Soil carbon pools and dynamics in the Sal forests of Bangladesh

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DECLARATION

I, Md. Habibur Rahman, hereby declare that the thesis entitled "Soil carbon pools and dynamics in the Sal forests of Bangladesh", submitted in partial fulfillment for the degree of Ph. D. in Botany at Ecology and Environment Laboratory, Department of Botany, University of Dhaka, is the result of my investigation. This work has not been submitted before to this University or any other institution to obtain any degree, diploma, associateship, fellowship or any other similar title.

January 2026

Md. Habibur Rahman

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Dedicated

To My

Parents And Teachers

Abstract

Carbon (C) concentrations in different Sal forests of Bangladesh have not yet been estimated to explore their C storage potential. The present study compared the C pools among three selected Sal forests located in Madhupur, Lalmai and Singra to examine the effect of management intensity on C stocks. A total of 19 plots (each 10 m × 10 m for tree, 5 m × 5 m for shrubs and 0.5 m × 0.5m for herbs in size), 9 from Madhupur forest and each 5 from the other two forests, were established to collect data on plant composition, plant DBH and organic C concentrations. Allometric method was used to estimate C concentrations for both aboveground and belowground parts of juvenile and adult tree plants of the selected plots. Wood biomass was converted to C content by multiplying the value with the van Bemelen factor (1.724). Litter biomass C, soil organic C and fine root C were determined during winter (December) and summer (May) of 2016. Seasonal variation in culturable soil bacterial colony counts was also studied in three replicated plots selected from Madhupur Sal forest. The results showed that woody C concentration was significantly ($p = 0.0156$) higher in Lalmai (552.46±64.09 t/ha) and Singra forests (547.13±62.43 t/ha) than in Madhupur Sal forest (354.03±38.43 t/ha). The mean DBH of Sal tree at breast height was significantly ($p = 0.022$) higher in Lalmai (38.84±2.12 cm) and Singra (37.36±1.97 cm) forests than in Madhupur forest (30.72±1.93 cm). On the other hand, fine root C and soil C were determined at three different depths: 0-10 cm, 10-20 cm and 20-30 cm. The litter and fine root dry biomass were converted to C content and expressed as tonnes C per hectare area. Soil C content was calculated using the bulk density method. The decomposition of Sal leaf litter and seasonal changes in bacterial communities were studied to explain the observed temporal changes in biomass C content in the study area. The decomposition rate (mass loss and N mineralization rate) of Sal leaf litter was studied by incubating leaf litter with soil collected from three selected Sal forests following a reciprocal experimental design where each Sal leaf litter was incubated with soil collected from three Sal forests. The number of bacterial colonies was compared in summer, monsoon, late autumn and winter seasons in a plot of Madhupur Sal forest. Litter biomass C was significantly higher in May compared to December, although the effect of forest was not significant. Fine root biomass C was significantly affected by forest type ($p < 0.0001$) and depth ($p < 0.0001$) where the maximum amount was found in Madhupur sal forest and the lowest in Lalmai Sal forest and 0-10 cm depth showed the highest value among the three selected Sal forests. Soil C content was significantly affected by both forest type ($p < 0.0001$) and depth ($p < 0.05$) where the value was higher in Singra National Park, followed by Madhupur Sal forest and Lalmai Sal forest, however, the highest value was recorded at 10 cm depth, followed by 20 cm and 30 cm depth. Nitrogen mineralization rate was significantly affected by soil type and the mean value was higher in Lalmai Sal forest. For fast-growing bacteria, the number of small- sized colonies was higher in late autumn but lower in winter, while the number of large-sized colonies was higher in winter but lower in late autumn. For slow-growing bacteria, the number of small-sized colonies was higher in late autumn but lower in winter, while the number of large-sized colonies was higher in winter but lower in late autumn. This study suggests that long-term forest conservation may be an effective method for increasing C stocks in forest ecosystems. Result also suggest to consider assessment of C stocks of temporal scale for more accurate estimation of C dynamics.

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CHAPTER 1

INTRODUCTION

1.1 The Carbon (C) cycle in nature

The C cycle in nature is a dynamic process that interconnects several components of the environment including atmosphere, lithosphere, biosphere and hydrosphere (Rackley 2023). The global C cycle describes the continuous movement of C atoms between non-living components such as atmosphere, oceans, and land and the living component such as plants, animals and microbes (Figure 1.1). Carbon is an important constituent for the formation of the backbone of organic molecules (Verbančič *et al*. 2017). Carbon present in the C cycle takes part in the cellular formation and organization of all living organisms.

The C cycle involved both envirionment phase (non-living phase) and the organismal phase (living phase) as shown in the Figure 1.1. There are several reservoirs of the C in the C cycle. These are atmosphere, oceans, terrestrial biosphere, lithosphere, and earth interior. Carbon exchange processes include photosynthesis, respiration, decomposition, combustion, weathering, volcanic eruption and ocean-atmosphere exchange. These reservoirs and exchange pools are described as follows:

1. Carbon reservoirs: The following are the reservoirs where C is stored or C remains as sink:

Atmosphere: C remains in the atmosphere as CO_2 and methane (CH_4).

Oceans: Ocean acts as a significant sink of C and absorb CO_2 from the atmosphere storing it in dissolved form and in marine organisms.

Terrestrial biosphere: C is stored in plants, animals, microbes and soil.

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Lithosphere: A vast amount of C is stored in rocks and sediments including fossil fuels such as coal, oil, and natural gas.

Earth interior: C is released into the atmosphere from the volcanoes of the interior of the Earth.

2. Carbon Exchange Processes:

Photosynthesis: C is fixed into green plants from the atmosphere through the process of photosynthesis and release O_2.

Respiration: CO_2 is released from plants and animals through respiration.

Decomposition: By decomposition of dead organisms, microbes release CO_2 into soil and atmosphere.

Fossil fuel combustion: C is released back to the atmosphere as CO_2 by buring of fossil fuels such as coal, octane, petroleum etc,

Ocean-atmosphere exchange: C is exchanged between ocean and atmosphere by dissolving it into the ocean water and released out in to the atmosphere.

Weathering: C is released back to the atmosphere by breaking down of rocks and it eventually reaches the ocean.

Volcanic eruption: C is released into the atmosphere from the interior of the earth**.**

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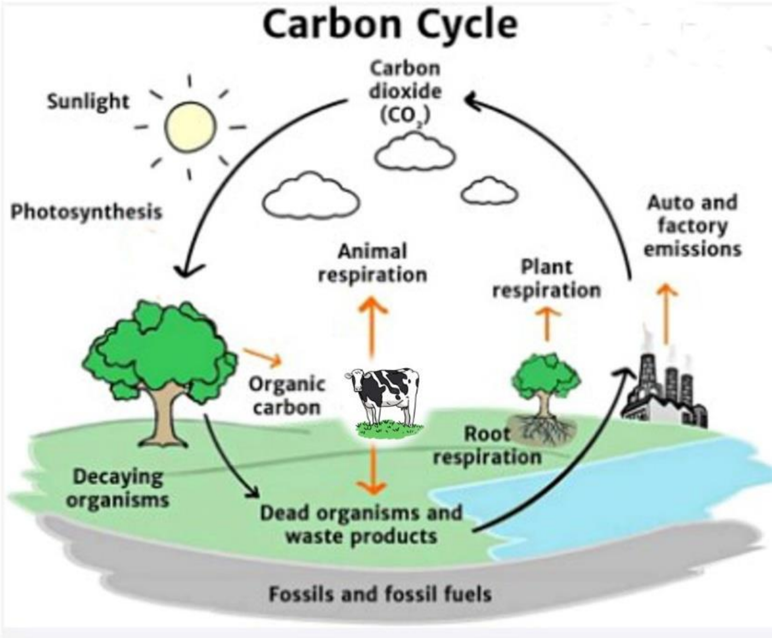

Figure 1.1: Global carbon cycle in the nature.

1.2 Soil carbon (C)

The carbon (C) held in the soil of the Earth crust is known as soil C. Carbonate minerals contain both inorganic C and organic materials from the soil. In the global C cycle, soil C serves as a sink for C and is important for biogeochemical cycles, mitigating climate change, and predicting the global climate. There are two types of C in soil: inorganic and organic. The mineral forms of C found in soil are created either by the weathering of the parent material or by the reactions of soil minerals with atmospheric CO_2. In desert regions, the primary source of soil C is carbonate minerals. Organic matter in the soil is the source of soil organic C. These include highly inert C found in materials formed from plant residues (humus and charcoal) and relatively rapidly available C found in fresh plant residues (Zamanian *et al*. 2021). The C found in the organic matter of soil is known as soil organic C (SOC). This is not the same as soil inorganic C, which is made up of soil minerals like carbonates (like limestone) that are typically found in alkaline or calcareous soils. Approximately twice as much C is stored in soil as it is in the atmosphere and three times more than it is in vegetation (Schlesinger and Bernhardt 2022).

Carbon and other elements make up the large component known as soil organic matter (SOM). They consist of dead organisms (including macro- and microorganisms), the O layer in the soil profile (such as leaf litter and fluff), sensitive plant material inside the mineral soil matrix, microbial and root exudates, and organic material deposited on mineral surfaces. One of the most dynamic elements of soil is SOC. The annual processing capacity of soil microorganisms is roughly equivalent to the input of plant waste. The ecosystem services that SOCs offer, or the benefits that people derive from ecosystems are largely dependent on their remarkable dynamics in the nature (Jian *et al*. 2023).

An essential measure of the health of the soil is measuring SOC contents. Schoenholtz *et al*. (2000) defined soil health as the ability of the soil to function effectively as part of a healthy ecosystem. Important soil functions like nutrient calcification, aggregate stability, transportability, aeration, water retention, infiltration, and flood protection are correlated with the amount and quality of SOC. Numerous attributes of the ecosystem are connected with these soil processes. For instance, high SOC in mineral soils is typically linked to high plant productivity (Oldfield *et al*. 2019), which benefits the habitat, abundance, and dispersion of wildlife.

Therefore, when SOC shifts or disappears in forest or rangeland areas, it may have an impact on ecosystem services. Assessing and tracking SOC levels can help gain a deeper understanding of the ecology and soil health of a specific area. SOC measurements are among the indicators of soil health that can be used to monitor changes in the state of the soil over time and in response to management actions (Lehmann *et al*. 2020).

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The biggest known reservoir of terrestrial C is thought to be soil C (IPCC 2019). Among the different pools, storage capacity of soil C is much higher than that of the atmosphere and plants. Understanding soil C storage and its potential for storage is currently of significant importance. The increasing number of studies mapping soil C reserves at national and global scales indicates the tremendous interest in mapping the geographical distribution of soil C (FAO 2020). This is in line with the goal of improving the resolution and accuracy of soil C stock assessments. Quantifying and mapping soil C stocks at field, landscape, regional, continental, and global scales has been the subject of numerous published articles (Padarian *et al*. 2020).

Measurements of soil C content in 1981 and 2002 showed a correlation with soil organic matter content (Liang *et al*. 2017). In 1981, the percentage of C in soil was around the same in both conventional and organic systems 2%. However, as of 2002, the proportion of SOM in organic systems was about 5%, whereas that of conventional systems was about 2% (Lori *et al*. 2017). An organic system with higher soil organic matter content retains more water in the soil, which increases crop yields during dry spells, decreases soil erosion, and improves crop nutrient retention and biodiversity rises. In 2002, the amount of soil C in conventional systems was about 4,000 kg/ha, whereas the amount in organic systems was about 10,000 kg/ha. Globally, soils have an estimated 1500 Pg (1 Pg = 1 Gt = 1015 g) of organic C (Batjes 2016), which is more than the C in the atmosphere and roughly three times higher than that of vegetation (IPCC 2001). According to Patterson *et al*. (2019), estimates of the world's SOC stocks range from 1500 to 2400 Pg C. These data suggest that disturbance (e.g. agricultural activities) can play significant role in changing C contents in soil.

Soil is the greatest C pool in terrestrial ecosystems with over 2500 Pg C, or 3.3 times more than the atmospheric C pool of 760 Pg, (Lal 2004, Batjes 2016). The potential of soils to reduce C emissions is considerable; by putting in place suitable mitigation measures, soil carbon emissions can be lowered by as much as 50% of 2010 levels by 2050 (Edenhofer *et al*. 2014). In order to mitigate global change, it is essential to determine how to address the soil C sink function using proper methods. However, since soils are such intricate systems, a variety of factors, such as land use change (LUC), soil management, and climate change, have an impact on soil C pools (Franko 2018, Lal 2018). An all-encompassing and cohesive examination of the various influences on soil C can aid in managing soil C and mitigating the effects of climate change. Even while soil C research has made significant progress, the majority of earlier studies concentrated on a small number of variables or habitats. An in-depth grasp of global soil C cycling and soil C management may be hampered by the lack of a thorough worldwide investigation of soil C under various influencing circumstances.

A high level of organic matter in the soil helps to retain nitrogen in the soil, boosts microbial biodiversity, and encourages the growth and presence of arbuscular mycorrhizal fungi. Improved crop development and yield are the outcome of arbuscular mycorrhizal fungi invading crop roots and facilitating the transport of plant nutrients from the soil to the crop (Begum *et al*. 2021). Increased soil C prevents soil erosion by binding soil particles together (Lehmann *et al*. 2020). Because forest soils store a lot of C, human actions like deforestation can release C from these stores. These activities greatly raise the atmospheric concentrations of greenhouse gases (GHGs). It is anticipated that future atmospheric CO_2 concentrations may be significantly impacted by even small losses from this enormous reservoir. Thus, when it comes to climatic C cycle feedbacks, soil responses to global warming are crucial. The combined effects of climate and C cycle models exhibit significant differences in the expected amount of atmospheric biosphere feedbacks.

As per the obligation by the United Nations Framework Convention on Climate Change (UNFCCC), every country has to estimate and report greenhouse gas emissions. It is also mandatory to report changes in C stocks in all five pools (soil C, dead wood, biomass, and above- and below-ground biomass). Globally, deforestation of tropical forests is responsible for around 23% of all anthropogenic greenhouse gas emissions (IPCC 2022). The atmospheric release of C from soil can result from land management practices, deforestation, and forest degradation. For these reasons, in order to report greenhouse gas emissions under the UNFCCC and to minimize emissions from deforestation and forest degradation, accurate assessments of soil organic C stocks and changes in stocks are required.

1.3 Carbon and the global warming

According to IPCC Working Group I (IPCC 2007), rising global average and ocean temperatures provide strong evidence of the global warming. The main cause of the temperature rise is an increase in greenhouse gas emissions into the atmosphere, especially carbon dioxide (CO_2). Since 1750, emissions from the burning of fossil fuels, agriculture, and changes in land use have led to an increase in atmospheric CO_2 concentrations that are currently significantly higher than pre-industrial levels (IPCC 2007). According to the observed record of surface temperature of the Earth, eleven of the last twelve years have been among the twelve warmest years since 1850. The linear trend over 100 years, from 1906 to 2005, is 0.74 °C. The past 50 years have seen an average linear warming rate of 0.13 °C (0.10–0.16) each decade, which is nearly twice as high as the prior 100 years (IPCC WGI, 2007).

Global net primary production (NPP) and respiration and fire from the land to the atmosphere each contribute about 60 Pg C of CO_2 to the atmosphere annually (IPCC 2001). During the 1990s, the combustion of fossil fuels and the production of cement released 6.3 ± 1.3 Pg C annually into the atmosphere, whereas changes in land use released 1.6 ± 0.8 Pg C annually (IPCC 2001). The ocean absorbs 2.3 ± 0.8 Pg C annually, the land absorbs 2.3 ± 1.3 Pg C annually, and the atmospheric C grows at a rate of 3.2 ± 0.1 Pg C per year. Soil carbon stores are currently lower than they were prior to human influence. Due to farming and disturbance, soils have historically lost 40–90 Pg C worldwide (Sanderman *et al*. 2017).

The amount of CO_2 in the atmosphere can shift dramatically even with little changes in the SOC pool. Consequently, reaction of SOC to global warming is crucial. Bond-Lamberty *et al*. (2018) suggested that the possible influence of rising terrestrial C emissions on additional climate change. They demonstrated this concept using a coupled C cycle climate model that warming-related global C emissions have positive feedbacks that exacerbate global warming. Since then, other models—referred to as C_4 models—that combine the climate and the carbon cycle have been created. The magnitude of land-based feedback, however, remains highly unknown, with model discrepancies implying variations in atmospheric CO_2 concentrations of nearly 250 ppm by 2100 (Friedlingstein *et al*. 2022). This is similar to the variation in fossil fuel-related C emissions under the IPCC SRES emissions scenario (Riahi *et al.* 2017). It is obvious that a more accurate assessment of the response of terrestrial C—a large portion of which originates from soils—is necessary in order to comprehend the character and scope of Earth's reaction to global warming.

