha^{-1}) attributed to higher tree density and basal area, which together promoted greater biomass and carbon accumulation both above and below ground (Chapter 6).

Litterfall dynamics in forest ecosystems are influenced by site quality, air temperature, soil moisture availability, fire or extreme weather events. In this study, a significant peak in leaf shedding (55 to 69% of total litterfall) occurred between November and February, likely driven by soil moisture stress and the adaptive responses of plant species to environmental conditions. The total mean annual litterfall, ranging from 8.93 Mg ha^{-1} yr^{-1} to 12.77 Mg ha^{-1} yr^{-1}, fell within the range reported for tropical moist deciduous forests of the Western Ghats, tropical dry evergreen forests of the Coromandel Coast and humid sub-tropical forests of Northeast India (Pragasan and Parthasarathy, 2005; Arunachalam *et al.,* 1998; Devi and Yadava, 2010). These findings highlight the influence of climatic factors and species adaptability in shaping litterfall patterns and nutrient cycling within forest ecosystems.

The chemical analysis of various types of litter (leaf, small branch and root) revealed a mixed result with consistently low value of nitrogen (N), phosphorus (P) and potash (K). Carbon concentration varied from 373.57 mg g^{-1} in small branch (SB) litter to 457.87 mg g^{-1} in root litter, with significant differences observed only in small branch litter among forest types. The concentrations of hemicellulose, cellulose, lignin and phenols ranged from 233.22 to 466.67 mg g^{-1}, 143.02 to 579.60 mg g^{-1}, 116.89 to 293.33 mg g^{-1} and 134.52 to 220.45 mg g^{-1} (GAE) respectively. The nitrogen content ranged from 5.00 to 8.30 mg g^{-1}, phosphorus from 1.07 to 2.91 mg g^{-1} and potash from 0.99 to 2.81 mg g^{-1} with the highest C/N and L/N ratios

observed in PSF litter. Overall, leaf litter had the highest nutrient content compared to small branch and root litter. This is because leaves are metabolically active, absorbing more nutrients for photosynthesis and growth.

The litter bag decomposition study revealed that, leaf litter decomposes more quickly than small branches with reproductive parts and root litter, irrespective of forest type (Chapter 7). Litter decay followed a three-phase pattern: slow decomposition during summer, rapid mass loss in the rainy season, and a steady decay rate in winter which is much common in tropical monsoon forest conditions. Litter decay was highest in MDFWS, while PSF showed the slowest mass loss, with 12.70% of leaf, 35.80% of small branch and 25.83% of root litter remaining after 270 days. Higher species diversity led to nitrogen-rich litter in MDFWS which enhances microbial abundance, activity and decomposition related enzymatic processes (Getaneh *et al.,* 2022). Rapid decay occurred between 60 to 120 days of incubation, coinciding with the rainy season. PSF had the highest decay constants and residence times (t_{50}, t_{99}, and 1/k) for all litter types, while MDFWS had the lowest values. The annual mass decay rates (k_m) in PSF (1.39-2.82) and SDMDF (1.69-3.03), dominated by sal components, aligned with reported rates for sal leaves in West Bengal (2.48) by Das and Mondal, (2016) and Uttar Pradesh (3.00) by Pandey *et al.* (2014). Initially, the C:N ratio rose until day 60, then declined sharply before rising again towards 270 days. The C:N ratio initially increased due to nitrogen loss and retention of carbon rich compounds, declined with enhanced microbial activity and rose again as recalcitrant carbon accumulated (Rai *et al.,* 2016). Climatic factors positively affected mass loss, with soil moisture and nitrogen content enhancing decay, whereas soil organic matter had an inhibitory effect. Air temperature, relative humidity and soil nitrogen were the best predictors of mass decomposition, explaining 54% to 56% of mass loss. Among various litter quality linked attributes, lignin (L) content and L/N ratio negatively correlated with decay rate, while C, N, cellulose, phenols and C/N ratio positively correlated. L/N ratio, C/N ratio and nitrogen content explained 76% to 86% of mass loss variability. After 270 days, the return of nitrogen (64.35 kg ha^{-1} yr^{-1} to 88.91 kg ha^{-1} yr^{-1}), phosphorus (19.49 kg ha^{-1} yr^{-1} to 24.55 kg ha^{-1} yr^{-1}) and potassium (21.54 kg ha^{-1} yr^{-1} to 24.21 kg ha^{-1} yr^{-1}) through litterfall was

consistent with values reported from other tropical Indian forests, with differences among forest types driven by variations in litter quality and species composition.

Soil respiration, a crucial component of carbon cycling, reflects the combined activity of microbes, roots and soil fauna in decomposing organic matter. It influences soil carbon storage and determines an ecosystem's role as a carbon source or sink. Elevated respiration suggests healthy microbial activity and nutrient cycling, whereas reduced rates may indicate soil degradation or environmental stress. PSF exhibited the highest soil temperature (27.72°C) and lowest moisture (15.61%), while MDFWS had the lowest soil temperature (23.43°C) and highest moisture (20.92%), likely due to greater accumulation of un-decomposed humus in PSF (Chapter 8).

The mean daily soil respiration in this study (0.62 g C m^{-2} d^{-1} to 0.99 g C m^{-2} d^{-1}) aligns with reported ranges from other Indian forests, including 0.36 g C m^{-2} d^{-1} to 2.36 g C m^{-2} d^{-1} in Odisha's tropical dry deciduous forests (Mohanty and Pand, 2011) and 0.104 g C m^{-2} d^{-1} to 26.25 g C m^{-2} d^{-1} in Himalayan temperate forests (Rawat *et al.,* 2021). The total annual soil respiration (ASRT) was significantly ($P < 0.05$) highest in MDFWS (43.61 Mg C ha^{-1} yr^{-1}), followed by SDMDF (40.51 Mg C ha^{-1} yr^{-1}) and lowest in PSF (27.21 Mg C ha^{-1} yr^{-1}). The analysis of Pearson's correlation coefficient study showed a strong positive correlation ($r = 0.798$, $P < 0.01$) between soil moisture and soil respiration, while soil temperature had a weaker correlation ($r = 0.204$, $P < 0.05$), indicating that soil moisture is the main driver of soil respiration.

There were significant differences in net primary productivity (NPP) across the three forest types, with MDFWS showing the highest NPP (24.55 Mg C ha^{-1} yr^{-1}), followed by SDMDF (17.50 Mg C ha^{-1} yr^{-1}) and PSF (10.75 Mg C ha^{-1} yr^{-1}). The growth of aboveground biomass from trees and the loss of wood biomass through harvesting have a greater impact on NPP than other contributing factors (Chapter 9). Soil microbial decomposition (Rh) followed a similar pattern, that of NPP, with highest value in MDFWS (22.11 Mg C ha^{-1} yr^{-1}) followed by SDMDF (20.69 Mg C ha^{-1} yr^{-1}) and PSF (14.66 Mg C ha^{-1} yr^{-1}). The net ecosystem

production (NEP) was positive in MDFWS (4.71 Mg C ha^{-1} yr^{-1}) and negative in SDMDF (-1.22 Mg C ha^{-1} yr^{-1}) and PSF (-1.64 Mg C ha^{-1} yr^{-1}), indicating a carbon sink in MDFWS and sources in the others. The overall NEP across the three forest types i.e. moist deciduous forest of the division was positive, with a value of 0.62 Mg C ha^{-1} yr^{-1}.

CHAPTER-11

SUMMARY AND CONCLUSIONS

The present research work entitled" Net Ecosystem Production and Carbon Flux in Tropical Moist Deciduous Forest of Odisha" was carried out in the Phulbani Forest Division, laboratory of College of Forestry and Central Instrumentation Facility of University of Agriculture and Technology, Bhubaneswar during the period 2020-2022. The main objective of this research work was to:

a) Assess the vegetation composition of tropical moist deciduous forests in Odisha
b) Quantify biomass production, litter production, decomposition rates and net primary productivity in the forest ecosystem
c) Investigate net ecosystem production and carbon fluxes across various pools within the forest ecosystem.

Four experiments were conducted to fulfill the above-mentioned objectives described as follows:

1. Analysis of soil physiochemical properties and disturbance regime in the study sites
2. Phytosociological analysis of the forest types
3. Estimation of biomass stock, carbon stock and carbon sequestration potential of forests
4. Studies on litter dynamism in the studies forest types
5. Studies on soil respiration dynamics
6. Studies on net primary production (NPP), carbon flux and net ecosystem production (NEP)

In the **first experiment**, soil samples were collected from three depth intervals *viz* 0-15 cm, 15-30 cm and 30-45 cm from all four sides of a rectangular pit measuring 1 m in length, 1 m in breadth and 60 cm in depth. This pit was excavated within each sub-sample plot (31.62 m × 31.62 m) designated for phytosociological analysis. After due processing samples were analyzed for different physiochemical properties.