Low soil temperatures and/or anaerobic circumstances encourage the development of thick organic layers and peat in cold and humid places. The storage of about 500 Pg of C and latitudinal gradients is in soil C stocks (Garcia-Palacios *et al*. 2021). The role of climate factors is important for soils or strata that are mixes of organic and mineral soils and contain more than two thirds of the world's soil C stocks (Jackson *et al*. 2017). There is growing doubt about control over C storage (Doetterl *et al*. 2015, González-Domínguez *et al*. 2019). The long-term persistence of SOM in mineral soils without anaerobic conditions is now understood to depend more on accessibility of SOM' to decomposers than on its innate capacity for decomposition (Schmidt *et al*. 2011, Dungait *et al*. 2012). Use of SOM by microorganisms is restricted by physicochemical stabilization mechanisms, which also permit the survival of organic matter. These mechanisms include the attachment of organic matter to the mineral surface and physical protection within the aggregate. The impact of temperature in influencing C storage may be underestimated due to the importance of certain soil qualities, and there may be a considerable release of C from soils in areas with warmer temperatures (González-Domínguez *et al*. 2019, Doetterl *et al*. 2015, Giardina *et al*. 2014). The temperature sensitivity of the physicochemical stabilization processes themselves, however, is poorly understood (Wiesmeier *et al*. 2014). For instance, sorption (stabilization) processes should be less sensitive and more sensitive than desorption (destabilization) reactions; however, the relative temperature sensitivity can vary based on the affinity of organic matter for minerals (Conant *et al*. 2011). Destabilization processes may be extremely sensitive to temperature, and degradation of older, better-protected SOM has been shown to be more temperature sensitive than rapidly disintegrating SOM (Jia *et al*. 2019, Zhou *et al*. 2018, Lefèvre *et al*. 2014). However, little is known about this issue. It is, therefore, uncertain whether or not mineral soils are more or less susceptible to global warming than soils.

To create a database that will assist in addressing some of the most important environmental concerns, such as the consequences of climate change, considerable efforts have been made in recent years to gather soil data from all over the world (Ribeiro *et al*. 2018). As an illustration, a sample of publicly accessible soil profile data from six continents was released via the World Soil Information (WoSIS) database (Batjes *et al*. 2017).

In the 21st century, there are several global challenges. The amount of CO_2 in the atmosphere is 379 ppm, which has increased by more than 1.8 ppmv and impacts how much carbon is stored in the soil and how it changes over time. According to Achard *et al*. (2002), 7.1 million hectares of tropical forests are cut down each year, land degradation affects 1.2 billion hectares at a somewhat positive level, about 1 billion people face global food insecurity, and there is too much dependence on fossil fuels for energy. To fulfill the growing food needs of emerging nations, which are expected to rise quickly between 2025 and 2050, it is essential to restore soil quality through improved SOC pools (Rosegrant and Cline 2003).

Soils store two to three times as much carbon as the atmosphere does worldwide (Quéré *et al*. 2016). Thus, even little changes in carbon stocks can have a significant impact on reducing the effects of climate change. Historically, the conversion of land to agriculture, drainage of peat lands, simplification of crop rotation, removal of crop residues, separation of crop and livestock production, and losses from soil erosion have all dramatically decreased global stocks of SOC (Reise *et al*. 2022). SOC stocks will keep declining in the absence of improvements in ordinary agriculture management techniques. Moreover, additional SOC losses are expected to result from climatic changes alone (Wiesmeier *et al*. 2020).

The possibility for reduction connected to soil varies by region. For instance, according to Smith *et al*. (2014), the regions with the highest mitigation potential include East and Southeast Asia (40%), Western Europe (26%), and the Russian Federation (11%). These regions have restored cultivated organic soils. There is little chance of further soil C sequestration in high-latitude, humid tropical regions, which are home to agricultural soils with the highest C storage (Minasny *et al*. 2017). The possibility for additional considerable C sequestration is assessed, in addition to maintaining the current C stocks. Unreported greenhouse gas emissions from cultivated land are projected to be over 70 million tons CO_2eq/year in the national greenhouse gas inventories of EU Member States, whereas unreported emissions from grassland are estimated to be around 15 million tons CO_2 eq/year. Moreover, 150 million tons of combined mineral and organic soils might be produced annually by the year 2050 if C-intensive agricultural practices like peat land restoration, agroforestry, or switching to grasses in place of fodder crops are extensively adopted. It is possible to prevent an additional 350 million tons of CO_2-eq/year (Bellassen *et al*. 2022).

One of the most pressing challenges of the modern era is the rise in C emissions, which constitute the primary driver of anthropogenic global warming (IPCC 2023). The Kyoto Protocol (1997) established early requirements for lowering emissions; however, the Paris Agreement (2015) has adopted more inclusive and comprehensive mitigation targets (UNFCCC 2023) and has therefore taken over climate governance. Bangladesh is qualified to engage in efforts to mitigate greenhouse gas emissions under the Clean Development Mechanism (CDM) of the Kyoto Protocol. The CDM enables poor nations to acquire carbon credits via afforestation, reforestation initiatives, and the preservation of natural forests (UNFCCC 2004). Nonetheless, forest coverage of Bangladesh remains severely restricted. The Global Forest Resources Assessment (FAO 2020) indicates that merely 14.5% of Bangladesh's total land area, which encompasses 14.757 million hectares, is forested, amounting to around 2.14 million hectares (FAO 2020). This includes 1.02 million hectares of natural forests and 1.12 million hectares of plantations (FAO 2020, MoEFCC 2022). Notwithstanding afforestation initiatives, deforestation and degradation continue, intensifying issues related to carbon storage (World Bank 2022, Rahman *et al*. 2023).

The largest environmental catastrophe on the planet is climate change, which is the outcome of human-caused global warming (Mal *et al*. 2018, O'Beirne 2017). Climate change has the capacity to bring about unthinkable humanitarian calamities. The IPCC proposed in its Fifth Assessment (AR5) of 2014 that rising concentrations of greenhouse gases (GHGs), mostly from human activity, are the cause of global warming. According to Stocker *et al*. (2013), the AR5 climate model projected increases in global surface temperature of 0.3–1.7 °C and 2.6–4.8 °C, respectively, for the lowest and maximum emissions scenarios. Houghton and Nassikas (2018) noted that REDD+, C allocation, and CDM apply to AR6. They also noted that permitting secondary forest growth and halting deforestation will cut global C emissions by about 120 Pg C between 2016 and 2100. Forests, trees, and other vegetation can be exploited to create defenses against the detrimental consequences of climate change since they act as C sinks (Shin *et al*. 2007).

1.4 Factors affecting C cycle

Global C cycle is influenced by both natural and anthropogenic factors. Among the natural factors, volcanic eruptions, weathering, erosion, respiration and photosynthesis of living organisms are notable. On the other hand, anthropogenic factors include burning of fossil fuels, deforestation, and agricultural activities. Intensive agriculture causes reduction of C content in soil (Lehmann *et al*. 2020, IPCC 2022).

Since temperature and precipitation have an impact on SOC resources, there are concerns that anticipated climate change may destabilize SOC resources, especially in regions where permafrost exists. SOC stocks, however, have the potential to play a significant role in limiting climate change provided they are properly managed. According to Friedlingstein *et al*. (2020), the mineralization of merely 10% of the SOC inventory (estimated at 1500 Pg at 1 m deep) is fifteen times more than the 10 Pg C emitted by burning fossil fuels in 2019. Meanwhile, according to Friedlingstein *et al*. (2020), land (soil and vegetation) now absorbs around one-third of anthropogenic emissions. The use of land-based sinks will lower the cost of mitigating and adapting to climate change, assuming that land-based C absorption capacity can be increased by implementing sensible soil/crop management techniques and judicious land use. Enhancements in the soil quality and functionality of agro-ecosystem can lead to the accomplishment of the 2030 Agenda of the United Nations and the advancement of many interconnected Sustainable Development Goals (Lal *et al*. 2021).

Global warming and biodiversity loss are two of the world's most pressing issues today. According to scientists and policy officials worldwide, burning fossil fuels and deforestation in recent decades are the main causes of both issues (IPCC 2013). The world temperature rose by 0.74°C over the past century, and the atmospheric concentration of CO_2 reached 379 ppm. By 2050, global temperatures might double and rise by as much as 2-4°C if current rates of warming persist (IPCC 2013). By the end of the twenty-first century, melting polar ice is expected to raise global sea levels by 28 to 98°C, according to IPCC projections from 2013. This will significantly alter livelihood patterns in low-lying coastal countries like Bangladesh, the Maldives, and the Netherlands.

Data on land use change are not comprehensive in the available literature. This is because estimations of emissions are based on estimates of emissions from biomass loss and decomposition. However, they do not account for lateral transport, like soil erosion that occurs more quickly. A disproportionate amount of the SOC stock in the planet is stored in forests. Though forests make up less than 40% of surface area of the planet, they store more than 45% of its stock of SOC per square meter, with an average of 400 μg (FAO 2012, Nave *et al*. 2019). Other estimations (Dixon *et al*. 1994, FAO 2020) indicate that forests make up 25–40% of the surface area of the Earth and that SOC stocks range from 400 to 800 Pg C, with a worldwide total of 1200–1600 Pg C. Recent research has examined the vast range of SOC densities seen in global forests and forest floors in relation to global ecological zones (GEZs) of the Earth (FAO. 2012, Nave *et al*. 2019).

Around the world, 18% of CO_2 emissions are caused by deforestation (Stern 2006). Nonetheless, greenhouse gas (GHG) emissions can be decreased by the biosphere on Earth (Ardö and Olsson 2004). Globally, C forestry techniques may help lower these atmospheric greenhouse gas emissions (Polglase *et al*. 2011). Reforestation and afforestation initiatives in under developed countries can yield C credits (FAO 2001). Forests maintain an equilibrium in atmospheric CO_2 concentrations (Rotter and Danish 2002). Additionally, forests have the ability to mitigate climate change by lowering atmospheric C concentrations through management (Brown *et al*. 1996, Matthews *et al*. 2000).

1.5 Carbon pools of the Earth

"C pool" is defined as an area of the climate system that may absorb, store, and release C. All of the C in the soil is contained in its "soil C stocks". However, various factors including management activities affect how much of it is present there. Because soil stores more C than plants and the atmosphere combined, soil C storage is significant. Feces, decomposing animal tissue, plant matter, and soil microorganisms (fungi and bacteria) all contribute to the storing of C in the soil. As more C is added, this pool is continually changing. Soil microorganisms can partially breakdown C into microbial waste products or transform some of the C back into CO_2, leaving some C in the soil C pools are repositories of C that have the ability to emit and absorb C.

The global C cycle is formed by the flow of C, or "C fluxes," between the reservoirs. The global C cycle involves several major C pools where carbon is stored. The major pools to the global C include (i) continental crust and upper mantle, (ii) deep and intermediate ocean, (iii) soil and vegetation, (iv) permafrost, (v) surface ocean, (vi) atmosphere, (vi) industrial emission and (vii) land-use change. There are five major interconnected C pools on the Earth (Figure 1.2). The total amount of C in the five interconnected global C reservoirs (e.g. the atmosphere, oceans, terrestrial biosphere (including plants and soil), fossil fuels, and lithosphere (rocks, including sedimentary rocks like limestone and shale) is 50.4 trillion tons (Falkowski 2020). Together, these pools create a worldwide C cycle. 3.120 Pg or 6.2% of all pedologically and physiologically circulating C is found in terrestrial pools. Moreover, carbonate rocks contribute 20 × 10 6 Pg C in marine sediments.

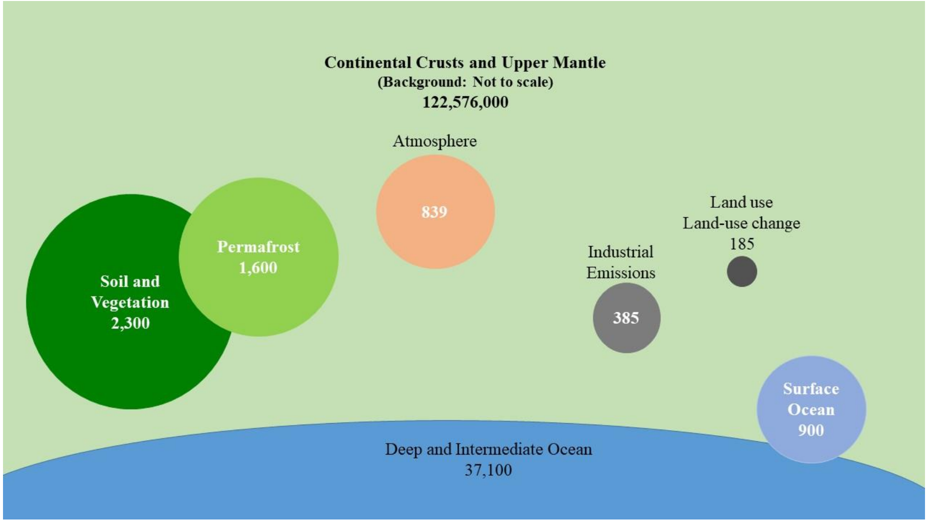


Figure 1.2: Global carbon pools. Carbon stores are shown in billion metric tons (Source; Redrawn from Falkowski 2020).

1.5.1 Continental crust and upper mantle

The sedimentary rocks that make up the Earth's crust contain the majority of the C on Earth. These are the rocks that are created throughout geological time when mud that contains organic matter hardens into shale or when calcium carbonate particles from marine animals' shells and skeletons accumulate in limestone and other carbonaceous sedimentary rocks. The amount of C stored in the continental crust and upper mantle is 122,576,000 billion MT.

1.5.2 Deep and intermediate Ocean

Carbon stored in the deep and intermediate ocean is 37,100 billion MT. Through physical processes like the breakdown of CO_2 gas in water and biological processes like the growth, death, and destruction of plankton, this C is rapidly exchanged with the atmosphere. While the majority of this surface C is quickly cycled, some of it is transported to deep ocean basins by sedimentation, where it can be stored for longer periods of time.

1.5.3 Soil and vegetation

Plants, animals, and soil microorganisms (bacteria and fungi) are the sources of C in terrestrial ecosystems. Soil and vegetation stores about 2,300 billion MT of C. Organic matter makes up the majority of the carbon in terrestrial ecosystems. The term "organic" here refers to substances that are created by living things, including wood, roots, leaves, dead plant matter, and brown organic matter, which is the decaying remnants of once-live tissue found in soil.

The IPCC developed best practice guidelines that state that woody debris, SOM, below ground biomass (BGB), or root and leaf litter biomass (LB), and above ground biomass (AGB) make up the total amount of C stock in forest ecosystems. As a result, evaluating the C stored in these various pools is crucial for creating new conservation strategies linked to sequestering C and halting global warming. According to Eggleston *et al*. (2006), AGBs and BGBs are contributing to C reservoirs found in forests that supply significant amounts of C to terrestrial ecosystems. Since LB adds very little C to the terrestrial pool, it is regarded as a tiny pool (Ravindranath and Ostwald 2008). SOM is the biggest and most significant C pool found in terrestrial ecosystems. SOC, found in SOM, is essential to the cycling of nutrients and C between the lithosphere and atmosphere (Lal 2005).

Temperature, precipitation, terrain, forest type and structure (Vayreda *et al*. 2012), species diversity, tree species composition (Hu *et al*. 2015), and species composition all affect C pools in various forest ecosystems. Accordingly, in order to create the appropriate management plans for C sequestration and storage, it is necessary to estimate the current C stocks in various forest types (Domke *et al*. 2022)**.**

Because they store a lot of C in the soil and vegetation, forests are crucial to the global C cycle (Pan *et al*. 2011). For instance, the ecosystems of forests store 638 Gt of C, of which

238 Gt is biomass, or 80% of the C in biomass of terrestrial vegetation (FAO. 2005). Roughly, 47% of the Earth's surface is made up of dry and semi-arid zones, which span 6.5 million km^2 and contain 4,357 M ha of forest land worldwide (Bastin *et al*. 2017). Drought, desertification, and land degradation in these ecosystems will be significantly impacted by the combined effects of population increase and climate change (Huang *et al*. 2012, 2016). This has additional effects on soil fertility, productivity, biodiversity, and the composition of organic matter, which lowers the potential for sequestering and storing carbon.

Meza *et al*. (2018) demonstrate that soil moisture availability is one of the abiotic variables that affect soil C storage in dry and semi-arid habitats. Mitigating climate change and its ecological effects can be achieved by management measures that prioritize sequestering C through the restoration of existing vegetation, as demonstrated by Malagnoux *et al.* (2007). Few research on biomass and C pools in these ecosystems have been done yet (Bonino 2006, Wagner *et al*. 2015). By breaking down various forms of soil C, soil microorganisms play a crucial role in controlling soil C cycling and affecting C dynamics (Zhao *et al*. 2018, Yu *et al*. 2022).

1.5.4 Permafrost

Permafrost acts as a massive carbon sink, storing approximately twice as much carbon as currently exists in the Earth's atmosphere. This carbon, primarily in the form of dead plant and animal matter, has been frozen and preserved in permafrost soils for thousands of years. However, with rising global temperatures, permafrost is thawing, releasing this stored carbon into the atmosphere as greenhouse gases like CO_2 and methane, potentially accelerating climate change. Permafrost contains about 1,600 billion MT of C (Yi *et al*. 2024).

1.5.5 Surface ocean

The surface ocean holds a vast amount of C, approximately 900 billion metric tons, which is a significant portion of the Earth's total C storage. This C is stored in the form of dissolved inorganic carbon (DIC), which includes CO_2, carbonic acid, bicarbonate ions, and carbonate ions. The surface of the ocean acts as a "carbon sink," absorbing a substantial amount of CO_2 from the atmosphere. This absorption is influenced by physical, geochemical, and biological processes, and the ocean plays a crucial role in regulating atmospheric CO_2 levels. Surface ocean stores nearly about 900 billion MT of C (Qu *et al*. 2023).

1.5.6 Atmosphere

The major contributors to the atmospheric C are CO_2 and methane gases. Carbon in the atmosphere is very important because it impacts the greenhouse effect and climate, even though it is much less than that present in the oceans and Earth crust. The atmospheric C pool is rather small, which increases its sensitivity to perturbations from growing C sources or sinks from other Earthly pools. Carbon stored in the atmosphere accounts for 839 billion MT. The increase in recent centuries has raised the quantity of C released into the atmosphere from the Earth crust (fossil fuels) and terrestrial ecosystems (deforestation and other land clearance practices). This is relevant to global pools and rivers.

1.5.7 Industrial C emission

This is a process of capturing CO_2 which is released by the industries. Carbon is stored in the form of CO_2 as an industrial emission through Carbon Capture and Storage (CCS) technologies. CCS involves capturing CO_2 from industrial sources like power plants and factories, transporting it, and then storing it underground in geological formations, or utilizing it in various applications. Industrial C emission accounts for about 455 ± 25 Gt C (Friedlingstein *et al*. 2023).

1.5.8 Land-use change

Land-use changes significantly impact C storage, often resulting in a decrease in C sequestration capacity. Deforestation, agricultural expansion, and urbanization can release stored carbon into the atmosphere, while practices like afforestation and sustainable agriculture can enhance C storage. Land-use changes contribute about 230 ± 60 Gt C (Friedlingstein *et al*. 2023).

1.5.9 Soil Organic Matter (SOM)

Land use and management techniques have a long-term impact on how much SOM is stored (West and Post 2002). Although the effect of various management techniques on SOM dynamics in dry land cropping systems varies by region (Ghimire *et al*. 2017, Wang *et al*. 2017), SOM generally tends to decrease when native ecosystems shift to cropping systems (Machado *et al*. 2006). However, due to soil-specific heterogeneity, changes in SOM stocks in response to tillage can be challenging to identify (Cookson *et al*. 2008). More critically, it can take years to see noticeable changes in SOM because of the delayed recovery of SOM stocks, which frequently causes a delay in decision-making and corrective action (West and Post 2002). Moreover, additional research indicates that tillage-induced alterations in SOM are frequently site-specific in both their degree and direction (Purakayastha *et al*. 2008, Morrow *et al*. 2016). In contrast to bulk SOM, the following microbiological characteristics and degradable SOM pools have recently been investigated: particulate organic matter (POM), water-extractable organic matter (WEOM), permanganate-oxidizing C (POXC), microbial respiration, microbial biomass C (MBC) and

N (MBN), and microbial respiration (Dou *et al*. 2008, Culman *et al*. 2013, Morrow *et al*. 2016). Compared to the more resilient bulk SOM pool, these physical, chemical, and microbiological pools can endure for weeks, months, or even years, despite making up a very small fraction of the SOM quick turnover rates are shown (Jian *et al*. 2023). According to Purakayastha *et al*. (2008), early intervention is possible to prevent severe losses in SOM by identifying early markers of SOM dynamics.

According to Awale *et al*. (2013), SOM pools can symbolize a range of interconnected soil processes and activities. For instance, POM acts as an energy source for soil microbial biomass and is crucial for soil aggregation and WEOM formation (Cotrufo *et al*. 2023). WEOM turnover is crucial for nutrient cycling since it includes C substrate and other related nutrients (N, P, S, etc.) (Gregorich *et al*. 2006). Organic materials and nutrients in the soil are transformed by soil microbes (Mooshammer *et al*. 2014). Dependent on substrate availability and soil moisture conditions, basal respiration (BR) and C calcification are useful markers of microbial activity (Balota *et al*. 2004). Long-term stabilization of SOM is indicated by the accumulation of POXC in the soil (Culman *et al*. 2012, 2013; Hurisso *et al*. 2018). In light of this, examining SOM pools and describing their interactions could help us comprehend how management affects SOM dynamics.

SOC is a crucial fertility feature that influences a variety of soil parameters, which in turn influences soil quality and ecological functioning (Benbi *et al*. 2015, Yadav *et al*. 2018). It has a tendency to trap carbon and contributes significantly to both climate change (Zhang *et al*. 2017) and the global C cycle (Lal 2018). However, soil loss and the deterioration of C stocks are primarily caused by anthropogenic disturbances, which presents significant challenges to the sustainability of ecosystems (Yadav *et al*. 2018).

Labile organic carbon (LOC) is one of the fractions that is most sensitive to changes in the soil microclimate, vegetation, and management techniques (Cheng *et al*. 2008, Sainepo *et al*. 2018, Sahoo *et al*. 2019). Changes in land use and climate have a significant impact on soil carbon (Lal 2018). Depletion of SOC pools occurs when natural systems are replaced by managed ones (Kalambukattu *et al*. 2013, Panagos 2016, Somasundaram *et al*. 2018, Meena *et al*. 2018). According to Kalambukattu *et al*. (2013), cropping sequence in the Kashmir Himalaya has a major impact on C sequestration and alters the physical, chemical, and biological characteristics of the soil. Additionally, it has been discovered that, when compared to other management techniques in agricultural soils, conservation tillage systems and agroforestry systems have better SOC storage capacity (Lal 2002, Luo *et al*. 2010, Nath and Lal 2017). Up to a depth of two meters, soils store four times as much C as the biosphere (Jackson *et al*. 2023). Little variations in SOC can have a significant impact on variations in atmospheric C storage (Babu *et al*. 2020). Thus, it is crucial to maintain SOM in order to preserve ecological balance and soil quality.

Carbon instability and the storage of organic C have a direct impact on the physical, chemical, biological, and self-assembly capabilities of soils (Addiscott 1995, Blair and Crocker 2000). Because of this, their incorporation into CMI could be a crucial sign when evaluating management systems' capacity to enhance soil quality (Blair *et al*. 2006, Diekow *et al*. 2005). By storing C through suitable land use systems, the greenhouse effect can also be lessened (Han *et al*. 2013, Sofi *et al*. 2016). When it comes to land uses, using forest areas has the most potential to sequester soil C (Kooch *et al*. 2012).

The proportional contributions of various SOC fraction types to SOC sequestration are essentially determined by soil microbes. Under various land use changes, Proteobacteria, Actinobacteria, Bacteroidetes, Nitrospire, and Chloroflexi, all had a substantial impact on soil DOC and MBC (Ren *et al*. 2018). During the early stages of growth, fungal communities are closely related to coarse Particulate Organic Carbon (POC) (Günther *et al*. 2006). Thus, differing SOC ratios dictate the composition and activities of soil microbial communities (Wang *et al*. 2021, Li *et al*. 2022). The study also discovered that, in different land use modifications and management techniques, the labile SOC percentage has a significant role in microbial alpha-diversity, community structure and hydrolyses activity related to C cycling (Baiano *et al*. 2021). Soil microorganisms gradually change from oligotrophic to co-trophic due to improvements in soil physicochemical qualities, particularly the rise in SOC following afforestation (Zhang *et al*. 2016).

High phylogenetic levels allow microorganisms with identical functions to be categorized into separate microbial taxa. This allows for the categorization and identification of soil microorganisms in this research (Wang *et al*. 2020). According to network analysis, microbial communities can be separated into various functional modules to gain a better understanding of the connection between soil functions and microbial community composition (Byers *et al*. 2024). It is currently unclear, though, how various functional features of microbial species interact to regulate soil C cycling.

1.6 Carbon pools of the forests

Forests are one of the largest C stores on Earth. They retain roughly 45% of the organic C present in biomass (Baul *et al*. 2021). Forests serve as a C sink by capturing 7.6 billion metric tons of CO_2 each year (Streiff 2021). Therefore, they play a vital role in regulating the global carbon cycle by absorbing CO_2 from the atmosphere and storing it in the biomass of trees, plants, and soil. Forests are crucial for mitigating climate change as they act as significant carbon sinks, absorbing more C than they release. Among all forest types, tropical forests play an important role in global C sinks, absorbing and storing terrestrial C and accounting for about 25% of the atmospheric C of the world (Kreier 2022). Forest C pools are the various reservoirs within a forest ecosystem where C is stored (Figure 1.3). These pools comprise living plant biomass, deceased plants, forest floor detritus, and soil (Figure 1.2). Comprehending these reservoirs is essential for administering forests as C sinks, so aiding in the mitigation of climate change.

1.6.1 Live plant biomass

This category encompasses all live plant matter, including trees, shrubs, and underbrush vegetation. Carbon is stored in leaves, stems, branches, and roots. This is often separated into aboveground biomass of plants and belowground biomass of plant roots.

1.6.2 Dead wood

This category includes both standing dead trees (snags) and fallen dead timber on the forest floor. It can be further classified into coarse woody debris (logs) and fine woody debris such as twigs, small branches. The decay of dead wood emits C into the environment.

1.6.3 Forest floor litter

This assemblage consists of decomposed or partially decomposed leaves, needles, twigs, and assorted organic debris on the forest floor. It is a rapidly replenishing C reservoir arising from decomposition.

1.6.4 Soils

Soils represent a substantial C storage reservoir, encompassing both mineral and organic C. Soil organic matter derives from the decomposition of plant and animal materials. Soil C can be a long-term storage pool, but its stability depends on factors like soil type and climate.

1.6.5 Wood products

This pool includes harvested wood used for various purposes, such as construction, furniture, and paper. The C stored in wood products can be released back into the atmosphere when they are burned or decomposed.

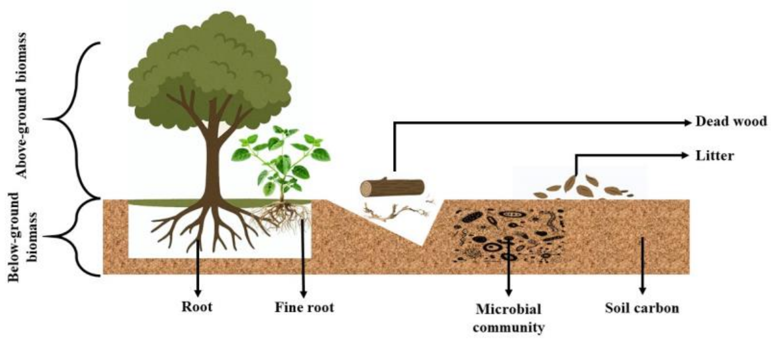


Figure 1.3: A simplified diagram showing the carbon pools of a forest.

1.7 Importance of forests in global climate

Burning of fossil fuels and deforestation are responsible for the elevated concentrations of atmospheric CO_2 (IPCC 2007). By the end of the twenty-first century, atmospheric concentrations of CO_2 will have doubled at the current rate of emissions. The United Nations formed the IPCC and the Kyoto Protocol, the first worldwide accord to reduce greenhouse gas emissions, under the UNFCCC in response to the threat of global warming. The goal of this protocol is to lower each country's greenhouse gas emissions between 2008 and 2012 by at least 5% as compared to 1990 levels (van Kooten 2000).

Forests are significant terrestrial ecosystem C sinks that can help alleviate the consequences of climate change. However, forests are subject to human and environmental influences, which can significantly vary how effective they are as C sinks. Given this, it is imperative to comprehend the primary drivers of forest dynamics and the ways in which they interact with the growth of human infrastructure and global climate change (McDowell *et al*. 2020). Recent research has demonstrated that both direct (such as deforestation) and indirect (such as invasive species) human activities result in a loss of biodiversity, land degradation, and major alterations in the structure of forests, all of which have a detrimental effect on the health of ecosystems. With only 40% of natural forests remaining in operation, the effects are understood to be substantial (Grantham *et al*. 2020). For instance, natural forests shift to younger stands with more uniformity and a poorer supply of ecosystem services following deforestation. Thus, it is critical to comprehend the mechanisms underlying vegetation dynamics in order to make precise projections on the future state of terrestrial ecosystems worldwide. To mitigate these effects, new methods of managing forests are required, such as safeguarding the forest cover and preserving ecosystem service provision at a level that is sustainable (Keith *et al*. 2014). By changing net productivity of a stand, or its net C exchange with the environment, various forestry practices can influence C stocks and fluxes (Fahey *et al*. 2010). Using techniques that account for long-term shifts in forest C dynamics at the landscape scale, one of these novel approaches, known as forest C management (FCM), seeks to increase C capacity and storage (Ameray *et al*. 2021). As a result, precise C stock calculations are now crucial for C accounting.

The gradual increase in the Earth's atmospheric average temperature caused by the absorption of heat from the sun into the atmosphere rather than its radiation into space is known as global warming. The Earth's atmosphere has always functioned as a greenhouse, retaining solar heat and maintaining a temperature on the planet that allowed life as we know it to evolve, including human existence. The Earth would be extremely cold in the absence of atmospheric greenhouses. But global warming is like high-efficiency reflecting glass fitted inside out in a greenhouse.

The IPCC suggested a number of ideas to be put into practice in its most recent report, which was released in April 2022. Indeed, according to UN climate experts, global warming is already posing a threat to between 3.3 billion and 3.6 billion people who live in "high-risk" areas (IPCC 2023). One billion people are predicted to reside in coastal regions at risk from rising sea levels by the year 2050. Furthermore, all of these effects on populations and ecosystems will happen faster, more frequently, and with greater severity than first anticipated.

The significance of forests and forest soils for accomplishing climate protection objectives is examined in this narrowly focused collection of studies. Since the UNFCCC (Grassi *et al*. 2021) was established, most national policies have concentrated on lowering emissions from the burning of fossil fuels, with relatively little attention paid to stabilizing or increasing the rate of carbon removal from the atmosphere. The UNFCCC 1992 set forth the goal of "stabilizing greenhouse gases in the atmosphere at levels that prevent dangerous anthropogenic interference with the climate system." The 2015 Paris Climate Agreement (UNFCCC 2015), which was adopted twenty-three years after the original climate agreement, gave particular attention to lowering emissions by safeguarding forests, preventing deforestation and degradation, and utilizing forests' capacity to absorb more CO_2 from the atmosphere was accepted (REDD+). Because the plans did not appropriately account for C credits from forest sinks under the requirements of the Paris Agreement, governments at the 25th Conference of the Parties in 2019 could not agree on C trading (Schneider *et al*. 2019). According to Solomon *et al*. (2009), climate scientists have realized that taking into account the complete C cycle is crucial to preventing excessive increases in atmospheric CO_2 that might cause dangerous climate change and irreversible warming.

According to the 1.5 degrees report of IPCC (IPCC 2018), the Paris Agreement asks for a 45% reduction in net emissions by 2030 and a net zero reduction by 2050. It also sets strict temperature restrictions. According to the 2019 UN Emissions Gap Report, net CO_2 emissions must decrease by 7.6% yearly to below 2010 levels over the next ten years starting in 2020 in order to reach the Paris commitments (The 2019 Emissions Gap Report by the United Nations). This calls for raising sequestration and lowering C emissions at the same time. Thus far, none of these attempts have yielded any fruit. Long-term C storage in plant biomass and soils is provided by forests and soils. Meeting the 1.5°C global temperature increase limit set forth in the Paris Climate Agreement requires accurate monitoring, reporting, and verification of carbon stocks and emissions (UNFCCC 2015). When it comes to forests, this entails precisely estimating the amount of C released into the atmosphere as a result of changing land use, taking into account emissions from soil erosion, forest management techniques, and the rates at which trees, forest soils, and forest products sequester carbon.