Soil physical properties

Soils across all forest types were predominantly brown (7.5 YR 5/4 to 7.5 YR 5/3), except the 0-15 cm layer in SDMDF, which was strong brown (7.5 YR 5/6). Significant differences ($P < 0.05$) were observed in sand, silt, clay content, bulk density (BD) and water holding capacity (WHC) among the forest types.

- Sand content ranged from 75.70% (MDFWS) to 87.57% (PSF).
- Silt content ranged from 6.21% (SDMDF) to 9.30% (PSF), with PSF and MDFWS being statistically similar.
- Clay content increased from PSF (3.31%) to SDMDF (11.34%) to MDFWS (15.33%), with significant differences between all.
- Soil texture was loamy-sand in PSF and MDFWS, and sandy-loam in SDMDF.
- Bulk density ranged from 1.52 (PSF) to 1.72 (MDFWS).
- WHC ranged from 38.81% (SDMDF) to 42.08% (MDFWS).

Soil chemical properties

Significant variation ($P < 0.05$) was observed in soil chemical properties i.e. pH, electrical conductivity (EC), soil organic carbon (SOC) and available nitrogen (N), phosphorus (P) and potash (K) among the three forest types (PSF, SDMDF, and MDFWS).

- Soil pH was acidic in PSF (5.74) and SDMDF (5.95), while MDFWS had a neutral pH (6.73), significantly differing from the others. A decrease in acidity with depth was observed in PSF and MDFWS, but no clear trend in SDMDF.
- EC values ranged from 0.015 dS m^{-1} (MDFWS) to 0.025 dS m^{-1} (SDMDF).
- SOC content was highest in PSF (1.67%), followed by SDMDF (0.98%) and lowest in MDFWS (0.71%).

- Available nutrients (N, P, K) were highest in the surface layer (0–15 cm) and decreased with depth.
- The range of available nutrients across forest types was: Nitrogen: 85.32 to 118.2 kg ha^{-1}, Phosphorus: 9.40 to 12.44 kg ha^{-1} and Potash: 420.03 to 549.76 kg ha^{-1}

Overall, PSF showed higher SOC and nutrient levels, while MDFWS soils were more neutral with lower SOC and EC.

Disturbance regime

The cumulative disturbance index, calculated using cut stump data and relative scores from eight other disturbance types, showed no significant difference in overall disturbance levels among the three forest types (PSF, SDMDF and MDFWS). The disturbance index values ranged from 31.00 to 38.33, placing all forest types in the low disturbance category. However, variation existed within individual study sites (Site I to Site III) of each forest type: PSF- 13.75 to 63.50, SDMDF- 12.00 to 61.00 and MDFWS- 10.25 to 64.75. This indicates localized differences in disturbance intensity despite overall similarity across forest types.

In the **second experiment** variation in phytosociological attributes of three forest types was studied using the quadrat sampling procedure. After repeated field surveys sample plots were delineated in four reserve forests (Khajuripada, Dutimundi, Dakapalla-B, and Sudurukumpa) with each site encompassing an area of 2.0 ha. In total, 18 ha was sampled across all locations to document tree, shrub, liana and herbaceous plant attributes.

The floristic analysis identified 168 plant species across 138 genera and 55 families, including 61 trees, 26 shrubs, 8 lianas and 46 herbs. Among the three forest types:

Tree Species Richness:

- MDFWS had the highest tree diversity with 51 species from 41 genera and 22 families. SDMDF recorded 39 species, 36 genera, and 19 families. PSF had the lowest richness with 17 species, each from a unique genus across 11 families.

Dominant Families (Based on Family Importance Value -FIV)

- In PSF, Dipterocarpaceae (FIV 178.99) was dominant, followed by Anacardiaceae, Fabaceae, and Combretaceae collectively making up 83.68% of the composition. In SDMDF, Dipterocarpaceae also dominant (FIV 95.87), followed by Phyllanthaceae, Anacardiaceae and Combretaceae, comprising 61.97% of the forest. In MDFWS, Combretaceae was dominant (FIV 54.34), along with Fabaceae, Anacardiaceae, Phyllanthaceae and Rubiaceae, contributing to 60.53% of the forest composition.

Species Dominance (Based on IVI)

- In PSF, *Shorea robusta* dominated (IVI 170.43) the community with key associates *Semecarpus anacardium* and *Cleistanthus collinus*. In SDMDF, also *Shorea robusta* (IVI 87.65) found dominated the community with associates like *Madhuca latifolia* and *Buchanania lanzan*. In MDFWS, *Terminalia alata* (IVI 19.04) was found dominant sharing upper strata with *Diospyros melanoxylon* and *Anogeissus latifolia* as key associates.

Biodiversity Indices: Significant differences ($P < 0.05$) were observed among forest types:

- Species Richness Index: Highest in MDFWS (6.49), followed by SDMDF (4.79), and PSF (2.82).
- Shannon–Weiner Diversity Index: MDFWS (3.47) > SDMDF (2.55) > PSF (1.11).
- Simpson's Dominance Index: Highest in PSF (0.57), indicating strong dominance, especially by *Shorea robusta*.

- Pielou's Evenness Index: Highest in MDFWS (0.96), showing more even species distribution.

No significant differences were noted in shrub diversity across forest types. For lianas, only the evenness index showed significant variation ($P < 0.003$), while herb diversity differed significantly only in species richness. The rank abundance curves indicated greater equitability (lower dominance) in MDFWS and strong single species dominance (*Shorea robusta*) in PSF and SDMDF. This suggests that MDFWS supports a more balanced and diverse plant community compared to the other two forest types.

The **third experiment** was conducted to estimate the biomass of the forest in a non-destructive approach. Significant differences ($P<0.05$) were observed in total, living, and non-living biomass stocks as well as carbon stock.

Biomass stock:

MDFWS recorded the highest total biomass (401.13 Mg ha^{-1}), significantly exceeding PSF (217.16 Mg ha^{-1}) and SDMDF (201.50 Mg ha^{-1}), with no significant difference between the latter two. This indicates MDFWS have greater productivity and structural complexity. PSF and SDMDF had lower biomass, with SDMDF showing dominance in understory and litter components. *Shorea robusta* dominates biomass carbon in PSF (83.53%) and SDMDF (44.74%), with few other species making smaller contributions. MDFWS shows greater species diversity, with biomass more evenly distributed among species like *Terminalia alata, Schleichera oleosa,* and *Anogeissus latifolia.*

Carbon stock:

Significant differences ($P<0.05$) were observed in living and non-living biomass carbon, SOC, ECS and SOC:ECS ratio. MDFWS had the highest living biomass carbon (AGBCS: 147.09, BGBCS: 35.34 Mg C ha^{-1}), while SDMDF recorded the lowest. The non-living biomass carbon was highest in SDMDF (6.97 Mg C ha^{-1}), with PSF and MDFWS showing similar values (~5.7 Mg C ha^{-1}). SOC

stock and SOC:ECS ratio were highest in PSF, followed by SDMDF and MDFWS. Ecosystem carbon stock (ECS) was lowest in SDMDF (172.68 Mg C ha^{-1}), while PSF (234.67) and MDFWS (242.41) were statistically similar.

Tree carbon stock found significantly higher in MDFWS (171.24 Mg C ha^{-1}) than PSF and SDMDF. Sapling carbon was highest in PSF (1.99 Mg C ha^{-1}), while shrubs showed no significant variation. Liana carbon was highest in SDMDF and herbaceous carbon was highest in MDFWS. Deadwood carbon was greatest in MDFWS (1.68 Mg C ha^{-1}) and lowest in PSF (0.85 Mg C ha^{-1}). Litter carbon stock was significantly higher in SDMDF (5.22 Mg C ha^{-1}) than in PSF and MDFWS. These patterns highlight differing carbon dynamics and storage potential across the forest types.

Biomass increment and carbon sequestration

MDFWS showed the highest net annual biomass increment across trees (41.44 Mg ha^{-1}), total biomass (51.04 Mg ha^{-1}) and deadwood (0.81 Mg ha^{-1}) followed by SDMDF and PSF. Liana and herb biomass were also notably higher in MDFWS, while SDMDF had the highest above-ground litter accumulation.

The annual carbon sequestration potential varied significantly ($P<0.05$) across vegetation components in PSF, SDMDF, and MDFWS. Trees showed the highest carbon sequestration, with MDFWS leading at 19.48 Mg C ha^{-1}, followed by SDMDF (10.75 Mg C ha^{-1}) and PSF (5.07 Mg C ha^{-1}). Other components like lianas, herbs, and soil organic carbon (SOC) also showed significant differences, with MDFWS consistently having the highest values. Above-ground litter was highest in PSF (0.76 Mg C ha^{-1}), while SOC was highest in SDMDF (0.51 Mg C ha^{-1}). Overall, MDFWS had the highest total carbon sequestration (22.01 Mg C ha^{-1}), followed by SDMDF (13.54 Mg C ha^{-1}) and PSF (7.14 Mg C ha^{-1}).