The current consensus is that one of the main causes of global warming is raising CO_2 and other greenhouse gas concentrations in the atmosphere. A total of 3.5 Pg (Pg = 1015 g or 1 billion tons) of C are added to the atmosphere year, primarily as a result of burning fossil fuels and the conversion of tropical forests for agricultural use (Paustian *et al*. 2000). It is believed that the rise in atmospheric concentrations of greenhouse gases (GHGs) is the primary cause of global warming, which is the recent increase in temperature of the Earth's surface atmosphere and seas. CO_2 is one of the main greenhouse gases.

Reducing greenhouse gas emissions in the atmosphere involves two primary actions (IPCC 2007). In light of these two options—reducing anthropogenic CO_2 emissions and storing atmospheric carbon in the biosphere—the following land use systems are suggested: Reforestation and silviculture are crucial components of agroforestry (Montagnini and Nair 2004). Forests have two main possibilities in light of the challenges surrounding global climate change and the reported rise in CO_2 concentrations in the atmosphere. First, a rise in forest biomass can lower atmospheric CO_2 levels. This can be done by enabling existing forests to accrue more biomass or by planting trees in regions that are currently devoid of forests. The second main strategy, known as bio-energy and thought to be a carbon-neutral energy source, involves using trees directly as a source of raw materials for energy production. The issue of CO_2 concentration is positively impacted by the use of bioenergy to replace fossil fuels (Van Kooten 2000).

The global carbon cycle depends heavily on forests (Dixon *et al*. 1994). The use of forests for C sequestration is an approach that has a lot of potential for lowering greenhouse gas emissions. Because forests absorb carbon dioxide, they are associated with climate change. Furthermore, 90% of the yearly C exchange between the atmosphere and terrestrial ecosystems is attributed to global forest ecosystems (Dixon *et al*. 1994). Compared to the 3 μg of C that is accumulated annually in the atmosphere, 0.5 to 1.5 μg of C may be saved annually on land by slowing down global land degradation, and especially by averting desertification (IPCC 2019).

Compared to shrubs and herbs, trees can increase soil C sequestration more effectively by generating significant amounts of biomass both above and below ground (Brady and Weil 2002). Both above-ground waste output and below-ground root activity increase with increased biomass. Research has demonstrated that the addition of trees to pasture or grassland systems can raise SOC levels considerably. The tree component of agroforestry systems has limited atmospheric C absorption potential, according to Montagnini and Nair (2004). Another argument for higher tree densities is that they produce more biomass above and below ground, which could lead to the accumulation of SOC through root and leaf breakdown and leaf litter.

1.8 Methods used to determine C stocks

Determination of forest C can be done by using various methods as described in Table 1.1. A combination of field measurements, remote sensing data, and modeling techniques is used to calculate forest C content. These methods help estimate the amount of C stored in different forest components like trees, soil, and undergrowth. Traditional methods rely on field inventories and allometric equations, while modern techniques leverage satellite imagery and LiDAR data for more comprehensive assessments. At the moment, diameter at breast height (dbh) is being used in allometric models based on tree density to estimate tree biomass C at the species level (Pandey *et al*. 2014). But given that basal area and biomass C have a strong correlation with dbh, an allometric model based on basal area might be a useful alternative for quickly calculating biomass C. The calculation of above-ground C stocks at the ecosystem level using tree biomass was greatly aided by this study.

Table 1.1 Various methods used for the determination of Carbon stocks.

Type	Name of methods	Description	Reference
Field Measurements	Forest inventories	Involve measuring tree diameter, height, and density in designated plots to estimate aboveground biomass, which is then converted to C by using established factors. This method is more accurate but costly and time consuming	Picard *et al*. (2016)
	Soil sampling	Involves collecting soil samples from different depths and locations to determine soil organic C content, bulk density, and other relevant parameters. This method is more accurate but costly and time consuming	Black (1965)
Remote sensing	LiDAR (Light Detection and Ranging)	Provides detailed 3D information about forest structure, allowing for biomass estimation and carbon stock assessment. It offers a powerful method for forest carbon measurements, with advantages like high accuracy and efficiency in mapping forest structure, but also faces limitations such as high initial costs and data processing complexities.	Reutebuch *et al*. (2005)
	Satellite imagery	Uses spectral data to map vegetation cover and estimate biomass, often in conjunction with field data for calibration offers significant advantages for forest C estimations, including broad spatial	Goetz *et al*. (2009)

		coverage, cost-effectiveness, and the ability to monitor changes over time. However, challenges like data variability, signal saturation in dense forests, and reliance on accurate calibration and modeling also exist.	
	Fusion Data	Integrates data from different remote sensing methods to improve accuracy and efficiency. It offers advantages like improved accuracy and broader coverage for forest C measurements, but can also present challenges related to data integration and cost	Kulawardhana *et al*. (2014)
Modelling	Ecosystem models	Simulate C cycling processes within an ecosystem based on various factors like climate, vegetation, and soil characteristics. It allows for large-scale estimations, can fill data gaps, and helps predict future carbon dynamics. However, it faces challenges related to data accuracy, model complexity, and the ability to capture the full range of factors influencing carbon cycling.	Quijas *et al*. (2018)
	Statistical models	Use statistical relationships between measured variables (e.g., tree size, biomass) to predict C stocks. It offers a relatively quick and scalable approach, especially useful for large areas. However, it can be less accurate than direct	Khan *et al*. (2020)

		measurements and may not capture the full complexity of carbon storage, particularly in heterogeneous environments or with varying species	
Tiered Approach (IPCC Guidelines):	Tier 1	Uses default factors and equations for C stock estimation, suitable for countries with limited data. A key advantage is the ability to adapt the approach to different national circumstances and resource availability. However, Tier 1 may have limited accuracy.	IPCC (2006)
	Tier 2	Employs country-specific parameters and activity data for more accurate estimations.	IPCC (2006)
	Tier 3	Utilizes detailed models and inventory systems, requiring high-resolution data and thorough validation. Tier 3 requires significant resources and expertise.	IPCC (2006)
Inflow-outflow methods	Lifetime analysis	Estimates carbon outflow from harvested wood products based on assumed product lifespans. While they can capture the movement of carbon through different pools, they often require extensive data and can be complex to implement and validate.	Dias *et al.* (2009)
	Direct observation	Tracks carbon outflow through statistical data on harvested wood products. Advantages include the ability to account for carbon storage in wood	Dias *et al.* (2009)

		products and their potential to substitute for more carbon-intensive materials, potentially reducing overall emissions. Disadvantages include the complexity of tracking product lifecycles, potential uncertainties in data collection, and the challenge of accounting for carbon in products that are traded internationally	
Stock-Data Methods	Change in stocks	Estimates changes in carbon stocks by comparing carbon stocks at different points in time. While they can offer high accuracy for specific areas and are relatively cost-effective at the local level, they can be time-consuming, spatially limited, and struggle with large-scale estimations	Marziliano *et al*. (2017)

1.9 Methods for estimating soil organic C

The assessment of SOC employs two primary methodological categories: wet oxidation and dry combustion. Wet oxidation methods, like the Walkley and Black method (which uses $K_2Cr_2O_7$ and H_2SO_4 to oxidize soil organic carbon) and photometry (which analyzes the oxidized solutions), are easier to access but require dangerous chemicals and might not fully oxidize tough C, leading to inconsistent results that depend on the soil's minerals and texture. On the other hand, dry combustion methods avoid using chemicals but require very high temperatures: the Loss on Ignition (LOI) method estimates SOC by measuring how much mass is lost when soil is heated to 400–430°C, while Automated Dry Combustion (ADC) uses special machines to directly measure CO_2 released at 950–975°C after treating the soil with acid to remove inorganic carbon. While ADC is regarded as the benchmark for precision, its elevated cost and technical requirements restrict accessibility (Carmo and Silva 2012). Importantly, estimates of SOC can vary a lot between different methods because of differences in SOM makeup, clay levels, and carbonate effects, with SOC usually making up 50–58% of SOM, though this percentage can change. This methodological inconsistency hinders cross-study comparisons and global C stock evaluations, highlighting the necessity for standardized protocols (Nelson and Sommers 1996).

1.10 Difference between C pool and C stocks

Carbon sinks, like forests, actively remove CO_2 from the environment through photosynthesis. On the other hand, carbon pools, like the atmosphere and seas, are reservoirs that store C. Sinks absorb and store C, whereas pools store it, which helps to slow down climate change **(**Canadell *et al*. 2021**)**. The total amount of C stored in a given reservoir, such as the atmosphere, soil, oceans, living things, etc., is represented by a C stock, which is similar to a stockpile or reserve. It is the total amount of C that is awaiting its major release. On the other hand, a C pool is similar to a certain section of that reservoir where the C remains before being utilized.

The long-term storage of C in different man-made or natural reservoirs for extended periods of time is known as C storage. Terrestrial ecosystems (forests, grasslands, and soils), seas, geological formations (fossil fuels, carbonate rocks), and C-based products (wood products, construction materials) are examples of these reservoirs. Natural processes like the buildup of organic matter in soils and the development of vegetation in forests are examples of C storage, as are human-caused processes like the use of CCS technologies to store CO_2 emissions in subterranean geological formations.

The process of extracting and storing CO_2 from the environment or from industrial sources is known as C sequestration. This prevents CO_2 from being released back into the atmosphere, lowering greenhouse gas emissions and slowing down climate change. Both natural processes, like photosynthesis in plants, which takes CO_2 from the atmosphere and stores it in biomass and soil, and human interventions, like CCS technologies, which take CO_2 emissions from industrial sources and trap them underground for long-term storage, contribute to C sequestration. To summarize, C sequestration is the process of capturing and storing CO_2 in order to prevent its release into the atmosphere and thereby mitigate climate change, whereas C storage refers to the long-term storage of C in various reservoirs, including both natural and man-made processes. In the context of initiatives to lower greenhouse gas emissions and enhance the removal of C from the atmosphere, C sequestration is a C storage technique **(**IPCC 2022).

The biological, chemical, and physical characteristics of the soil determine the dynamic nature of the underlying soil C pools and fluxes (Schmidt *et al*. 2011, Tiemann and Grandy 2015). The long-term dynamics of total C stocks can be accurately predicted by widely used soil C simulation tools like the Century and Roth C models (Jenkinson *et al*. 1991, Parton *et al*. 1998), but the system quickly becomes unstable and shifts uncertainly in the expression of the soil C pool and its dynamics. For instance, the impacts of humidity and temperature on regulating decomposition rates have received a lot of attention (Davidson and Janssens 2006; Martinez-Moyano and Richardson 2013); however, the effects of environmental constraints on C transport and transformation have received less attention. It causes the organic materials in the soil to either stabilize or destabilize. Moreover, it is well known that soil C fractions in agricultural systems are quite sensitive to management **(**Lehmann *et al*. 2020**)**. Crow *et al*. (2018) highlight the dynamic elements of aggregate-protected C pools, which may affect how soil C reacts to upcoming changes since they are susceptible to inter annual changes in the soil environment. Prediction on changes in land use, management, and climate changes depends on the ability to comprehend the dynamic component of what is generally referred to as the mesoperiod C pool and to constrain the factors that control the size and responsiveness of this dynamic component.

Soil has a greater amount of carbon (C) than both the atmosphere and vegetation put together (Lal 2004). Even relatively slight changes in SOC in response to rising temperatures could release huge volumes of greenhouse gases into the atmosphere and exacerbate global climate change. It has been demonstrated that the initial size and spatial variability of the soil C pool have a significant impact on the influences of warming on soil C (Crowther *et al*. 2016).

Therefore, forecasting terrestrial cycle feed backs to climate warming and enhancing our understanding of ecosystem C dynamics depend on accurate estimation of soil C stocks and their regional variability. Climate change has recently brought greater attention to cold locations, where large volumes of SOC accumulate because of poor soil decomposition rates under prolonged cold weather conditions.

1.11 Carbon stocks in the major forest biomes of the world

Forests are the important C storage on Earth holding more carbon than any other terrestrial ecosystems. The major notable forests of the Earth are tropical, temperate, and boreal each of which have distinct carbon storage capacities (Figure 1.4).

1.11.1 Tropical forests

Tropical forests constitute the most extensive terrestrial C reservoir on the planet. Total ecosystem C stocks generally vary from 200 to 400 Mg C per hectare (Mg C/ha), allocated among components: 120–200 Mg C/ha in aboveground biomass (trees, canopy), 30–50 Mg C/ha in belowground biomass (roots), and 70–150 Mg C/ha in SOM (Pan *et al*. 2011, Baccini *et al*. 2017). These forests have considerable global importance, sequestering roughly 55–60% of the total C contained in the world's forests (Pan *et al*. 2011, Baccini *et al*. 2017). The most substantial regional reservoirs include the Amazon Basin (~120 Pg C), the Congo Basin (~60 Pg C), and the forests of Southeast Asia (~40 Pg C) (Saatchi *et al*. 2011). This vital C reservoir faces significant jeopardy due to deforestation, which is projected to emit 1–1.5 Pg of C into the atmosphere each year (Harris *et al*. 2021).

1.11.2 Boreal forests

Boreal forests, located in the northern high latitudes, are distinguished by substantial C reserves, predominantly sequestered in their soils. Total ecosystem C reserves vary between 200 and 500 Mg C/ha. Aboveground biomass has 30–60 Mg C/ha, belowground biomass contains 10–20 Mg C/ha, whilst the soil pool predominates with 150–400 Mg C/ha. Significantly, in vast peatland regions prevalent in boreal zones, soil C reserves can exceed 1,500 Mg C/ha (Bradshaw and Warkentin 2015, IPCC 2019). Soils comprise more than 80% of the total carbon sequestered in these forests, resulting in boreal forests containing approximately 30% of the global forest C (Bradshaw and Warkentin 2015, IPCC 2019). The principal reservoirs are Russia (about 110 Pg C) and Canada (approximately 60 Pg C) (Yu *et al*. 2010). A significant vulnerability exists in permafrost thaw induced by climate change, which might release 40–150 Pg C by the end of the century (Schuur *et al*. 2015).

1.11.3 Temperate forests

Temperate forests possess substantial C reserves and function as vital continuous C sinks. Total ecosystem C reserves typically range from 180 to 310 Mg C/ha. This is allocated as 80–150 Mg C/ha in aboveground biomass, 20–40 Mg C/ha in belowground biomass, and 80–120 Mg C/ha in soils. These forests are crucial for C sequestration, extracting a net 0.2–0.5 Pg C annually from the atmosphere (Luyssaert *et al*. 2010). Significant regional C reservoirs comprise the forests of the US Pacific Northwest (about 25 Pg C) and European forests (around 20 Pg C) (Keith *et al*. 2009). Forest management approaches substantially influence C storage capacity; specifically, old-growth forests are estimated to sequester nearly three times more C than logged forests (Law *et al*. 2018).

1.11.4 Global forest carbon

The global forest contain an estimated 550–650 Pg C when aggregating stocks across biomes. Tropical forests dominate the distribution (250–300 Pg C), followed by Boreal forests (200–230 Pg C) and Temperate forests (80–100 Pg C) (Pan *et al*. 2011, FAO 2020). These habitats collectively offer an essential climate regulation service. They sequester around 7.6 ± 1.3 Pg of CO_2 (equivalent to ~2.07 ± 0.35 Pg C) each annum (Friedlingstein *et al*. 2022). This substantial absorption counterbalances around 30% of worldwide anthropogenic CO_2 emissions annually. This essential C sink is compromised by land-use alterations, namely deforestation and forest degradation, resulting in a reduction of the global forest C sink by approximately 1.3 Pg C annually (Le Quéré *et al*. 2018).