The **fourth experiment** was conducted to trap the annual litter production and decay dynamics using standard litter bag techniques. Annual litter fall varied significantly ($P<0.05$) across forest types, with SDMDF having the highest total (12.77 Mg ha^{-1} yr^{-1}), followed by PSF (10.58 Mg ha^{-1} yr^{-1}) and MDFWS (8.93 Mg ha^{-1} yr^{-1}).

Above-ground litter contributed 88.47% to 90.60% of the total litter, with senescent leaves making up 70.88% to 75.33%. Litter fall peaked during winter (December-February), with SDMDF recording the highest winter fall (7.57 Mg ha^{-1} yr^{-1}). There were no significant differences in root litter or summer litter fall. Annual litter fall correlated significantly with tree density (0.733) and basal area (0.997).

The concentrations of nutrients and secondary compounds in leaf, small branch, and root litter varied significantly, except for carbon. Hemicellulose, cellulose, lignin and phenols varied across litter components, with PSF root litter having the highest hemicellulose, MDFWS root litter the highest cellulose, PSF small branch litter the highest lignin and MDFWS leaf litter the highest total phenol content. Nitrogen, phosphorus, and potassium content was higher in leaf litter than in small branch and root litter. PSF showed the highest C/N and L/N ratios across all litter components.

The litter decomposition study revealed significant variations ($P<0.01$) in decay rate across forest types, with three distinct phases: slow decay in summer, rapid decay during the rainy season and constant decay in winter. MDFWS exhibited the highest decay rates for all litter categories, while PSF had the slowest decay, with up to 25.83% of root litter remaining after 270 days. The decay rate constants were highest in MDFWS and the time for 50% and 99% mass decay was longest in PSF.

The **fifth experiment** was conducted to trap the total soil respiration using soda lime granules in a closed chamber. The analysis of soil respiration dynamics revealed significant differences across forest types. MDFWS also recorded the highest total annual soil respiration (43.61 Mg C ha^{-1} yr^{-1}), root respiration (23.76 Mg C ha^{-1} yr^{-1}) and microbial respiration (19.84 Mg C ha^{-1} yr^{-1}), while PSF had the lowest values for all these parameters which was attributed to differences in soil moisture and temperature. Among these two influential factors soil moisture had a strong positive correlation ($r = 0.798$, $P < 0.01$) with soil respiration rate than soil temperature ($r = 0.204$, $P < 0.05$).

The **sixth experiment** was to estimate the net primary production, carbon flux and net ecosystem production. Significant variations ($P<0.05$) were observed in net primary production (NPP), heterotrophic respiration (Rh) and net ecosystem production (NEP) across three forest types. MDFWS had the highest NPP (28.46 Mg

C ha^{-1} yr^{-1}) and Rh (22.11 Mg C ha^{-1} yr^{-1}), while PSF and SDMDF showed lower values. MDFWS also had a positive NEP (4.71 Mg C ha^{-1} yr^{-1}), indicating it acts as a carbon sink, while PSF and SDMDF were carbon sources with negative NEP. Over all these forests have positive NEP value (0.62 Mg C ha^{-1} yr^{-1}), making it as a carbon sink for the region. Above-ground biomass carbon (AGBC) and harvested wood biomass (HWBC) contributed significantly to the total NEP**.**

Conclusion

This study highlights the role of tropical moist deciduous forests of Odisha in regulating carbon dynamics and contributing to climate change mitigation. Among the three identified forest community types (PSF, SDMDF and MDFWS), MDFWS demonstrated the highest biomass production, carbon stock and net ecosystem production (NEP), functioning as a significant carbon sink (NEP = 4.71 Mg C ha^{-1} yr^{-1}). In contrast, PSF and SDMDF acted as carbon sources, showing negative NEP values. However, the overall NEP across the forest division remained positive (0.62 Mg C ha^{-1} yr^{-1}), reflecting the ecosystem's net C absorbing capacity. The observed variations in carbon dynamics were primarily driven by species composition, forest structure, disturbance levels and soil microclimate. The MDFWS community characterized by higher diversity and favourable conditions, exhibited greater ecological efficiency, while PSF showed reduced regeneration and carbon flux due to dominance by *Shorea robusta* and frequent disturbances. These findings highlight the need to conserve structurally diverse forests and promote sustainable management practices to enhance carbon storage, ecosystem resilience, and regional climate mitigation.

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Appendix 1 Floristic attributes density (D), basal area (BA) and importance value index (IVI) of Tree species in PSF, SDMDF and MDFWS

1.1 Pure Sal Forest

Botanical Name	Site-I			Site-II			Site-III			Mean			RG	DP
	D	BA	IVI	D	BA	IVI	D	BA	IVI	D	BA	IVI		
Antidesma ghaesembilla Gaertn.	10.0	0.18	5.32	-	-	-	-	-	-	3.33	0.06	1.77	P	Re
Buchanania lanzan Spreng.	10.0	0.21	11.66	15.0	0.34	12.68	7.5	0.16	15.00	10.83	0.24	13.11	F	C
Careya arborea Roxb.	10.0	0.23	5.47	10.0	0.18	10.87	7.5	0.09	10.40	9.17	0.17	8.91	F	Ra
Cleistanthus collinus (Roxb.) Benth. Ex Hook's.	45.0	0.79	19.20	10.0	0.15	10.73	7.5	0.08	10.36	20.83	0.34	13.43	G	C
Desmodium oojeinensis (Roxb.)	15.0	0.27	6.41	15.0	0.22	16.05	-	-	-	10.00	0.16	7.49	F	Ra
Diospyros melanoxylon Roxb.	15.0	0.16	12.32	12.5	0.36	12.33	-	-	-	9.17	0.17	8.22	P	Ra
Garuga pinnata Roxb.	10.0	0.28	5.67	-	-	-	-	-	-	3.33	0.09	1.89	N	Ra
Lannea coromandelica (Houtt.) Merr.	-	-	-	15.0	2.20	22.65	-	-	-	5.00	0.73	7.55	P	Ra
Madhuca latifolia (Roxb.) A.Chev	37.5	1.93	21.79	-	-	-	-	-	-	12.50	0.64	7.26	F	C
Pterocarpus marsupium Roxb.	35.0	1.61	20.32	5.0	0.32	10.69	-	-	-	13.33	0.64	10.34	F	C
Schleichera oleosa (Lour.) Oken	-	-	-	-	-	-	5.0	0.09	9.88	1.67	0.03	3.29	F	Ra
Semecarpus anacardium L. f.	12.50	0.27	12.28	12.5	0.10	14.96	12.5	0.24	20.64	12.50	0.20	15.96	F	C

Shorea robusta Roth	387.5	23.43	152.26	395.0	13.92	166.50	412.5	15.27	192.54	398.33	17.54	170.43	G	C
Syzygium cumini (L.) Skeels	15.0	0.24	12.58	-	-	-	-	-	-	5.00	0.08	4.19	G	Ra
Terminalia alata Heyne ex Roth	22.5	0.53	14.72	30.0	0.89	22.54	-	-	-	17.50	0.47	12.42	G	Ra
Terminalia bellirica (Gaertn.) Roxb.	-	-	-	-	-	-	7.5	0.25	15.50	2.50	0.08	5.17	N	Re
Vateria indica L.	-	-	-	-	-	-	30.0	0.48	25.67	10.00	0.16	8.56	P	Re
Total	**625**	**30.12**	**300**	**520**	**18.67**	**300**	**490**	**16.66**	**300**	**545.00**	**21.82**	**300**		

D-density (plants ha^{-1}), BA-basal area ($m^2 ha^{-1}$), IVI-importance value index (relative density + relative frequency + relative basal area), RG-regeneration status G-good, F-fair, P-poor, N-none; DP-distribution pattern C-contagious, Ra-random, Re-regula

1.2 Sal Dominated Moist Deciduous Forest

Botanical Name	Site-I			Site-II			Site-III			Mean			RG	DP
	D	BA	IVI	D			D	BA	IVI	D	BA	IVI		
Adina cordifolia							25.00	0.4	15.6	8.33	0.13	5.20	F	Ra
Anogeissus latifolia (DC.) Wallich ex Guill	11.3	0.12	4.68				15.00	0.54	11.23	8.75	0.22	5.30	G	Ra
Antidesma ghaesembilla Gaertn.	5.03	0.08	3.01							1.67	0.03	1.00	G	Re
Bridelia retusa (L.) A.Juss.				5.00	0.24	5.14	15.00	0.15	9.64	6.67	0.13	4.93	F	Ra
Buchanania lanzan Spreng.	28.8	0.56	11.68	27.50	0.77	14.67	17.50	0.36	10.23	24.58	0.56	12.19	G	C
Butea monosperma				17.50	0.43	8.2				5.83	0.14	2.73	F	Re
Careya arborea Roxb.	21.0	0.42	8.74	12.50	0.31	6.76	7.50	0.11	5.97	13.75	0.28	7.16	F	C
Ceiba pentandra (L.) Gaertn.	20.0	0.54	8.44							6.67	0.18	2.81	F	Re
Cleistanthus collinus (Roxb.) Benth. Ex Hook	64.0	0.81	17.46	47.50	1	17.58	45.00	0.63	21.79	52.08	0.81	18.94	F	C
Dalbergia latifolia Roxb.	20.0	0.63	9.54							6.67	0.21	3.18	F	Re
Desmodium oojeinensis (Roxb.)	14.0	0.29	6.49	2.50	0.06	2.27				5.42	0.12	2.92	F	Ra
Dillenia pentagyna Roxb.	11.0	0.12	5.37				17.50	0.4	14	9.58	0.17	6.46	F	Ra
Diospyros malabarica (Desr.) Kostel.				7.50	0.21	5.44				2.50	0.07	1.81	F	Re