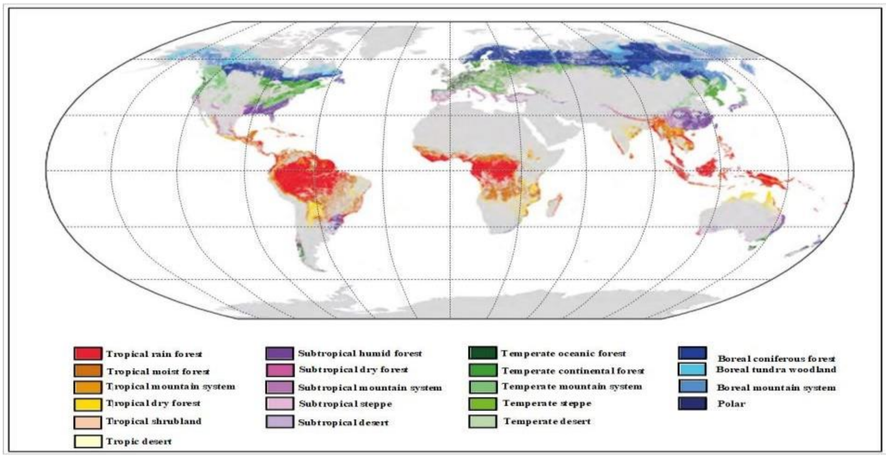


Figure 1.4: Map showing global forest cover of the world. Source: (FAO 2012, Buchhorn *et al.* 2019).

1.12 Forests of Bangladesh

Bangladesh has diverse forest ecosystems with tropical evergreen/semi-evergreen in the hill areas, deciduous Sal forests in the central and north-Western part, semi-deciduous in the north-eastern part and mangrove forests, particularly the Sundarbans in the south-western part of Bangladesh (Figure 1.5). The Ministry of Lands oversees certain portions of forests, while the Ministry of Forests is largely responsible for managing the forests of Bangladesh, the country. From an ecological perspective, forests of Bangladesh can be broadly divided into five categories.

1.12.1 Tropical evergreen or mixed hilly evergreen forest

Covering an area of 680,000 hectares, montane forests are mixed evergreen forests mostly found in northeast and southeast part of Bangladesh (Feeroz 2014). While there are still sizable tracts of mixed evergreen forests in the southeastern part of Chittagong Hill Tracts (CHT), the northeast forests are primarily fragmented. These forests are mostly home to *Dipterocarpus turbinatus*, *D. pilosus*, *Syzygium grande*, *Hopea odorata*, *Lophopetalum fimbriatum*, and *Duabunga sonnerationides*. Mixed evergreen woods are dominated by evergreen vegetation. The most significant kind of forest is a tropical mixed evergreen forest, where the majority of the tree species are Dipterocarps. The districts of Sylhet, Moulvibazar, Habiganj, Raghunamati, Bandarban, Khagrachari, Chittagong, and Cox's Bazar are home to the forested areas.

The forests in the hilly parts of Bangladesh are undergoing significant degradation as a result of agricultural growth, unsustainable land-use practices, and population pressure (Hossain *et al*. 2023). Alamgir and Al-Amin (2007) observed that natural forests of Bangladesh have diminished to fragments, with merely 11% of the land area of the country remaining wooded. The extensive degraded highland regions of the country, covering roughly 1.2 million hectares (MoEFCC 2022), might significantly contribute to climate change mitigation via reforestation and carbon credit creation under international frameworks such as the Paris Agreement. Forests offer vital ecosystem services, such as climate adaptation, biodiversity preservation, and support for the livelihoods of local communities (Sohel *et al*. 2009).

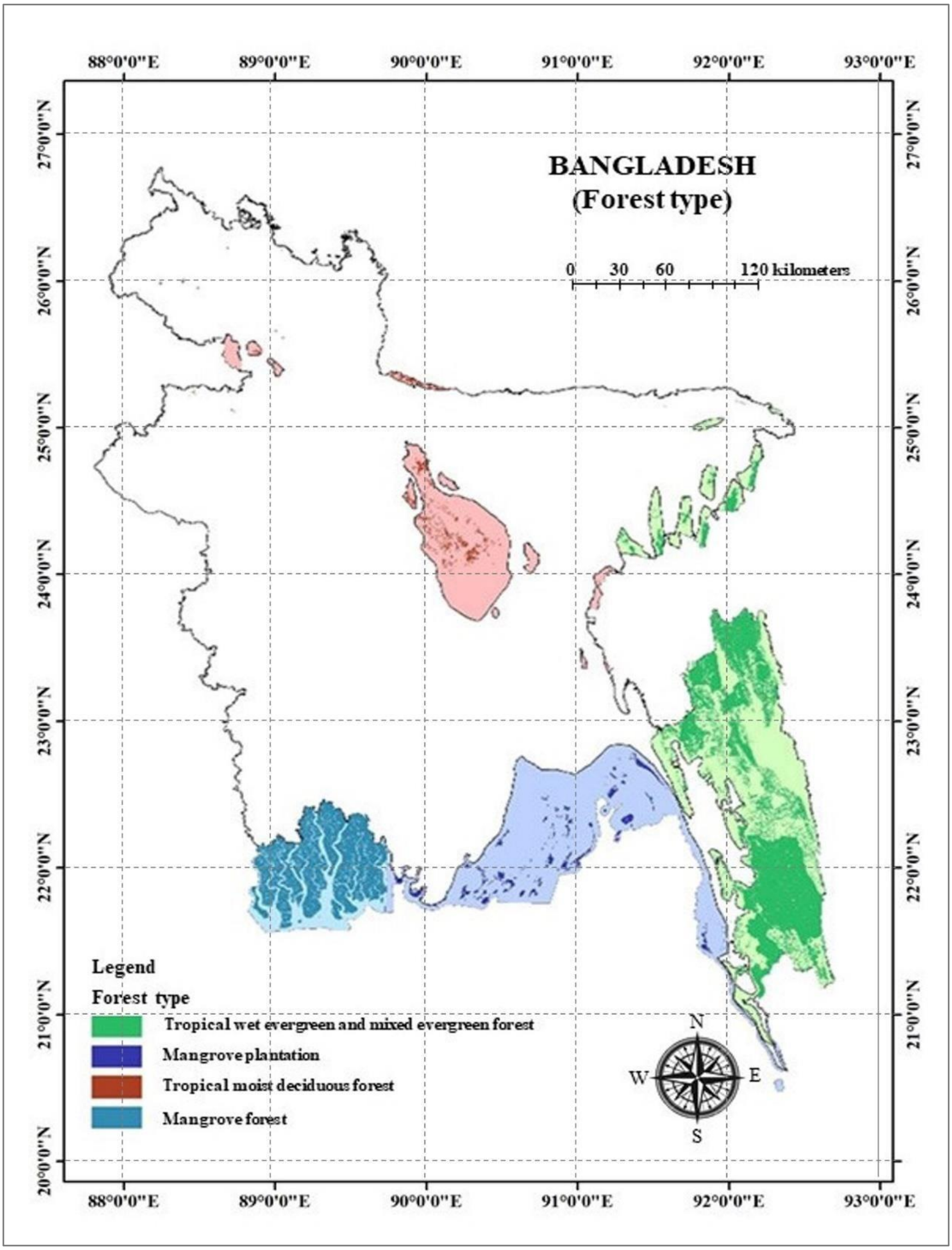


Figure 1.5: Map showing the distribution of different types of forests in Bangladesh.

1.12.2 Deciduous (Sal) forests

One of the important ecological features of the deciduous forest plants is to limit water loss through transpiration by having their main tree constituents lose their leaves in the winter or dry season. A significant portion of the principal floral composition in this type of forest is made up of *Shorea robusta* Roxb. *ex* Gaertn. Sal trees, which are the dominant species. The largest area of continuous deciduous forests in the nation is found in the central region. The districts that contain the forests are Rangpur, Dinajpur, Rajshahi, Mymensingh, Ghazipur, Tangail and Cumilla. Sal (*S. robusta*) is the dominant plant of this forest. The other species of this forest are *Butea monosperma*, *Careya arborea*, *Terminia belerica*, *Terminia chebula*, *Dillenia pentagyna*, *Aphanamixis polystachya*, *Streblus asper*, and *Phyllanthus emblica* (Mukul *et al*. 2014).

According to Hossain *et al*. (2010), the districts of Madhupur and Dinajpur are home to respectively moist and dry deciduous trees. Sal forests of Bangladesh are regarded as having some of the richest ecosystems when compared to other forests. Area of 1,21,884 hectares make up the whole Sal Forests, which accounts for 7.9% of the forest managed by the Forest Department and 0.83% of the nation's overall area of the country.

According to Alam (2008), Sal forests are found throughout the central and northern districts of Bangladesh. There are estimated 3.25 million cubic meters of timber in the Sal Forests, which is a rising stock. In accordance with a benefit-sharing arrangement with the nearby communities living in and around the forest region, a large-scale plantation operation is underway under the Social Forestry initiative (Khan *et al*. 2006). According to Chichele and Behera (2012), Sal forests are found in consociation and association depending on their location, the climate, and interspecific exchanges. The diversity of ground flora in Sal forest is high.

Despite the fact that Sal trees are the most significant species in the Sal forest, there have been reports of approximately 500 understory species growing along side Sal trees (Gain 2004). According to Alam (2006), the Sal forests are unique microclimatic ecosystem that contribute to the enormous association of undergrowth species. The ground floor of Sal forest is comprised of ferns, herbs, grass, and liana in addition to trees and shrubs (Gautam and Devoe 2004). Typically, these forested areas receive 2000 mm of rainfall annually (Dey 2007). Sal forests of Bangladesh are regarded as having some of the richest ecosystems when compared to other forests.

1.12.3 The Sundarbans mangrove forests

The mangrove forests span an area of 801,700 hectares along the Bay of Bengal. The Sundarbans, the biggest tract of productive mangrove forest in the world, make up 601,700 hectares of the whole coastal forest; 200,000 hectares are coastal plantations (Payo *et al*. 2016, Khan 2011). A reasonably dense variety of evergreen plant species that are suited to living in salty environments and experiencing periodic tidal floods can be found in the forest. The most frequently found species in this forests are *Heritiera fomes*, *Excoecaria agallocha*, *Sonneratia apelata*, *Avicennia officinalis*, *Avicennia alba*, *Hibiscus tiliaceus*, *Phoenix paludosa*, and *Acrostichum aureum*.

There are 269 different species of wild animals and 334 plant species in the Sundarbans. For significant portions of South Asia's endangered mega fauna, such as the Bengal tiger, Ganges and Irrawaddy dolphins, saltwater crocodiles, several endangered bird species, and at least 176 fish species, the Sundarbans currently serve as their only remaining habitat (Dey 2018, IUCN 2015). The predominant species in this forest is *Heritiera fomes* for which the name mangrove is derived from. In 2010, the International Union for Conservation of Nature (IUCN) Red List of Threatened Species included the mangrove as a "Threatened" species (IUCN 2000).

1.12.4 Freshwater swamp forests

The only fresh water swamp forest named Ratargul forest is located in the northeastern lowlands of Bangladesh. The dense canopy of the freshwater swamp forest is made up of flood-tolerant trees that are between 10 and 12 meters tall and have extensive root systems. *Barringtonia acutangual*, *Pongamia pinnata*, *Saccharomyces spontaneum*, *Phragmites calca*, *Acanthus ilisifolius*, *Alpinia arborescens*, and *Schumannianthus dichotoma* are the dominant tree species in this forest (Dey 2018, Khan 2018, Hossain *et al*. 2023). These trees are related to mangroves and spread their seeds in tidal flats through a process called hydrochory. More than two hundred and fifty different kinds of avian, terrestrial, and aquatic animals call freshwater swamp forests home (Dey 2018, Rahman *et al*. 2023**,** Hossain *et al*. 2024).

1.13 Carbon stock assessment of Bangladesh

Literature review shows that assessment of C stocks in the forest has just started and data are not substantial yet. Of the studies on C stock estimation in the forests ecosystems of Bangladesh, majority has focused on the coastal mangrove forest and some on the plantation forests while less attention has been paid on the deciduous Sal forests (Table 1.2). Mukul *et al*. (2014) showed that estimated total C stock in the forest ecosystems of Bangladesh was 251.8 million mg in 2014. Of that amount, an astounding 49.4% was stored in the mangrove forests of the Sundarbans. However, it is a rough estimate. Bangladesh lacks mangrove C stocks that are equivalent to those of other mangrove-rich nations.

Notwithstanding this potential, scant research has evaluated forests of Bangladesh as carbon sinks, partially attributable to insufficient biomass estimating techniques (e.g., dependence on obsolete allometric equations or restricted field measurements) (Ahmed *et al*. 2023). Advanced forest management and refined remote sensing techniques (e.g., LiDAR, satellite-based biomass mapping) are crucial for improving carbon sequestration strategies (IPCC 2022, Mukul *et al*. 2023).

C stocks must be evaluated at the national level using statistically verified methodologies in order to realize the maximum potential for C reduction (Mahmood *et al*. 2016). Bangladesh, being a Kyoto Protocol member, needs precise national C stock estimates in order to carry out CDM carbon trading schemes (Saatchi *et al*. 2011). The Bangladesh government has developed the REDD+ Readiness Road map (BFD 2018) and is currently gathering data on the country's C stock. Policy makers, researchers, and business people of the countries like Bangladesh will benefit from accurately estimating the amount of C sequestered by vegetation in order to more effectively market verified emissions reductions to wealthy nations in the form of global carbon (Ahmed and Glaser 2016, Ahmed *et al*. 2014). Owing to the requirement to counteract the rise in per capita C emissions, REDD+ and CDM-based markets (Al-Amin 2016, Shin *et al*. 2008). Bangladesh must estimate its C emissions in order to put mitigation measures in place for climate change (Miah and Shin 2009, Saatchi *et al*. 2011). Quantifying soil organic carbon, C from living trees, understory vegetation, woody debris, and C from the forest floor in the form of above- and below-ground C are all part of the estimation of C stocks (Gibbs *et al*. 2007, Patra *et al*. 2013).

Researchers in Bangladesh created an allometric model after estimating C stocks in various regions of the nation using different methods. But the majority of estimates that are now available only take into account a small number of variables, ignoring the enormous C stores that ecosystems hold (Donato *et al*. 2011, Miah and Shin 2009).The majority of studies include allometric equations for a few common species of palms, shrubs, and trees (Mahmood *et al*. 2016).

Agroforestry initiatives that combine afforestation and reforestation with forest conservation, particularly in tropical regions, can significantly contribute to the mitigation of global climate change. Additionally, because many plant species have the capacity to store C, they may also serve as a carbon sequestration strategy. They are significant atmospheric C sinks due to their quick development and great productivity of sequestering carbon (Montagnini and Nair 2004). It is possible to absorb C and lessen the effects of climate change by incorporating trees into agricultural production systems such as agroforestry, community forests, village forest plots, and road planting under participatory management (Rahman *et al*. 2015). Agroforestry now covers 1.023 billion hectares worldwide (Nair *et al*. 2009).

The community targets landless and land-poor individuals as well as rural women from nearby rural regions as program participants for the roadside plantation. Roadside tree planting is a popular practice in Bangladesh as part of participatory forest management; it may help augment livelihoods and store C, but it has not been considered in research up to this point, especially when assessing C storage.

Table1.2 Studies on estimation of carbon stocks in forest ecosystems of Bangladesh.

Sl. No.	Ecosystem	Description	Reference
1	Homestead forest	176 homestead forests at three altitudes in the Chittagong Hill Tracts were surveyed to estimate C stocks. Woody vegetations, litter and soil (0–30 cm depth) were sampled in the study.	Baul *et al*. (2021)
2	Homestead forests	Drivers affecting carbon stocks of homestead forests	Baul *et al*. (2021)
3	Roadside plantation	Carbon stock in participatory roadside plantation	Rahman *et al*. (2015)
4	Sundarbans mangrove forest	Oligohaline zone of the Sundarbans Reserve Forest was selected to study biomass accumulation and carbon storage.	Kamruzzaman *et al*. (2018)
5	Sundarbans mangrove forest	Carbon estimation in young mangrove plantation	Ahmed *et al*. (2022)
6	Sundarban mangrove forest	Stan structure, fine root production and carbon storage	Hredoy *et al*. (2023)
7	Tropical forests	Soil carbon stock in the tropical forest ecosystems	Saimun *et al*. (2021)
8	Coastal forests	Estimation of carbon storage in the plantation forest	Hoque *et al*. (2021)

1.14 Importance of determining C pools in the forests of Bangladesh

Anthropogenic greenhouse gas (GHG) emissions, mainly CO_2 from the burning of fossil fuels in both industrial and non-industrial processes, have been linked to global warming, changes in land use including deforestation (Fearnside 2006, Houghton 2005, Nordell 2003). Between 2002 and 2019, global humid tropical forests had a projected loss of 4.1 (±0.6) million hectares annually, with secondary forests and fragmentation intensifying the deterioration (Tyukavina *et al*. 2022). Previous studies (Achard *et al*. 2002, Mayo *et al*. 2005) reported high annual losses (5.8 ± 1.4 Mha/year throughout the 1990s); however, improvements in remote sensing have improved these estimates.