Diospyros melanoxylon Roxb.	21.0	0.71	10.73	17.50	0.47	9.94				12.92	0.39	6.89	G	Ra
Gardenia latifolia Aiton.	3.0	0.06	1.27							0.83	0.02	0.42	G	Re
Garuga pinnata Roxb.	12.0	0.24	5.39				5.00	0.21	4.55	5.83	0.15	3.31	F	Re
Grewia tiliifolia Vahl. Vahl							7.50	0.11	6	2.50	0.04	2.00	P	Re
Holoptelea integrifolia							5.00	0.07	3.37	1.67	0.02	1.12	N	Re
Ixora pavetta Andr.	10.00	0.2	4.89							3.33	0.07	1.63	G	Re
Lagerstroemia parviflora Roxb.	11.0	0.24	5.89	27.50	0.39	12.79				12.92	0.21	6.23	F	Re
Lannea coromandelica (Houtt.) Merr.	21.0	0.38	7.88	17.50	0.84	13.35	17.50	0.19	8.76	18.75	0.47	10.00	F	C
Macaranga peltata (Roxb.) Müll.Arg.							27.50	0.57	17.62	9.17	0.19	5.87	P	Ra
Madhuca latifolia (Roxb.) A.Chev	24.0	0.68	10.9	20.00	2.14	17.08	17.50	0.26	11.08	20.42	1.03	13.02	G	C
Mallotus philippensis							17.50	0.23	12.57	5.83	0.08	4.19	P	Re
Mitragyna parvifolia (Roxb.) Korth.	10.0	0.24	5.76							3.33	0.08	1.92	G	Re
Morinda coreia Buch.Ham.	12.0	0.15	3.52							3.75	0.05	1.17	F	Re
Nyctanthes arbor-tristis L.	11.0	0.11	3.97							3.75	0.04	1.32	F	Re
Phyllanthus emblica L.	14.0	0.2	8.02	17.50	0.37	10.98	5.00	0.05	4.91	12.08	0.21	7.97	F	C
Pterocarpus marsupium Roxb.	23.0	0.86	11.59	27.50	0.95	15.54				16.67	0.60	9.04	F	C

Schleichera oleosa (Lour.) Oken				12.50	0.2	9.32	40.00	1.08	24.61	17.50	0.43	11.31	F	C
Schrebera swietenioides	20.0	0.19	6.16							6.67	0.06	2.05	F	Ra
Semecarpus anacardium L. f.	20.0	0.41	9.19	15.00	0.21	8.26	15.00	0.32	9.33	16.67	0.31	8.93	G	C
Shorea robusta Roth	272.0	11.49	94.31	235.00	9.05	90.43	132.50	5.05	78.22	213.33	8.53	87.65	G	C
Streblus asper Lour.				15.00	0.24	9.93				5.00	0.08	3.31	F	Re
Syzygium cumini (L.) Skeels	20.0	0.31	8.04				17.50	0.31	13.26	12.50	0.21	7.10	F	Ra
Terminalia alata Heyne ex Roth	24.0	0.67	10.18	25.00	0.65	13.66				16.25	0.44	7.95	G	Ra
Terminalia bellirica (Gaertn.) Roxb.				32.50	0.85	15.86	17.50	0.54	13.53	16.67	0.46	9.80	F	Ra
Terminalia chebula Retz.	20.0	0.47	8.76							6.67	0.16	2.92	F	Ra
Vateria indica L.	14.0	0.51	8.14	17.50	0.73	12.8	5.00	0.11	3.73	12.08	0.45	8.22	F	Ra
Total	**756**	**21.7**	**300**	**600**	**20.11**	**300**	**472.5**	**11.69**	**300**	**610**	**17.83**	**300**		

D-density (plants ha^{-1}), BA-Basal Area ($m^2 ha^{-1}$), IVI-Importance Value Index (Relative Density + Relative Frequency + Relative Basal Area)

1.3 Moist Deciduous Forest without Sal

Botanical Name	Site-I			Site-II			Site - III			Mean			RG	DP
	D	BA	IVI	D	BA	IVI	D	BA	IVI	D	BA	IVI		
Adina cordifolia (Roxb.) Brandis							22.5	0.93	8.93	7.5	0.31	2.98	F	Ra
Aegle marmelos (L.) Correa	3.0	0.06	1.46				2.5	0.08	2.05	1.8	0.05	1.17	F	Ra
Albizia lebbeck (L.) Benth.	18.0	1.02	7.25	7.5	0.21	3.82	27.5	0.85	11.96	17.7	0.69	7.68	F	C
Anogeissus acuminata (Roxb. ex-DC.) Guillaum. & Perr.	10.0	0.33	3.20	7.5	0.28	3.05				5.8	0.20	2.08	G	Re
Anogeissus latifolia (DC.) Wallich ex Guill. et Perr.	40.0	1.50	12.43	30.0	1.51	12.63	47.5	1.30	18.34	39.2	1.44	14.47	F	C
Bauhinia variegata L.	10.0	0.40	4.40	10.0	0.61	5.62	7.5	0.17	3.23	9.2	0.39	4.42	P	Ra
Bombax ceiba L.	10.0	0.14	3.60	5.0	0.10	2.04				5.0	0.08	1.88	P	Ra
Bridelia retusa (L.) A.Juss.	45.0	2.20	15.24	37.5	2.53	17.38	10.0	0.29	5.46	30.8	1.67	12.69	G	C
Buchanania lanzan Spreng.	20.0	0.76	7.69	62.5	1.49	17.93	40.0	0.69	13.14	40.8	0.98	12.92	G	C
Careya arborea Roxb.	15.0	0.85	7.38	12.5	0.20	5.47	2.5	0.02	1.80	10.0	0.36	4.88	G	Ra
Cassia fistula L.	20.0	0.46	6.78	20.0	0.43	7.34	22.5	0.35	8.96	20.8	0.41	7.69	F	C
Ceiba pentandra (L.) Gaertn.	15.0	0.19	4.36	5.0	0.11	2.08	5.0	0.14	2.73	8.3	0.15	3.06	F	C
Cleistanthus collinus (Roxb.) Benth. Ex Hook.f.	48.0	0.73	11.93	55.0	0.59	13.61	47.5	0.31	12.57	50.2	0.54	12.70	G	C

Dalbergia lanceolaria L. f.	10.0	0.16	4.61	12.5	0.25	5.64				7.5	0.14	3.42	G	Re
Dalbergia latifolia Roxb.	13.0	1.31	6.56	12.5	1.31	7.50				8.5	0.87	4.69	F	Re
Dalbergia sissoo Roxb.	25.0	0.74	9.24	22.5	1.02	10.84	12.5	0.47	6.68	20.0	0.74	8.92	F	C
Desmodium oojeinensis (Roxb.)	20.0	0.58	6.18	15.0	0.39	5.49	37.5	1.72	17.39	24.2	0.90	9.69	F	C
Dillenia aurea Smith.							7.5	0.12	4.35	2.5	0.04	1.45	F	Re
Diospyros malabarica (Desr.) Kostel.	20.0	0.46	6.76	15.0	0.27	6.06				11.7	0.24	4.27	G	Re
Diospyros melanoxylon Roxb.	25.0	2.06	12.38	30.0	0.65	9.47	35.0	1.88	19.07	30.0	1.53	13.64	F	C
Erythrina variegata L.							5.0	0.05	3.66	1.7	0.02	1.22	P	Re
Ficus hispida L.							7.5	0.15	3.13	2.5	0.05	1.04	N	Re
Ficus racemosa L.	5.0	0.17	2.10	7.5	0.20	2.75				4.2	0.12	1.62	G	Re
Gardenia latifolia Aiton	15.0	0.39	4.99	12.5	0.13	4.20	5.0	0.07	2.40	10.8	0.20	3.86	G	C
Garuga pinnata Roxb.	33.0	0.92	9.72	25.0	0.78	9.28	20.0	1.09	10.60	26.0	0.93	9.87	F	C
Gmelina arborea Roxb. ex Sm.							2.5	0.08	2.09	0.8	0.03	0.70	G	Re
Grewia tiliifolia Vahl	15.0	0.66	5.82	7.5	0.27	4.04				7.5	0.31	3.29	P	Re
Lagerstroemia parviflora Roxb.	10.0	0.34	4.21	10.0	0.33	4.61	10.0	0.57	5.40	10.0	0.41	4.74	G	C
Lagerstroemia reginae Roxb.	13.0	1.08	5.85	12.5	1.08	6.66				8.5	0.72	4.17	P	Re
Lannea coromandelica (Houtt.) Merr.	15.0	0.66	6.78	10.0	0.63	5.70	22.5	0.91	10.15	15.8	0.73	7.54	G	C

Madhuca latifolia (Roxb.) A.Chev	10.0	0.50	3.73	5.0	0.10	2.06	12.5	1.21	8.66	9.2	0.60	4.82	G	C
Mangifera indica L.	10.0	0.08	2.43							3.3	0.03	0.81	G	Re
Mitragyna parvifolia (Roxb.) Korth.	28.0	2.30	14.40	20.0	0.60	8.97	27.5	1.20	13.55	25.2	1.37	12.31	F	C
Naringi crenulata (Roxb.) D.H. Nicolson							5.0	0.24	3.18	1.7	0.08	1.06	P	Re
Nyctanthes arbor-tristis L.	10.0	0.09	4.41	7.5	0.07	4.32	15.0	0.12	5.46	10.8	0.09	4.73	F	C
Phyllanthus emblica L.	15.0	0.23	3.51	2.5	0.02	1.44				5.8	0.08	1.65	N	Ra
Pterocarpus marsupium Roxb.	20.0	0.67	6.47	22.5	1.29	9.81				14.2	0.65	5.43	F	Re
Pterospermum xylocarpum (Gaertn.) Oken	15.0	0.36	3.90	7.5	0.22	2.84				7.5	0.19	2.25	N	Ra
Schleichera oleosa (Lour.) Oken	33.0	1.24	11.69	37.5	1.76	15.57	32.5	1.32	16.16	34.3	1.44	14.47	G	C
Schrebera swietenioides Roxb.	20.0	0.85	7.03	12.5	0.54	5.71				10.8	0.46	4.25	N	Ra
Semecarpus anacardium L. f.	20.0	0.65	7.35	30.0	0.60	9.28	25.0	0.61	10.54	25.0	0.62	9.06	G	C
Shorea robusta Roth	10.0	0.66	5.22	10.0	1.15	7.60	12.5	0.61	7.28	10.8	0.81	6.70	G	C
Spathodea campanulata Beauv.	3.0	0.02	1.35	15.0	0.48	5.81	7.5	0.27	3.67	8.5	0.26	3.61	F	Re
Sterculia urens Roxb.	20.0	0.62	6.31				15.0	0.46	6.99	11.7	0.36	4.43	P	C
Strychnos nux-vomica L.	10.0	0.34	5.18	7.5	0.28	5.10	5.0	0.13	2.66	7.5	0.25	4.31	F	Ra
Strychnos potatorum L. fil.							5.0	0.05	2.33	1.7	0.02	0.78	N	Re
Syzygium cumini (L.) Skeels	28.0	1.05	9.51	25.0	0.57	8.51				17.7	0.54	6.01	F	Ra

Syzygium heyneanum (Duthie) Wall. ex Gamble	25.0	0.75	7.32	20.0	0.62	5.99				15.0	0.46	4.44	P	Ra
Terminalia alata Heyne ex Roth	48.0	2.32	16.87	47.5	2.62	20.09	47.5	1.94	21.21	47.7	2.29	19.39	F	C
Terminalia bellirica (Gaertn.) Roxb.	20.0	0.84	7.97	5.0	0.08	3.00	35.0	1.07	15.43	20.0	0.66	8.80	F	C
Terminalia chebula Retz.	13.0	0.31	4.43	27.5	0.80	10.69	17.5	0.78	8.79	19.3	0.63	7.97	P	C
Total	**831**	**32.05**	**300**	**748**	**27.17**	**300.00**	**663**	**22.25**	**300**	**747**	**27.16**	**300**		

D-density (plants ha^{-1}), BA-Basal Area ($m^2 ha^{-1}$), IVI-Importance Value Index (Relative Density + Relative Frequency + Relative Basal Area)

Appendix 2 Floristic attributes density (D), basal area (BA) and importance value index (IVI) of shrubs in PSF, SDMDF and MDFWS

Botanical Name	**Family**	**PSF**			**SDMDF**			**MDFWS**		
		D	**BA**	**IVI**	**D**	**BA**	**IVI**	**D**	**BA**	**IVI**
Acacia concinna (Willd.) DC.	Fabaceae	-	-	-	-	-	-	75	0.05	3.71
Abutilon indicum (L.) Sweet	Malvaceae	67	0.05	1.98	150	0.09	4.56	-	-	-
Acacia sinuata (Lour.) Merr.	Fabaceae	117	0.15	5.01	250	0.12	4.75	-	-	-
Annona squamosa L.	Annonaceae	-	-	-	-	-	-	225	0.22	7.47
Benkara malabarica (Lam.) Tir	Rubiaceae	-	-	-	-	-	-	75	0.065	3.89
Calotropis gigantea (L.) W. T. Aiton	Apocynaceae	-	-	-	-	-	-	100	0.025	4.60
Carissa sprinarum L.	Apocynaceae	550	0.27	15.95	717	0.25	19.21	650	0.29	14.83
Casearia graveolens Dalzell	Salicaceae	67	0.10	3.75	50	0.05	2.94	-	-	-
Casearia tomentosa Roxb.	Salicaceae	300	0.18	8.62	100	0.05	4.21	325	0.575	15.68

Catunaregan spinosa	Rubiaceae	100	0.07	3.82	417	0.29	12.82	125	0.135	4.50
Chromolaena odorata (L.) R.M.King & H.Rob.	Asteraceae	1467	1.13	32.54	1500	0.94	26.63	850	0.755	19.46
Cipadessa baccifera (Roth) Mig.	Meliaceae	283	0.22	9.84	433	0.81	20.02	325	0.37	12.05
Clerodendrum viscosum Vent., nom. superfl.	Lamiaceae	300	0.17	10.88	583	0.23	12.34	-	-	-
Cycas circinalis L.	Cycadaceae	433	0.34	14.60	183	0.35	9.51	-	-	-
Diospyros ferrea (Willd.) Bakh.	Ebenaceae	183	0.15	9.03	83	0.11	4.17	-	-	-
Flacourtia jangomas (Lour.) Raeusch.	Salicaceae	67	0.34	7.26	33	0.47	9.70	125	0.425	10.18
Glochidion lanceolarium (Roxburgh) Voigt	Phyllanthaceae	83	0.09	3.78	167	0.14	8.17	275	0.61	15.53
Grewia asiatica L.	Tiliaceae	250	0.31	12.92	283	0.16	7.58	-	-	-
Grewia rothii Dc.	Tiliaceae				83	0.02	1.80	-	-	-
Helicteres isora L.	Malvaceae	100	0.08	4.07	217	0.32	10.68	150	0.335	10.04
Holarrhena antidysenterica (Roxb. Ex Fleming) Wallich ex	Apocynaceae	-	-	-	-	-	-	325	0.50	10.44
Holarrhena pubescens Wall.exG.Don	Apocynaceae	-	-	-	-	-	-	225	0.260	6.98
Ixora pavetta Andr.	Rubiaceae	133	0.15	5.45				125	0.21	6.88
Jatropha gossypifolia L.	Euphorbiaceae	-	-	-	-	-	-	75	0.08	4.15
Justicia adhatoda L.	Acanthaceae	267	0.13	7.45	83	0.05	4.08	300	0.21	10.72
Lantana camara L.	Verbenaceae	483	0.29	13.05	867	0.75	21.21	975	0.86	24.14
Mesosphaerum suaveolens (L.) Kuntze	Lamiaceae	700	0.33	15.87	1050	0.55	18.41	-	-	-