Studies have drawn attention to the stark disparity in the global distribution of income and greenhouse gas emissions between different regions. According to an analysis by Crum *et al*. (2000), the relative importance of different gases and emission sources varies by geography. Developing countries currently contribute about 48% of global CO_2 emissions, but under business-as-usual scenarios, their share is projected to rise to 65–75% by 2050 due to rapid industrialization and population growth (IEA 2023, IPCC AR6 2022). These countries now earn between 58 and 71% of their overall income, up from only 16% in 1990. Research indicates that anticipated climate change effects differ markedly based on the population size, economic development, and adaptive capabilities of poor countries (IPCC 2022). For instance, low-income countries with high population densities face disproportionately severe risks compared to wealthier nations, even under similar climatic changes (Diffenbaugh and Burke 2019, Callahan and Mankin 2023).

In its Special Report on Land Use, Land Use Change, and Forests, the IPCC states that forestry operations and land use change have a chance to have a beneficial impact on the C cycle (IPCC 2000). FAO (2001) proposes three potential approaches to managing forest C. The first is to create or enhance C sinks in order to increase the amount or pace of C buildup. The second is to stop or minimize the release of C that has already been stored in C sinks that are now in place. A third tactic is to decrease the need for fossil fuels by using more wood in the form of biofuels (which replace C) or durable timber goods (which replace items that require a lot of energy, like steel and concrete). Many C sequestration and conservation projects have already been developed, including the Land Use Change and Forest Carbon Project (FAO 2001) and the Action Jointly Implemented under the UNFCCC (AIJ). According to estimates done by others (Hansen *et al*. 2004; Cannell 2003; Pussinen *et al*. 1997; Karjalainen 1996), Ravindranath and Somashekhar (1995), Ismail (1995), C stored by national forests and afforestation/reforestation (A/R) initiatives is estimated. Depending on the species, location, and management practices, forests have varying capacities for sequestering C content. According to Brown *et al* (1996) hypothesis, there are 345 million hectares of land accessible worldwide for agroforestry and arable rice production. They calculated that throughout the next 50 years, about 38 Gt of C may be stored. For Bangladesh to achieve certified emission reductions (CER) and create CDM trees, the Kyoto Protocol's CDM legal framework must be incorporated. To attain domestic C credits, proper policy formation is also crucial. To realign Bangladesh to join international efforts to prevent global warming, it is critical to identify opportunities for forestry to do so.

Carbon storage is the process by which developing trees and plants actively absorb CO_2 from the atmosphere through photosynthesis and store it in their biomass (Matthews *et al*. 2000, Baez *et al*. 1977, Heath and Smith 2004). One way that helps reduce emissions and sequester C is through effective forest management (Sohel *et al*. 2009). In this situation, involving local populations in the implementation of C forestry is the best approach to achieving a green economy in Bangladesh. This is a viable method of repurposing air organic C as biomass. The primary goal of these non-cutting afforestation and reforestation techniques is to store CO_2 in the atmosphere (Rahman 2012). Additionally, some measures in currently-existing forests, like protecting secondary forests and other damaged forests and applying silviculture treatments, can assist raise the C stores of stands (Brown 1997).

Carbon storage by forestry is a possibility for some forest areas in the world. As a carbon sink, this forest absorbs and holds carbon. There are other biological processes that never change. The wealthy nations who emit the majority of CO_2 exchange the stored C credits (Rahman 2012). According to reports, a hectare of forest that is actively expanding may store between two and five tons of C annually (Brown 1996). Bangladesh has a huge potential for constructing C forestry (Rahman 2012).

Bangladesh may take into account exchanging forest biomass organic C with developed nations in accordance with the guidelines and protocols of the Kyoto Protocol (Sohel *et al*. 2009). In order to combat climate change and advance sustainable development, developing nations are able to expand their C forestry endeavors (UNFCCC 2002). Forest activities are acknowledged by the Kyoto Protocol as a sink for atmospheric C (IPCC 2000). Numerous programs for C sequestration and conservation such as REDD+ (MoEF 2012) and CDM (Miah *et al*. 2011), have already been taken. The Kyoto Protocol is significantly impacted by the legal structure of the CDM. In order to attain certified emission reductions (CER) as a non-Annex 1 nation, CDM forests are established in Bangladesh (Miah *et al*. 2011). Furthermore, the UNFCCC Mechanism to REDD+ offers a chance for the preservation of forest biodiversity and C credits Gardner *et al*. (2011). Some forest tree species in Bangladesh have the ability to store about 50% of C in their biomass (Akter 2011). Thus, wealthier nations might exchange this C credit stored in these tree species (Rahman 2012). Thus, Bangladesh can contribute significantly to reducing global warming through plantation and conservation of natural forests. Understanding the capacity of various species to sequester C in various types of plantations is crucial for the forestry sector of Bangladesh to reach its full emission reduction potential (Miah *et al*. 2011). Accordingly, in order to comprehend the uptake and storage of C by forest trees, one must grasp the idea of C sequestration (Bass *et al*. 2000). Particularly, in natural hill forests of Bangladesh, the potential organic C in forest stands is roughly 92 t C/ha (Miah *et al*. 2011). Research shows that, depending on species, age, and silvicultural methods, C stocks in managed plantations normally vary between 150 and 300 tons C/ha (Pandey *et al*. 2022). According to Brown *et al*. (1993), the actual biomass for Asian soils was 148 t C/ha, while the potential biomass was 255 t C/ha. Nonetheless, there is a lot of room for forests of Bangladesh to be transformed into C forests without sacrificing the environment. Although similar research has been done all over the world, there have been no findings on C pool dynamics in forests of Bangladesh to date. However, acquiring this knowledge is essential for improving our comprehension of how to respond to environmental threats, particularly in the context of scenarios involving global climate change.

1.15 Objectives

The primary goal of this study was to examine the concentrations and dynamics of soil C, litter biomass C and aboveground and belowground plant biomass C in the Sal forests spread across Bangladesh. The main goal of the study was to investigate the dynamics of soil C in these important forests of the country.

The specific objectives of this study were to:

- compare the soil C pools (litter, fine roots, aboveground plants and soil organic matter) among the three selected forests such as Madhupur Sal forest, Cumilla Sal forest, and Singra National Park,
- investigate the seasonal dynamics of the soil organic C components (soil, litter and plants) of Sal forests,
- study the decomposition and nutrient mineralization patterns of Sal leaf litter, and
- examine the temporal dynamics of soil bacterial community of a selected Sal forest.

CHAPTER 2

MATERIALS AND METHODS

2.1 Vegetation structure of the study area

2.1.1 Study site description

The tropical deciduous forests dominated by Sal (*Shorea robusta* Gaertn. f.) have fairly wide and interrupted distribution in the drier central and northern parts in the mainland of Bangladesh (Rahman *et al*. 2010). Sal forests mainly occur in the Gazipur, Tangail, Mymensingh, Jamalpur, Cumilla, Sylhet, Dinajpur, Thakurgaon, Rangpur, and Rajshahi districts (Figure 2.1). Geographically, these forests can be divided into two categories: the central plain land Sal forest and the northern plain land Sal forest. This central region holds about 86% of the Sal forest land, while the remaining 14% is located in the northern part of the country (Alam *et al*. 2008). Sal Forest lies on Plio-Pleistocene terraces in the central part of Bangladesh (Hassan 1999). The majority of the Sal forests lie in the districts of greater Mymensingh, Tangail and Gazipur. The present study selected Madhupur Sal Forest, Lalmai Sal Forest, and Singra Sal Forest to understand the vegetation sturcture of the deciduous Sal forest of Bangladesh.

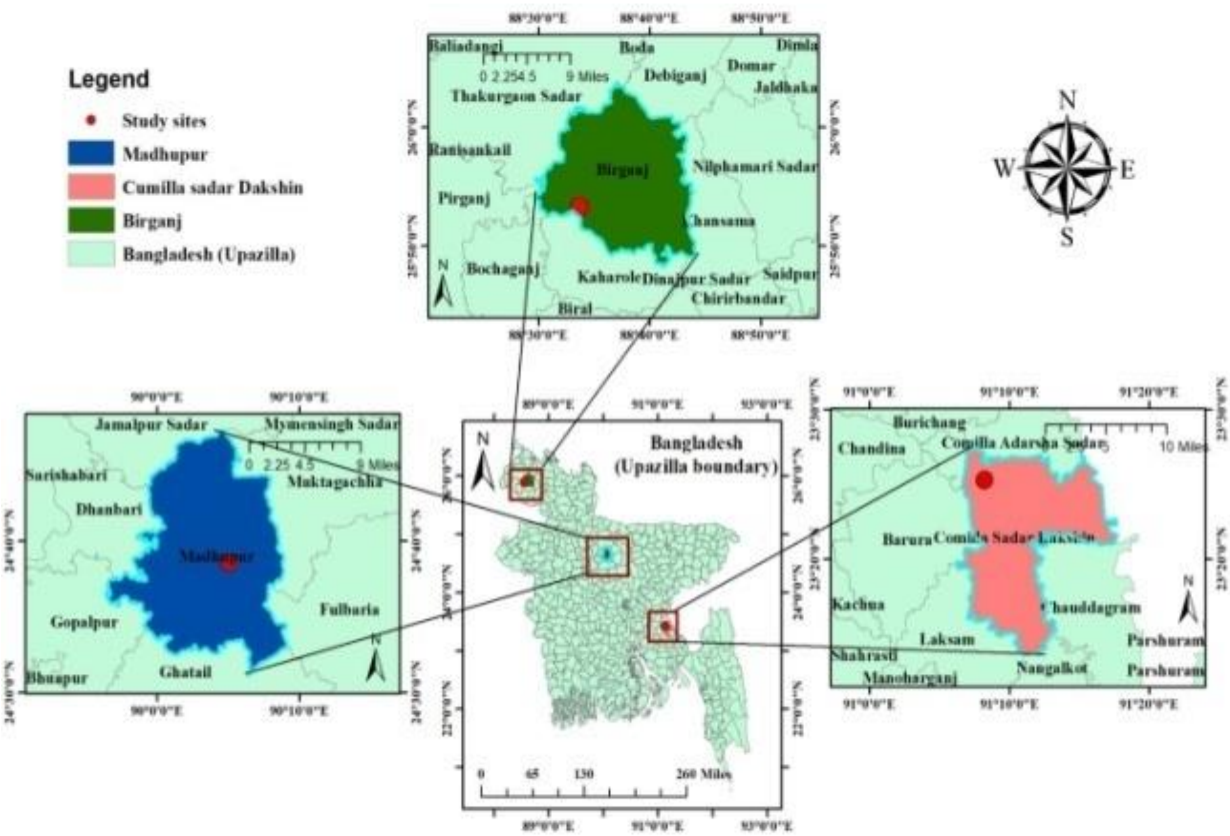


Figure 2.1: Map of Bangladesh showing the distribution of Sal (*Shorea robusta* Gaertn.) forests selected for the present study.

2.1.1.1 Deciduous forests in Bangladesh

The dominant tree species in a deciduous forest shed their leaves during winter or the dry season to reduce water loss through transpiration (Souza *et al.* 2020). The Sal tree (*S. robusta*) predominates in this forest type, comprising approximately 90% of the major floral composition (Uddin *et al.* 2021). Bangladesh features two types of Sal forests: moist deciduous and dry deciduous. Madhupur subdistrict features moist deciduous trees, but Dinajpur district is characterized by dry deciduous trees (Hossain *et al.* 2010). Sal forests constitute one of the most prosperous ecosystems relative to other forests in Bangladesh. Sal forests encompass 120,000 hectares, representing 0.83 percent of the total land area and 7.9 percent of the forestland managed by the Forest Department (Roy F. S. 2004, Khan *et* *al*. 2007). Sal forests are located in the central and northern areas of Bangladesh (Alam *et al*. 2008). A substantial planting initiative is in progress as part of the Social Forestry program, which operates on a benefit-sharing framework with local populations residing in and near the forest area (Khan *et al*. 2007). Sal forests exist in association and consociation, influenced by location, climatic conditions, and interspecific interactions (Chitale 2012). The floral diversity of the Sal forest is comparatively high. Although Sal is the predominant tree species in the Sal forest, around 500 undergrowth species have been documented in this forest (Hossain *et al*. 2013). Alongside trees and shrubs, the Sal forest ecosystem comprises ferns, herbs, grasses, and lianas (Gautam and Devoe, 2006). The annual precipitation in these forested regions is often approximately 2000 mm (Dey & K. 2007).

2.1.1.2 Distribution of Sal forests in Bangladesh

Sal forests comprise around 32% of the nation's total forested area (Mia *et al*. 2016). Gazipur, Tangail, Mymensingh, Cumilla, Dinajpur, Sherpur, and Naogaon are the most populous districts (Figure 2.2). The Madhupur Sal forests, sometimes referred to as Madhupur Garh, constitute the largest Sal forest belt in the nation. These forests are exclusively located in gently elevated areas, not exceeding 15 meters above the floodplain. Numerous other notable natural tree species, referred to as Sal allies, are also present in the forest (Hassan 2004). The forest is located between 23°50' and 24°50'N latitude and 89°54' and 90°50'E longitude. The soil is a highly oxidized reddish-brown clay including ferruginous nodules and manganese patches, situated within the bio-ecological zone of the Madhupur Sal Tract (Nishat *et al*. 2002). The soils exhibit a mild to high acidic reaction and lack organic matter and fertility (Alam 1995). The Madhupur Sal growing zone is categorized as a humid area according to Thornthwaite's classification. Over the past 30 years, average annual precipitation ranged from 2030 to 2290 mm, temperature varied between 10 and 34°C, and humidity levels between 60 and 86% in this site. Daily sunshine length of 5–9 hours and an average maximum wind velocity of 16 km/h. Sal forests are one of the most prosperous ecosystems relative to other forests in this country (Hossain *et al*. 2017).

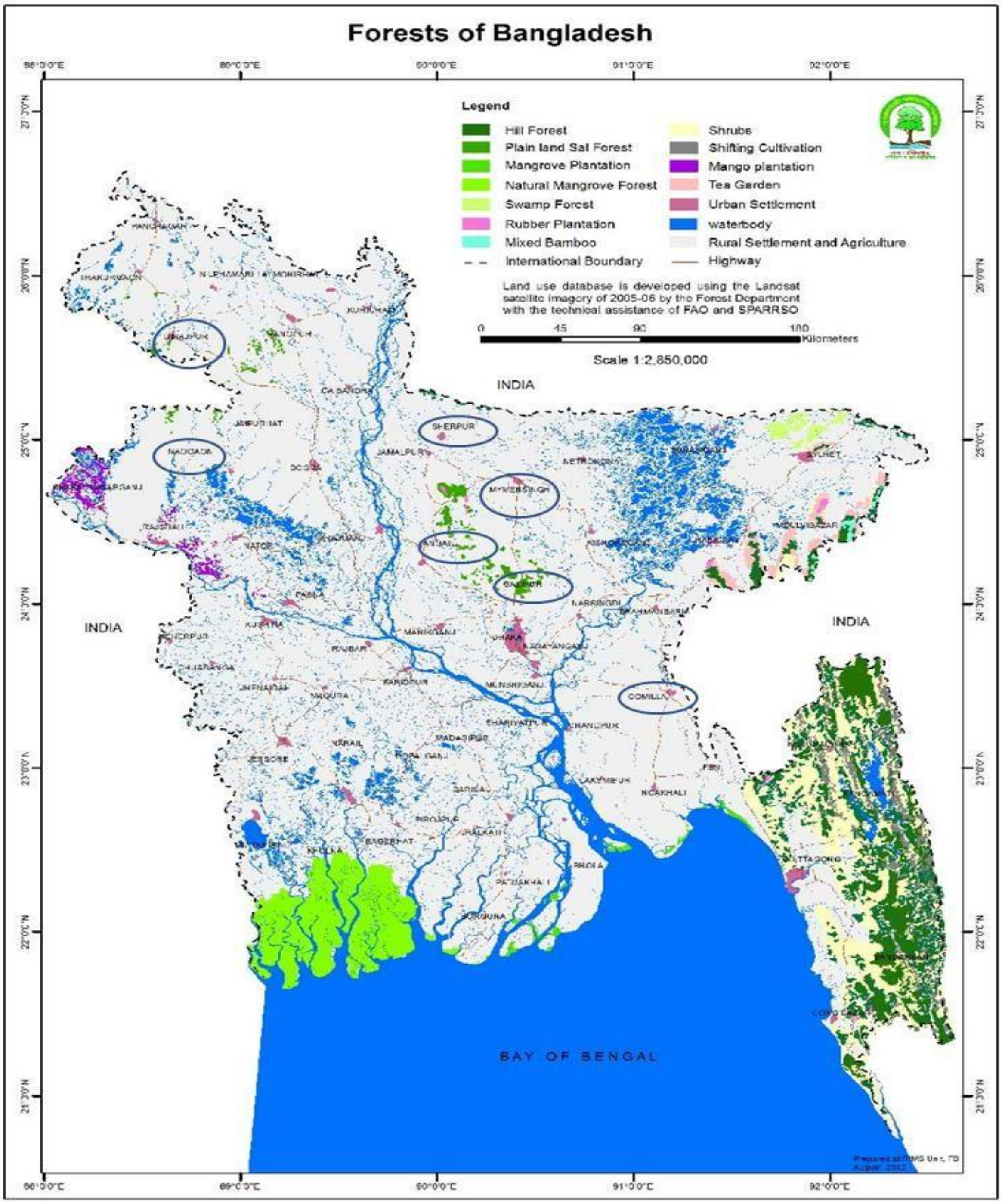


Figure 2.2: Map showing the distribution of Sal forests (Oval shape) in Bangladesh.

2.1.1.2.1 Madhupur Forest

Madhupur Sal Forest, also known as "Madhupur Garh" (Rasul 2009), is located in Madhupur Sub-district, which is part of Tangail district (Figure 2.2). It is situated 80 km north-east of Dhaka. It is located from 24.30^0 to 24.50^0 on the north axis and 90^0 to 90.10^0 on the east longitude. In the north-west of the forest, there is Jamalpur district; in the south-west, there are Madhupur and Dhonbari Upazillas of Tangail district; and in the east, there are Muktagacha and Fulbaria Upazillas of Mymensing district. The total area of Madhupur Sal forest is 45,565.18 acres, out of which 2,525.14 acres are declared as reserved forests, and the remaining 43,039.04 acres of land are in the process of being declared reserved forests (Sarker *et al*. 2018). In a gazette notification on February 24, 1982, the government of Bangladesh declared Madhupur National Park, comprising an area of 20,837.23 acres, for the purpose of biodiversity conservation. Out of that, 20,244.23 acres are under Madhupur Upazilla under the district of Tangail, and 593.00 acres are under Muktagacha in Mymensing district. The tropical deciduous forest *S. robusta*, commonly known as 'Sal', originally covered the area.

Some studies indicate that 70%-75% of the trees in Madhupur Sal forest are *S. robusta* (Malakar *et al*. 2010, Kashem *et al*. 2015). A total of 174 plant species under 131 genera and 54 families have been recorded in the Madhupur Sal forest, including about 102 tree species, 17 shrub species, 34 herbaceous species and 21 climber species (Malakar *et al*. 2010). Some species have been artificially cultivated, with *S. robusta* being the dominant tree species throughout the forest (Hossain *et al*. 2010, Kashem *et al*. 2015). Some photographs of the vegetation of Madhupur Sal Forest are shown in Figure 2.3.

Figure 2.3: Photographs showing the vegetation of Madhupur Sal Forest in Bangladesh.

Figure 2.3 (Contd.): Photographs showing the vegetation of Madhupur Sal Forest in Bangladesh.

2.1.1.2.2 Lalmai Sal Forest

Lalmai Forest is located in Cumilla district, about 8 kilometers west of Cumilla City. The hills are commonly known as the Mainamati-Lalmai range. Lalmai hill region is located between 23°25′18.8472″N to 23°2520.9424″N latitude and 91°8′12.0084″E to 91°8′12.444″E longitude (Fig 2.1). This forest is a tropical, moist deciduous forest. The total forest area in Kotbari is about 500 acres, of which 15 are natural Sal forests. The Chittagong-Tripura Fold Belt, particularly the Raghunandan hill of Indian Tripura hills, borders this region to the east, the Meghna river to the west, the Gumti river to the north, and the Dakatia river to the south-southeast (Khan *et al*. 2018). It consists of a north-south elongated low hill range of about 17 km long and 1-2.4 km wide, covering an area of about 33 sq km; locally, it is known as the Mainamati-Lalmai range (Islam 2021).

The climate of this regions' typically humid tropical, with hot, oppressive, and mostly cloudy wet seasons as well as warm, mostly clear dry seasons. A long, dry season usually extends from October to May of the year. The hot season lasts from March to June, and in this season, the maximum temperature ranges from 37°C to 39°C (https://en.banglapedia.org). The cool season lasts from December to January, and in this season, the minimum temperature varies from 7°C to 10°C. The temperature typically varies from 12°C to 33°C over the course of the year, the average temperature is 23°C to 35°C, and the hottest period occurs from June to mid-July. The area experiences extreme seasonal variation in monthly rainfall. The rainy period of the year lasts for 10 months, from February to November. The rainless period of the year lasts for two months, from December to January. The average rainfall is 1930–2700 mm, the average humidity is 67%, and about 90% of rainfall occurs in the months of May–October (https://weatherspark.com). This area primarily consists of fine Madhupur clay soil, which becomes extremely hard during the dry season (https://en.banglapedia.org).

This soil type is characterized by unconsolidated structure, fine texture (silt-loam to clay-loam), moderate drainage (hydraulic conductivity: 5–15 cm/day), strong acidity (pH 4.0–5.5), low nutrient availability (especially N, P, K), and limited water-holding capacity, making it prone to drought stress (Brady and Weil 2022, Adhikari *et al*. 2023). The topsoil is sandy-clay-loam to clay-loam in texture and yellowish-brown in color. The underlying subsoil is brown to yellowish-red. BBS (2013) earmarked an area near Kotbari as a forest belt, and the Lalmai hills were once densely wooded.

The vegetation was mainly deciduous, and the dominant tree species was *S. robusta* C.F. Gaertn (Sal) (Rahman *et al*. 2001). However, over the past 20 years, vegetation of this area has transformed into a semi-deciduous and mixed evergreen category, primarily consisting of planted forests, many naturally occurring plant species, and a few small patches of *S. robusta* forest. Some photographs of the vegetation of Lalmai Sal Forest are shown in Figure 2.4.

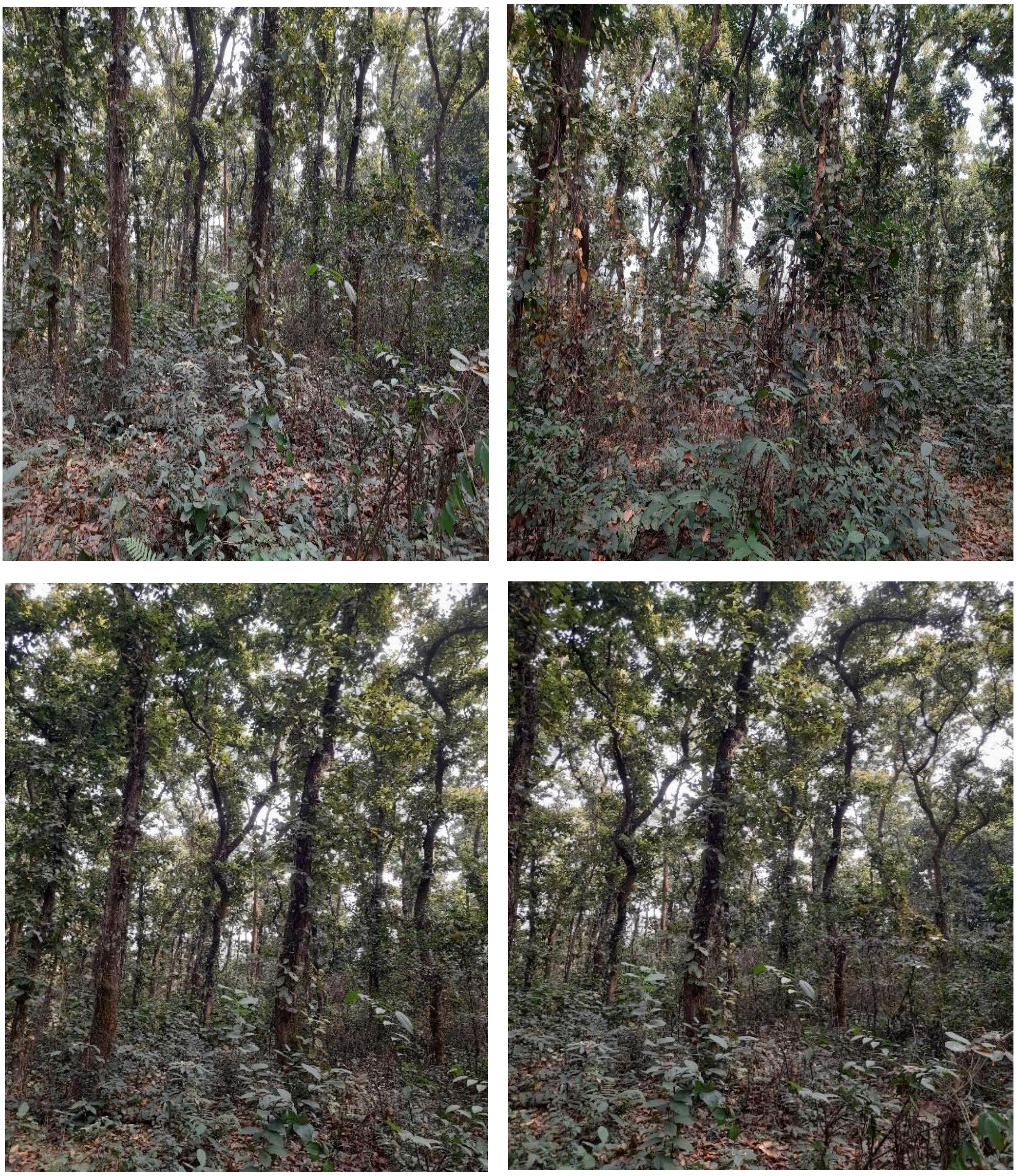


Figure 2.4: Photographs showing the vegetation of Lalmai Sal Forest. Cumilla, Bangladesh.

Figure 2.4 (Contd.): Photographs showing the vegetation of Lalmai Sal Forest. Cumilla, Bangladesh.

2.1.1.2.3 Singra National Park

Singra beat in Birganj upazila of Dinajpur district of Thakurgaon Range is under Dinajpur Forest Division (Fig. 2.1) locally it is known as Singra Sal forest which is about 40 km away from Dinajpur Sadar and 15 km away from Birgonj Upazila. Total area of Singra forest is about 355 ha. Of the total area, 305 ha of this forest is declared as national Park in 2010 (Chowdhury *et al*. 2017). Four rivers named Dalagram, Chawlia, Singra and the river Norto Nodi have passed in this area.

Singra National Park is an exceptional biodiversity rich region at the north of Bangladesh. This park of Sal forest still sustains many a rare plant and wildlife. Sal forest is a traditional forest of Bangladesh. Sal plant of this forest is the prevailing tree that re-sprouts from its remaining stump after being cut. For this trait, the forest is locally known as Gajari forest too. It is located from 25.889277^0 to 25.10^0 North latitude and 88.560535^0 to 88.60^0 East longitude (Rahman *et al*. 2021). Bhognagar Union is a remote area of Birganj Upazila, Dinajpur district. Singra Sal forest is situated in this Union. Geographically, Singra National Park is mostly flat and its land formation is different from hill forest or the Sundarbans. The park soil is radish or yellowish in color, as its mildly acidic containing iron and aluminium. Annual average highest temperature 33.5^0C and lowest 10.5^0C. Annual rainfall is also limited (2,536 mm) (Hossain *et al*. 2021).

Various plant species have flourished on this rugged soil. A diverse ecosystem has flourished centering the dominant species Sal tree. Along with Sal, trees like silk cotton (*Bombax ceiba*), golden shower (*Cassia fistula*), myrobalan (*Phyllanthus emblica*), Bahera (*Terminalia bellirica*), Arjun (*Terminalia arjuna*) and Queens's crape myrtle (*Lagerstroemia speciosa*) are seen in the forest. Herbs and shrubs include plant species like Muyna (*Meyna laxiflora*), Wild turmeric (*Curcuma aromatica*), these plants make the park a dense forest.

Various species of climbers grow in the forest. They climb spirally using tree trunks (Uddin S. N. 2012). Some photographs of the vegetation of Singra National Park are shown in Figure 2.5.

Figure 2.5: Photographs showing the vegetation of Singra National Park, Dinajpur, Bangladesh.

Figure 2.5 (Contd.): Photographs showing the vegetation of Singra National Park, Dinajpur, Bangladesh.

2.1.2 Collection of vegetation data

Vegetation data were collected using the quadrat method. Quadrats of 10 m × 10 m in size were used to collect data from different sites of naturally growing Sal forests such as Madhupur Forest, Lalmai Forest and Singra National Park selected in the present study. Quadrats were placed 50 m away from each other. Plant species were identified after establishing quadrat in selected locations of natural Sal forest sites and their numbers per quadrat were recorded. Plants that could not be identified in the field were brought to the laboratory for identification using herbarium sheets and were identified by comparing those with specimens at the Salar Khan Herbarium, Department of Botany, University of Dhaka.

2.1.3 Shannon-Wiener Index (Diversity Index)

Diversity index was calculated to measure the species diversity and community composition in different forest sites and national parks as well. The Shannon-Wiener diversity index (Shannon and Wiener 1963) was calculated from the following formula given by Magurran (1988):

Shannon-Wiener Index (Diversity Index) was determined by following equation as:

$$H = -\sum p_i \, (ln\, p_i)$$

Where, p_i is the proportion of the *i*th species and the number of all individuals of all species (n_i/N).

Dominant and rare species were determined

2.1.4 Importance Value Index (IVI)

The Importance Value Index (IVI) was measured to know the structural role and dominance of the species on the basis of relative frequency, abundance and dominance.

The relative values of frequency, abundance and density for each single species were used to calculate IVI plot wise according to:

Frequency = $\frac{Total\ number\ of\ quadrats\ in\ which\ the\ species\ occured}{Total\ number\ of\ quadrats\ studied}$

Abundance = $\frac{Total\ number\ of\ an\ individual\ present\ in\ all\ quadrats}{Number\ of\ quadrats\ in\ which\ species\ occur}$

Density = $\frac{Total\ number\ of\ an\ individual\ present\ in\ all\ quadrats}{Number\ of\ quadrats\ studied}$

Relative Frequency = $\frac{Frequency\ of\ a\ species}{Total\ frequency\ of\ all\ species} \times 100$

Relative Abunance = $\frac{Abundance\ of\ a\ species}{Total\ abundance\ of\ all\ species} \times 100$

Relative Density = $\frac{Density\ of\ a\ species}{Total\ density\ of\ all\ species} \times 100$

IVI (Importance Value Index) = Relative density + Relative frequency + Relative Dominance

2.2 Comparison of soil C pools among the forests

The pools show considerable variance among the three Sal forests, indicating disparities in forest integrity, disturbance history, and conservation status. Madhupur Forest, despite its vast expanse and historical prominence, exhibited low SOC stocks owing to sustained anthropogenic pressures (e.g., encroachment, selective logging), which hastened organic matter mineralization (Singh *et al*. 2022). In contrast, Singra National Park (protected since 2010) had the highest SOC pools due to minimal disturbance, a closed-canopy structure that promotes litter accumulation, and augmented fine-root biomass that improves belowground carbon input (Rahman *et al*. 2023). This aligns with global studies linking protected-area designation to enhanced carbon sequestration (Maxwell *et al*. 2020). Lalmai forest had the lowest soil organic carbon levels, indicative of its significant degradation: hardly 15 acres of natural Sal persist, and the transition to mixed-evergreen species has diminished the resistant litter (e.g., Sal leaves) essential for stable carbon synthesis (Khan *et al*. 2018, Sarker *et al*. 2021).