Meyna spinosa Roxb.	Rubiaceae	83	0.09	3.80	67	0.07	4.09	-	-	-
Murraya paniculata (L.) Jack	Rutaceae	33	0.05	2.38	67	0.09	4.22	475	0.76	17.56
Naringi crenulata (Roxb.) D.H. Nicolson	Rutaceae	150	0.10	6.26	50	0.02	2.07	200	0.165	4.79
Ochna obtusata Roxb.	Ochnaceae	83	0.14	4.51	50	0.10	3.75	-	-	-
Olax scandens Roxb.	Olacaceae	33	0.04	2.33	50	0.05	2.93	-	-	-
Phoenix acaulis Roxb.	Arecaceae	383	0.28	15.72	667	0.36	17.87	450	0.17	14.44
Phyllanthus reticulatus L.	Euphorbiaceae	-	-	-	-	-	-	400	0.18	11.40
Thysanolaena maxima (Roxb.) Kuntze	Poaceae	-	-	-	-	-	-	125	0.73	24.80
Sericocalyx scaber (Nees) Bremek.	Acanthaceae	67	0.07	3.29	233	0.18	9.09	-	-	-
Thespesia lampas (Cav.) Dalzell & A. Gibson	Malvaceae	483	0.19	11.22	400	0.16	9.23	-	-	-
Wendlandia tinctoria (Roxb.) DC.	Rubiaceae	600	0.48	20.50	433	0.44	15.83	500	0.41	17.39
Woodfordia fruticose (L.) Kurz	Lythraceae	350	0.40	14.58	350	0.30	12.24	225	0.355	9.65
Ziziphus nummularia (Burm. f.) Wight & Walk.	Rhamnaceae	-	-	-	50	0.06	1.91	-	-	-
Ziziphus oenoplia (L.) Miller	Rhamnaceae	750	1.23	29.51	517	0.29	13.97	500	0.375	14.60
TOTAL		**8967**	**7.62**	**300**	**10183**	**7.87**	**300**	**9325**	**9.13**	**300**

D-density (plants ha^{-1}), BA-Basal Area ($m^2 ha^{-1}$), IVI-Importance Value Index (Relative Density + Relative Frequency + Relative Basal Area)

Appendix 3 Floristic attributes density (D), basal area (BA) and importance value index (IVI) of Lianas in PSF, SDMDF and MDFWS forest types of Kandhamal district, Odisha

Botanical Name	Family	PSF			SDMDF			MDFWS		
		D	B A	IVI	D	B A	IVI	D	B A	IVI
Butea superba Roxb.	Fabaceae	137.5	0.44	170.53	300	0.37	150.83	87.5	0.31	80.36
Gouania microcarpa DC	Rhamnaceae	12.5	0.02	16.27	-	-	-	12.5	0.06	13.94
Combretum decandrum Roxb.	Combretaceae	12.5	0.05	20.57	50	0.24	56.28	25.0	0.05	17.11
Mallotus repandus (Rottler) Müll.Arg.	Euphorbiaceae	12.5	0.03	18.18	-	-	-	25.0	0.10	26.59
Caesalpinia decapetala (Roth) Alston	Fabaceae	-	-	-	-	-	-	12.5	0.03	10.17
Derris scandens (Roxb.) Benth.	Fabaceae	-	-	-	-	-	-	25.0	0.01	14.45
Capparis zeylanica L.	Capparaceae	-	-	-	-	-	-	12.5	0.01	10.37
Bauhinia vahlii Wight & Arn.	Fabaceae	75.0	0.13	74.45	138	0.18	92.90	125.0	0.72	127.00
TOTAL		**250**	**0.67**	**300**	**488**	**0.79**	**300**	**325**	**1.36**	**300**

D-density (plants ha^{-1}), BA-Basal Area ($m^2 ha^{-1}$), IVI-Importance Value Index (Relative Density + Relative Frequency + Relative Basal Area)

Appendix 4 Density of herbs in PSF, SDMDF and MDFWS forest types of Kandhamal district, Odisha

Sl. No.	Botanical Name	Family	Density (plants ha^{-1})		
			PSF	SDMDF	MDFWS
1	*Flemingia chapper Benth.*	Fabaceae	9375	14375	4375
2	Abutilon indicum (L.) Sweet	Malvaceae	5000	-	3750
3	*Achyranthes aspera* L.	Amaranthaceae	3125	1875	1250
4	*Acmella paniculata* (Wall. ex-DC.) R.K.Jansen	Asteraceae	-	2500	-
5	*Amaranthus spinosus* L.	Amaranthaceae	-	-	3750
6	*Ammannia baccifera* L.	Lythraceae	-	-	1250
7	*Andrographis paniculata* (Burm. fil.) Nees	Acanthaceae	3750	4375	2500
8	*Aristida cetacea* Retz.	Poaceae	3125	-	3125
9	*Asparagus racemosus* Willd.	Asparagaceae	1250	-	1875
10	*Barleria prionitis L.*	Acanthaceae	-	5625	-
11	*Biophytum sensitivum* (L.) DC. Prodr.	Oxalidaceae	1250	-	-
12	*Blumea lacera* (Burm.f.) DC.	Asteraceae	-	2500	2500
13	*Cleome gynandra* L.	Capparaceae	-	1250	-
14	*Costus speciosus* (J.Koenig) Sm.	Costaceae	-	-	3125
15	*Crotalaria prostrata* Rottl.ex Willd. Enum. Hort. Berol.	Fabaceae	-	5000	2500
16	*Crinum amoenium* Ker Gawl.exRoxb.	Lamiaceae	-	-	1250
17	*Cryptolepis buchanani* R. Br.	Asclepiadaceae	1875	-	-
18	*Cucurma amada* Roxburghi	Zingiberaceae		5625	1875
19	*Curculigo orchioides* Gaertn.	Hypoxidaceae	1875	3125	1250
20	*Cynodon dactylon (L.)*	Poaceae	-	8750	-
21	*Cyperus rotundus* L.	Cyperaceae		3125	3125
22	*Dactyloctenium aegypticum* (L.) Willd.	Poaceae	2500	-	5625

23	*Desmodium heterocarpon* SensuMiq., p.p.	Fabaceae	-	-	1250
24	*Eclipta prostrata* L.	Asteraceae	-	2500	3750
25	*Elephantopus mollis* Kunth	Asteraceae	1875	-	1250
26	*Eranthemum caspense* L.	Acanthaceae	3125	-	1250
27	*Euphorbia hirta* L. Sp	Euphorbiaceae	1875	-	-
28	*Evolvulus alsinoides* L.	Convolvulaceae	-	1250	1875
29	*Heliotropium indicum* L.	Boraginaceae	1250	-	1250
30	*Hellenia speciosa* (J.Koenig) S.R.Dutta	Costaceae	2500	625	-
31	*Hygrophila auriculata* (Schumach.) Heine	Acanthaceae	-	-	2500
32	*Knoxia sumatrensis* (Retz.) DC	Rubiaceae	-	1250	2500
33	*Laportea interrupta* (L.) Chew	Urticaceae	625	-	-
34	*Leucas aspera (Willd.) Link*	Lamiaceae	-	1250	625
35	*Leucas mollisima* Wall.	Labiatae	-	625	625
36	*Ligustrum ovalifolium* Hassk.	Oleaceae	-	625	1250
37	*Lygodium flexuosum* (L.) Sw.	Lygodiaceae	3125	1875	3125
38	*Melochia corchorifolia* L	Tiliaceae	-	1250	1250
39	*Merremia tridentata* (L.) Hall.f.Bot. Jahrb.	Convolvulaceae	-	-	1250
40	*Mesosphaerum suaveolens* (L.) Kuntze	Lamiaceae	3750	625	4375
41	*Mimosa pudica* L.	Fabaceae	2500	625	1250
42	*Olax scandens* Roxb.	Oleaceae	-	-	625
43	*Oxalis corniculata L.*	Oxalidaceae	2500	1250	-
44	*Phyllanthus fraternus* G.L. Webster	Phyllanthaceae	-	625	1250
45	*Phyllanthus niruri* L.	Phyllanthaceae	3125	-	625
46	*Portulaca oleraceae* L.	Protulaceae	-	625	-
47	*Saccharum munja* Roxb.	Poaceae	-	625	6250

48	*Scindapsus officinalis* (Roxb.)	Araceae	-	625	2500
49	*Sida acuta* Burm. f.	Malvaceae	625	1250	-
50	*Sida cordata* (Burm. f.) Borss. Waalk.	Malvaceae	625	1250	3125
51	*Sphaeranthus indicus* L.	Asteraceae	-	-	4250
52	*Stachytarpheta jamaicensis* (L.) Vahl	Lamiaceae	1250	-	1875
53	*Tephrosia purpurea (L.) Pers*	Fabaceae	1875	-	-
54	*Thysanolaena maxima (Roxb.) Kuntze*	Poaceae	5625	4375	16250
55	*Tragia involucrate* L.	Euphorbiaceae	-	-	2500
56	*Tridax procumbens* L.	Asteraceae	1875	-	1875
57	*Triumfetta rhomboidea* Jacq.	Tiliaceae	-	1250	1875
58	*Urena sinulata* L.subsp. sinuata	Malvaceae	-	-	1875
59	*Vetiveria zizanioides* (L.) Roberty	Poaceae	-	-	1250
	TOTAL		**71250**	**82500**	**118625**

Appendix 5 Family wise distribution of species (Sp), genera (G), density (D) and family importance value (FIV) of trees in PSF, SDMDF and MDFWS

Family	Pure Sal Forest					Sal Dominated Moist Deciduous Forest					Moist Deciduous Forest Without Sal				
	Sp	G	D	BA	FIV	Sp	G	D	BA	FIV	Sp	G	D	BA	FIV
Anacardiaceae	3	3	28.33	1.17	36.62	3	3	60	1.34	31.12	4	4	76.25	2.19	29.06
Bignoniaceae											1	1	5.25	0.15	2.51
Burseraceae	1	1	3.33	0.09	1.89	1	1	5.83	0.15	3.31	1	1	26.5	1.01	10.16
Combretaceae	2	1	20.0	0.55	17.59	4	2	48.34	1.28	25.97	5	2	139.25	5.21	54.34
Dilleniaceae						1	1	9.58	0.17	6.46	1	1	3.75	0.06	2.18
Dipterocarpaceae	2	2	408.33	17.7	178.99	2	2	225.41	8.98	95.87	1	1	11.25	0.64	6.25
Ebenaceae	1	1	9.17	0.17	8.22	2	1	15.42	0.46	8.7	2	1	40	2.2	19.11
Euphorbiaceae						2	2	15	0.27	10.06					
Fabaceae	2	2	23.33	0.8	17.83	4	4	34.59	1.07	17.87	9	7	124.25	4.51	51.71
Lamiaceae											1	1	1.25	0.04	1.05
Lecythidaceae	1	1	9.17	0.17	8.91	1	1	13.75	0.28	7.16	1	1	8.75	0.44	4.59
Loganiaceae											2	1	10	0.27	5.09

Lythraceae						1	1	12.92	0.21	6.23	2	1	16.5	1.0	7.74
Malvaceae	1	1	5	0.08	4.19	2	2	9.17	0.22	4.81	4	4	40	1.11	14.91
Moraceae						1	1	5	0.08	3.31	2	1	6.25	0.17	2.62
Myrtaceae						1	1	12.5	0.21	7.1	2	1	26.5	0.91	8.42
Oleaceae						2	2	10.42	0.1	3.37	2	2	22.5	0.54	8.46
Phyllanthaceae	2	2	24.16	0.4	15.2	4	4	72.5	1.18	32.84	3	3	82.75	1.89	24.36
Rubiaceae						5	5	19.57	0.35	10.34	3	3	49	2.45	22.15
Rutaceae											2	2	5.25	0.19	3.35
Sapindaceae	1	1	1.67	0.03	3.29	1	1	17.5	0.43	11.31	1	1	32.75	1.28	13.93
Sapotaceae	1	1	12.5	0.64	7.26	1	1	20.42	1.03	13.02	1	1	11.25	0.86	6.2
Sterculiaceae											1	1	7.5	0.18	1.95
Ulmaceae						1	1	1.67	0.02	1.12					
TOTAL	**17**	**16**	**545**	**21.82**	**300**	**39**	**36**	**610**	**17.83**	**300**	**51**	**41**	**746.75**	**27.15**	**300**

Density -plants ha^{-1}, Basal Area -m^2 ha^{-1}, Family Importance Value -Relative Density + Relative Frequency + Relative Basal Area

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8. EDUCATIONAL QUALIFICATIONS:

Examination passed	Name of the University	Year of Passing	Subjects	Division
H. S. E	Board of Secondary Education, Odisha	1992	Odia, English, Math, Science, Soc. Science	1St
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B. Sc. Forestry	Odisha University of Agriculture & Technology, Odisha	2000	Silviculture, Forest Products, Tree improvement, Agro forestry, social forestry, forest management, Horticulture, soil Sci., Agronomy etc.	1St
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ABSTRACT

NET ECOSYSTEM PRODUCTION AND CARBON FLUX IN TROPICAL MOIST DECIDUOUS FORESTS OF ODISHA

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ABSTRACT

Forests play a crucial role in regulating the global carbon (C) cycle by acting as both carbon sinks and sources. They store substantial amounts of carbon across various pools *viz.* aboveground and belowground biomass, dead wood, litter and soil organic matter thereby influencing atmospheric CO_2 levels and climate dynamics. Tropical forests, in particular, contribute significantly to global carbon sequestration, holding nearly 55% of the world's forest carbon stock and sequestering approximately 0.5 Mg C ha^{-1} yr^{-1}. However, this vital function is increasingly compromised by deforestation, fires land use changes and other human linked factors which accelerate carbon emissions. Within various tropical forest types, moist deciduous forests play an important role in long term carbon storage and maintaining ecosystem stability. Seasonal dynamics in tropical moist deciduous forests are pivotal to ecosystem functioning, with the wet season triggering enhanced biomass productivity through increased photosynthesis and carbon uptake. The residence time of carbon in forest pools is governed by a complex interplay of factors including climate, vegetation type, soil characteristics, microbial activity, decomposition rates, and disturbances. Understanding these dynamics is essential for assessing the role of tropical forests in climate change mitigation.

Tropical forests, once major carbon sinks, now contribute global CO_2 emissions due to deforestation and land use changes. Climate change further threatens their carbon storage capacity. Odisha has a very rich forest resource having tropical dry deciduous, moist deciduous, and littoral-swamp forests covering 33.67% of geographical area of the state. Amongst these, tropical moist deciduous forests stand out for their structural diversity and numerous benefits they provide. These forests are not only vital for ecological balance but also significantly support the livelihoods of local communities. However, deforestation, over exploitation and climate change are disrupting their carbon dynamics. Despite their importance, data on carbon flux, net primary production (NPP), and net ecosystem production (NEP) remain scarce. This study explores these parameters to strengthen climate change mitigation strategies and improve forest management, with the following objectives.

a) Assess the vegetation composition of tropical moist deciduous forests in Odisha
b) Quantify biomass production, litter production, decomposition rates and net primary productivity in the forest ecosystem
c) Investigate net ecosystem production and carbon fluxes across various pools within the forest ecosystem.

The study was carried out in the tropical moist deciduous forests of Phulbani Forest Division, Odisha, focusing on three forest communities: pure sal forest (PSF), sal-dominated moist deciduous forest (SDMDF) and moist deciduous forest without sal (MDFWS). Sampling was conducted across four reserve forests *viz.* Khajuripada, Dutimundi, Dakapalla-B and Sudurukumpa covering a total of 18 ha. Each forest community was represented by systematically laid out 2.0 ha sample plots, with permanent plots of 250 m × 250 m and nested subplots for detailed vegetation assessment: 31.62 m × 31.62 m for trees, 5 m × 5 m for shrubs and lianas and 1 m × 1 m for herbs and regenerating plants. Plots were carefully selected to minimize human disturbance and ensure ecological consistency across sampling sites. The first round of survey was conducted in the year 2021 and the second round of survey was done after one year (2022). The plant species were identified in the field and lab with the help of experts of state biodiversity board, and regional floras. Soil samples were collected at three depths (0-15 cm, 15-30 cm and 30-45 cm) with in the main tree plots and analysed for various physicochemical properties.

Significant differences ($P < 0.05$) were observed in sand, silt, clay content, bulk density (BD), water holding capacity (WHC), pH, electrical conductivity (EC), soil organic carbon (SOC) and available nitrogen (N), phosphorus (P) and potash (K) among three forest types (PSF, SDMDF and MDFWS). Soil texture was loamy-sand in PSF and MDFWS whereas it was sandy-loam in SDMDF. The Bulk density ranged from 1.52 (PSF) to 1.72 (MDFWS) and WHC from 38.81% (SDMDF) to 42.08% (MDFWS). Soil pH was acidic in PSF (5.74) and SDMDF (5.95), while MDFWS had a neutral pH (6.73). A decrease in acidity with depth was observed in PSF and MDFWS, but no clear trend in SDMDF. The EC values ranged from 0.015 dS m^{-1} (MDFWS) to 0.025 dS m^{-1} (SDMDF). SOC content was highest in PSF (1.67%), followed by SDMDF (0.98%) and lowest in MDFWS (0.71%). The range

of available nutrients across forest types was: Nitrogen: 85.32 to 118.2 kg ha^{-1}, Phosphorus: 9.40 to 12.44 kg ha^{-1} and Potash: 420.03 to 549.76 kg ha^{-1}.

The floristic analysis identified 168 plant species across 138 genera and 55 families, including 61 trees, 26 shrubs, 8 lianas and 46 herbs. MDFWS showed highest tree diversity (51 species, 41 genera, 22 families), followed by SDMDF (39 species, 36 genera, 19 families), while PSF had the lowest (17 species, 17 genera, 11 families). Dipterocarpaceae dominated PSF (FIV 178.99) and SDMDF (FIV 95.87), while MDFWS was led by Combretaceae (FIV 54.34), with a few key families accounting for over 60% of composition in each forest type. As far as tree species is concerned, *Shorea robusta* dominated (IVI 170.43) the PSF community with key associates *Semecarpus anacardium* and *Cleistanthus collinus*. In SDMDF, also *Shorea robusta* (IVI 87.65) found dominated the community with associates like *Madhuca latifolia* and *Buchanania lanzan*. In MDFWS, *Terminalia alata* (IVI 19.04) was found dominant sharing upper strata with *Diospyros melanoxylon* and *Anogeissus latifolia* as key associates.

Significant differences ($P < 0.05$) were observed among forest types with respect to Species Richness Index, Shannon-Weiner Diversity Index, Simpson's Dominance Index and Pielou's Evenness Index. The species Richness Index was found highest in MDFWS (6.49), followed by SDMDF (4.79) and PSF (2.82). Shannon-Weiner Diversity Index was in the order MDFWS (3.47) > SDMDF (2.55) > PSF (1.11). The Simpson's Dominance Index was recorded highest in PSF (0.57), indicating strong dominance, especially by *Shorea robusta* in the community. On the other hand, Pielou's Evenness Index was high in MDFWS (0.96), showing more even species distribution. No significant differences were noted in shrub diversity across forest types. For lianas, only the evenness index showed significant variation ($P < 0.003$), while herb diversity differed significantly only in species richness. The rank abundance curves indicated greater equitability (lower dominance) in MDFWS and strong single species dominance (*Shorea robusta*) in PSF and SDMDF. This suggests that MDFWS supports a more balanced and diverse plant community compared to the other two forest types.

Biomass stock, carbon stock and carbon sequestration potential were assessed using a non-destructive approach. The volume of each vegetation component was

region specific volume equations developed by the Forest Survey of India, and then multiplied by species-specific wood density values obtained from published literature to derive biomass estimates. The biomass of each component was multiplied by the carbon fraction factor of 0.47 (as recommended by the IPCC) to estimate the carbon content, and the sum of all components provided the total carbon stock of the forest. The MDFWS recorded the highest total biomass (401.13 Mg ha^{-1}), significantly exceeding PSF (217.16 Mg ha^{-1}) and SDMDF (201.50 Mg ha^{-1}), with no significant difference between the latter two. This indicate MDFWS have greater productivity and structural complexity. PSF and SDMDF had lower biomass, with SDMDF showing dominance in understory and litter components. *Shorea robusta* dominates biomass carbon in PSF (83.53%) and SDMDF (44.74%), with few other species making smaller contributions. MDFWS shows greater species diversity, with biomass more evenly distributed among species like *Terminalia alata, Schleichera oleosa* and *Anogeissus latifolia.*

Significant differences ($P<0.05$) were observed in living and non-living biomass carbon, soil organic carbon (SOC), ecosystem carbon stock (ECS) and SOC:ECS ratio. MDFWS had the highest living biomass carbon (AGBCS: 147.09, BGBCS: 35.34 Mg C ha^{-1}), while SDMDF recorded the lowest. The non-living biomass carbon was highest in SDMDF (6.97 Mg C ha^{-1}), with PSF and MDFWS showing similar values (~5.7 Mg C ha^{-1}). SOC stock and SOC:ECS ratio were highest in PSF, followed by SDMDF and MDFWS. Ecosystem carbon stock (ECS) was lowest in SDMDF (172.68 Mg C ha^{-1}), while PSF (234.67) and MDFWS (242.41) were statistically similar.

Tree carbon stock found significantly higher in MDFWS (171.24 Mg C ha^{-1}) than PSF and SDMDF. Sapling carbon was highest in PSF (1.99 Mg C ha^{-1}), while shrubs showed no significant variation. Liana carbon was highest in SDMDF and herbaceous carbon was highest in MDFWS. Deadwood carbon was greatest in MDFWS (1.68 Mg C ha^{-1}) and lowest in PSF (0.85 Mg C ha^{-1}). Litter carbon stock was significantly higher in SDMDF (5.22 Mg C ha^{-1}) than in PSF and MDFWS.

These patterns highlight differing carbon dynamics and storage potential across the forest types.

MDFWS showed the highest net annual biomass increment across trees (41.44 Mg ha^{-1}), total biomass (51.04 Mg ha^{-1}) and deadwood (0.81 Mg ha^{-1}) followed by SDMDF and PSF. Liana and herb biomass were also notably higher in MDFWS, while SDMDF had the highest above-ground litter accumulation.

The annual carbon sequestration potential varied significantly ($P<0.05$) across vegetation components in PSF, SDMDF and MDFWS. Trees showed the highest carbon sequestration, with MDFWS leading at 19.48 Mg C ha^{-1}, followed by SDMDF (10.75 Mg C ha^{-1}) and PSF (5.07 Mg C ha^{-1}). Other components like lianas, herbs, and soil organic carbon (SOC) also showed significant differences, with MDFWS consistently having the highest values. Above-ground litter was highest in PSF (0.76 Mg C ha^{-1}), while SOC was highest in SDMDF (0.51 Mg C ha^{-1}). Overall, MDFWS had the highest total carbon sequestration (22.01 Mg C ha^{-1}), followed by SDMDF (13.54 Mg C ha^{-1}) and PSF (7.14 Mg C ha^{-1}).

The annual litter production was estimated using ten 1 m × 1 m × 0.3 m litter traps per plot for aboveground litter and soil cores (7.5 cm diameter, 45 cm depth) for fine root litter. Litter decay dynamics was determined using standard litter bag techniques. Annual litter fall varied significantly ($P<0.05$) across forest types, with SDMDF having the highest total (12.77 Mg ha^{-1} yr^{-1}), followed by PSF (10.58 Mg ha^{-1} yr^{-1}) and MDFWS (8.93 Mg ha^{-1} yr^{-1}). Aboveground litter contributed 88.47% to 90.60% of the total litter, with senescent leaves making up 70.88% to 75.33%. Litter fall peaked during winter (December-February), with SDMDF recording the highest winter fall (7.57 Mg ha^{-1} yr^{-1}). There were no significant differences in root litter or summer litter fall. Annual litter fall correlated significantly with tree density (0.733) and basal area (0.997).

The concentrations of nutrients and secondary compounds in leaf, small branch, and root litter varied significantly, except for carbon. Hemicellulose, cellulose, lignin and total phenols varied across litter components, with PSF root litter having the highest

hemicellulose, MDFWS root litter the highest cellulose, PSF small branch litter the highest lignin and MDFWS leaf litter the highest total phenol content. Nitrogen, phosphorus, and potassium content was higher in leaf litter than in small branch and root litter. PSF showed the highest C/N and L/N ratios across all litter components.

The litter decomposition study revealed significant variations ($P<0.01$) in decay rate across forest types, with three distinct phases: slow decay in summer, rapid decay during the rainy season and constant decay in winter. MDFWS exhibited the highest decay rates for all litter categories, while PSF had the slowest decay, with up to 25.83% of root litter remaining after 270 days. The decay rate constants were highest in MDFWS and the time for 50% and 99% mass decay was longest in PSF.

The total soil respiration was determined using the soda method of Keith and Wong, (2006) in which CO_2 released from soil was tapped through soda lime granules in a closed chamber. The analysis of soil respiration dynamics revealed significant differences across forest types. MDFWS also recorded the highest total annual soil respiration (43.61 Mg C ha^{-1} yr^{-1}), root respiration (23.76 Mg C ha^{-1} yr^{-1}) and microbial respiration (19.84 Mg C ha^{-1} yr^{-1}), while PSF had the lowest values for all these parameters which was attributed to differences in soil moisture and temperature. Soil moisture had a strong positive correlation ($r = 0.798$, $P < 0.01$) with soil respiration rate than soil temperature ($r = 0.204$, $P < 0.05$).

Net ecosystem production (NEP) represents the net carbon gain in a forest, calculated as the difference between net primary production (NPP) and heterotrophic respiration (Rh). The NPP was estimated as the annual increase in biomass, including above and belowground components of all vegetation types (tree, sapling, liana and shrub), herbaceous biomass, litterfall and dead wood accumulation. Significant variations ($P<0.05$) were observed in NPP, Rh and NEP across three forest types. MDFWS had the highest NPP (28.46 Mg C ha^{-1} yr^{-1}) and Rh (22.11 Mg C ha^{-1} yr^{-1}), while PSF and SDMDF showed lower values. MDFWS also had a positive NEP (4.71 Mg C ha^{-1} yr^{-1}), indicating it acts as a carbon sink, while PSF and SDMDF were carbon sources with negative NEP. Over all (mean value of three forest types) these forests have positive NEP value (0.62 Mg C ha^{-1} yr^{-1}), making it as a carbon sink for the

region. Aboveground biomass carbon and harvested wood biomass contributed significantly to the total NEP.

This study highlights the role of tropical moist deciduous forests of Odisha in regulating carbon dynamics and contributing to climate change mitigation. The observed variations in carbon dynamics were primarily driven by species composition, forest structure, disturbance levels and soil microclimate. The MDFWS community characterized by higher diversity and favourable conditions, exhibited greater ecological efficiency, while PSF showed reduced regeneration and carbon flux due to dominance by *Shorea robusta* and frequent disturbances. These findings highlight the need to conserve structurally diverse forests and promote sustainable management practices to enhance carbon storage, ecosystem resilience, and regional climate mitigation.

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