2.2.1 Outline of the Study

Carbon pools were studied by collecting samples from the sources of litter, fine roots and soil at different seasons, laboratory experiment was also done in this regard. This study quantified carbon (C) pools across three selected Sal forests (Madhupur, Lalmai, and Singra) through multi-season field sampling and controlled decomposition experiments. Field collections targeted three critical C reservoirs: (1) litter (leaf litter in 50 × 50 cm quadrats), (2) fine roots (<2 mm diameter; stratified at 0–10, 10–20, and 20–30 cm depths), and (3) soil organic C (analyzed via the Walkley-Black method at corresponding depths). Sampling occurred in May 2016 (pre-monsoon) and December 2016 (post-monsoon) to resolve seasonal dynamics in C storage driven by litterfall phenology and microbial activity. Complementing field measurements, a 12-month reciprocal litter decomposition experiment (Section 2.2.3) incubated Sal litter from each forest in all three soil types to model site-specific C mineralization rates. Figure 2.6 synthesizes this integrated approach, visually mapping (i) spatial stratification across forest types, (ii) paired wet/dry season sampling design, and (iii) analytical linkages between field observations and experimental outcomes. This framework captures total ecosystem C stocks while revealing how edaphic properties and seasonal climate regulate C turnover—addressing critical knowledge gaps in tropical dry forest biogeochemistry (Powers *et al*. 2022, Rahman 2024).

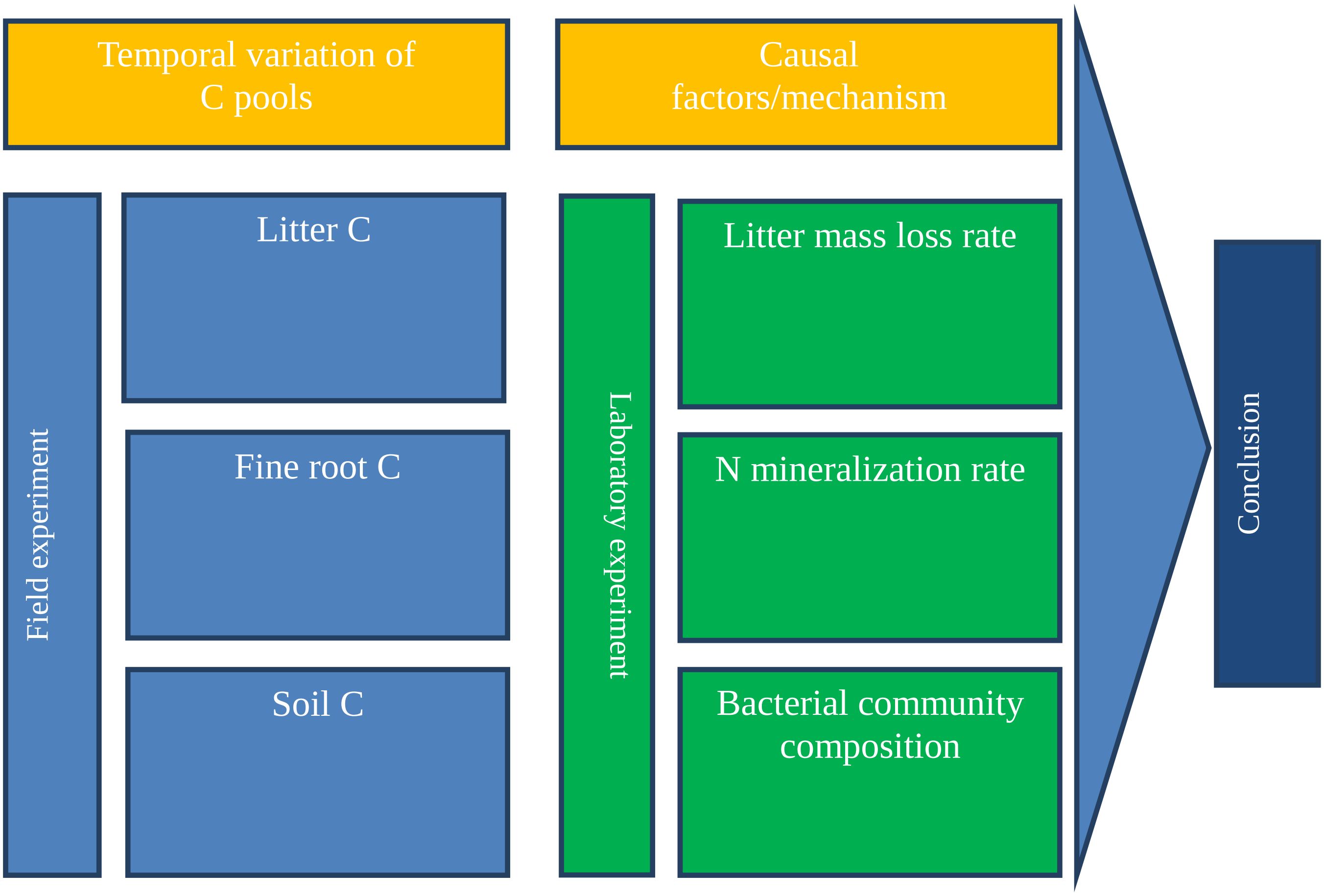


Figure 2.6: Layout of the comparative analysis of the seasonal dynamics of C pools of the study area.

2.2.2 Determination of tree biomass and C density

The height of the Sal tree species of the three selected forests was determined by applying the general rules of trigonometry as follows:

Tree height, $h = d \times \tan(A)$ + Observer's eye height

Two readings per tree (opposite sides) averaged to account for slope.

Where h is the height of the tree, d is the distance from the tree, and A is the angle of the tree top. To measure DBH (diameter at breast height) of the tree species, GBH (Girth at breast height) was measured using a tape measure at a height of 1.37 m per tree by following a standard method (Hossain 2022). DBH was determined from the GBH measurements using the formula $D = G/\pi$.

Only healthy, upright Sal trees with a GBH ≥ 30 cm were selected for height measurement to ensure consistency. Measurements were taken twice per tree (from opposite sides) to minimize errors caused by slope or irregular crown shapes. This method is widely used in tropical forestry for its non-destructive accuracy (Hossain 2022, Jucker *et al*. 2023).

2.2.2.1 Determination of tree biomass and C density

Carbon concentrations (t/ha) in tree biomass were quantified using non-destructive allometric equations. Aboveground biomass (AGB) of mature trees (GBH ≥ 30 cm) was estimated using the pantropical allometric model as per method described by Chave *et al*. (2005), incorporating wood density, height, and diameter at breast height (DBH).

$AGB = \exp(-2.187+0.916 \times \ln (\rho \times D^2 \times H))$

Where, AGB= Aboveground Biomass, D= Diameter, H= Height (m), ρ= Basic Wood Density

Aboveground biomass of juvenile tree populations (>10 cm- <30 cm GBH) was estimated by using allometric equations (Chaturvedi *et al*. 2012).

$AGB = 3.344+0.443 \times \ln (D^2)$

Mention D=Diameter

Wood specific gravity of each tree species mentioned was taken from published literature (Gisel *et al*. 1992, Cordero 2002, Mani and Parthasarathy 2007, Sundarapandian *et al*. 2014).

Belowground tree biomass (BGB) was calculated using the following formula (Kearns *et al*. 1997).

$BGB = \exp (-1.0587 + 0.8836 \times \ln (AGB))$

Belowground biomass of seedling tree populations was calculated by multiplying by 0.26 (Cairns *et al*. 1997).

Total carbon stock (TCS) was calculated by multiplying the total biomass (AGB+BGB) value by 0.4453 (Prado-Junior *et al*. 2016).

TCS = (AGB + BGB) x 0.445

GBH of mature plants was assumed to be greater than 30 cm. The shoot stage was considered when shoots continued to grow but did not reach full maturity with GBH > 10 cm. Tree biomass and C concentration (t/ha) of woody plants were measured using a non-destructive specific heat method. Aboveground biomass (AGB) of mature (GBH ≥ 30 cm) tree species was estimated using the colorimetric equation from (Chave *et al*. 2005).

2.2.2.2 Collection of leaf and soil samples

Plant and soil samples were collected by following standard methods. A quadrat of 10 m ×10 m in size was placed at each location in Madhupur Sal forest, Lalmai Sal forest and Singra National Park areas. A total of 9 quadrat were placed on 5 May 2016 and 5 quadrat on 14 December 2016 in Madhupur Sal forest. A total of 5 quadrat was placed on 21 May 2016 and 5 quadrat on 21 December 2016 in Lalmai Sal forest. Another 5 quadrats were placed in Singra Sal forest on 29 May 2016 and 24 December 2016.

During sampling, the fully expanded fresh leaves grown at the lowest height from the surface of soil. Soil samples were taken at depths of 0–10 cm, 10–20 cm and 20–30 cm. Leaf and soil samples were collected in plastic bags and brought to the Department of Botany, University of Dhaka for further analysis. The collected samples were labeled appropriately and sent to the laboratory as soon as possible. Leaf properties such as fresh leaf weight and dry leaf weight, soil properties such as pH, electrical conductivity, moisture and other soil chemical properties such as available N(%), total P(%), total organic C(%), Na and Ca were measured immediately after collection from the field.

Figure 2.7: Photographs showing collection of leaf and soil sampling from the study area.

2.2.2.3 Collection of litter and fine roots

Leaf litter and fine roots were collected from the three selected forest sites. Leaf litter was collected from a quadrat of 50 cm × 50 cm in size. Undecomposed leaf litter was collected from the surface of the forest floor (Figure 2.8). Litter collected from the field was kept in the polythene bag. Fine roots were collected at three depths (10 cm, 20 cm, and 30 cm) in each quadrat. Fine roots were collected using an auger. Fine roots were collected using a soil auger (stainless steel, 5 cm diameter) at three depths (10 cm, 20 cm, and 30 cm) within each quadrat. The auger enabled minimal soil disturbance, ensuring intact root systems were extracted. Post-extraction, adherent soil was meticulously washed from the roots, and samples were preserved in labeled polythene bags to avert moisture loss. This method aligns with standardized protocols for belowground biomass quantification (Freschet *et al*. 2021).

Fine roots collected along with the soil from the fields were kept in a polythene bag. Then, the samples were transported to the laboratory for further analysis. Dry roots were then separated from the soil using a 2 mm mesh sieve. Tap water was used to remove the soil from the roots. To measure dry biomass of leaf and root, all samples were placed in a 60°C oven for 24 h. Biomass of leaf litter and fine root was expressed per unit area.

Figure 2.8: Collection of litter samples from the selected Sal forests sites of Bangladesh.

2.2.3 Analysis of soil sample

2.2.3.1 Determination of soil pH

Soil pH was measured immediately after arrival at the laboratory within 24 hours of collection from the field (Jackson & L. 1973). To measure soil pH, a soil suspension was prepared in distilled water. The ratio of distilled water to soil was 2:1 (v: w). to measure soil pH, 10 g of soil wrapped in aluminum foil was weighed. The soil was then placed in a beaker. 20 ml of distilled water was then added. Soil suspensions were prepared by stirring with a glass rod. The suspension was left for some time to allow the particles to settle down. The pH meter (Hanna pH meter, pHeP) was calibrated with known pH values. The pH value of each soil sample was then recorded. This procedure was repeated for samples collected at depths of 10 cm, 20 cm, and 30 cm in each soil square over four different seasons.

2.2.3.2 Determination of soil electrical conductivity

Soil electrical conductivity was recorded in the laboratory within 24 h after collection from the field (Jackson & L. 1973). For the determination of soil conductivity, soil suspension was made with distilled water, where the ratio of distilled water and soil was 5:1 (v: w). for measuring soil conductivity, 10 g of soil was measured within an aluminum foil paper. Then, the soil was taken into a beaker. After that, 50 ml of distilled water was added. Soil suspensions were prepared by stirring with a glass rod. The suspension was left for some time to allow the particles to settle down. The electrical conductivity meter was calibrated with known conductivity values. The conductivity values of each soil sample were then recorded.

2.2.3.3 Determination of soil moisture content

Soil water content was analyzed following standard protocols (Jackson & L. 1973). To measure soil water content, 10 g of fresh soil was placed in an aluminum foil cup. It was then placed in an oven at 80 °C for 24 hours to dry. After drying, the dry weight of the soil was measured. Soil water content was determined using the following equation:

Soil moisture content (weight basis) (%) = $\frac{F-D}{D} \times 100$

Where,

F= weight of fresh soil

D= weight of dry soil

2.2.3.4 Determination of soil organic carbon (C)

Organic C of the soil was determined by Walkley and Black method (Black 1965). For the determination of organic C, 1 g of air-dried powdered soil was taken into a 500-ml clean, dry conical flask. Ten ml of normal potassium dichromate ($K_2Cr_2O_7$) solution was added. Then, 10 ml conc. H_2SO_4 was added and mixed thoroughly. The flask was cooled on an asbestos plate with occasional shaking for 30 minutes. When the color turned green, another 10 ml of $K_2Cr_2O_7$ was added. After 30 minutes, when the flask was cooled, about 150 ml of distilled water was added and mixed well. After several times, 10 ml of phosphoric acid was added and mixed well. Then, 3 ml of diphenylamine indicator was added. The color of the solution was deep purple. The excess chromic acid remaining in the flask was titrated using ordinary ferrous sulphate solution. At the end point, the color of the solution had changed to a deep bottle green. The readings were read from a burette. A blank experiment was run in the same way using all the reagents except soil. The percentage of organic C was calculated using the following formula:

Calculation:

1000 ml of N $K_2Cr_2O_7$ = 1000 ml of N C = 3 g of C(eq. wt. of C = 12/4= 3)

Or, 1 ml of N $K_2Cr_2O_7$ solution = 0.003 g of C

% of organic C = $\frac{3\times(B-T)\times N\times 100}{1000\times W}$

Where,

B = Amount in ml of N $FeSO_4$ solution required in this experiment

T = Amount in ml of N $FeSO_4$ solution required in experiment with soil

f = Strength of N $FeSO_4$ solution (from blank experiment)

W = Weight of soil taken

2.2.3.5 Determination of soil available nitrogen (N)

Available N present in the soil was measured using the Kjeldahl method (Black 1965). To measure available nitrogen, 5 g of soil was placed in a 100 ml plastic bottle. 50 ml of 1N KCl solution was added and shaken in an electric shaker. The solution was then left in the shaker for 1 hour. The sample was then filtered through Whatman filter paper. Subsequently, 10 ml of the extract was distilled with 10 ml of 10% NaOH using a micro Kjeldahl distillation apparatus. 0.2 g of Devarda's alloy was added to the funnel into which the sample and 10% NaOH were added. The distillate was collected in 10 ml of 2% H_3BO_3 until the volume was approximately 50 ml. Approximately 60 ml of the distillate (ammonium borate) was collected in a 125 ml Erlenmeyer flask containing 10 ml of mixed indicator boric acid. The distillate was then titrated against standard H_2SO_4. The end point was indicated by the pink color of the solution. The measurements were read from a burette. At the same time, blind tests were performed for all chemicals except for the soil. The percentage of available nitrogen (N) in the soil was calculated using the following formula:

Calculation:

1000 ml 1N H_2SO_4 = 1000 ml

Normal nitrogen = 14 g N

Or, 1 ml of 1N H

SO_4 = 0.014 g N

% of available nitrogen $= \frac{(T-B)\times f\times 0.014\times 50\times 100}{W\times volume\ of\ extract\ used}$

Where,

B = volume of N $FeSO_4$ solution in ml in this experiment

T = volume of N $FeSO_4$ solution in ml in soil test

f = strength of N $FeSO_4$ solution (from blank test)

W = weight of soil (g)

By this way the available nitrogen (N) was determined for different depth of soil in different quadrat in four seasons was determined.

2.2.3.6 Determination of total Phosphorus (P)

The total phosphorus content of the leaf sample was measured using the vanadomolybdic acid yellow color method (Jackson 1973). Total phosphorus was measured in five steps, which were digestion, filtration, color development, preparation of standard solutions, and absorption using a spectrophotometer.

Digestion: For digestion, a 45 ml beaker was taken and washed with distilled water. Then, 1 g of powdered air dry soil was taken. After that 10 ml of nitric acid (HNO_3) was added into the beaker and placed on the hot plate. It should be kept in hot plate until the liquid was dried. After few times later, 5 ml of 70% perchloric acid ($HClO_4$) was added and placed in hot plate for drying. After complete drying the beaker was removed from the hot plate.

Filtration: After complete digestion filtration was done. In the digestion beaker distilled water was added and filtrated with filter paper and the final volume of filtration was 50 ml.

Colour development: For colour development, 25 ml volumetric flask was taken. Then, 5 ml of filtrated sample was taken in a volumetric flask. After that, 5 ml of mixed solution (A+B) was added. Where ammonium molybdate was mixed with distilled water used as A solution and ammonium metabenadate with nitric acid and distilled water used as B solution. Mixed (A+B) solution was prepared with ratio of A: B = 1: 1.5. The final volume was made 25 ml with distilled water.

Standard solution preparation: Standard solution was prepared in five different concentration. They were 0, 1, 2, 3 and 4 ppm. In 25 ml volumetric flask, 0 ml, 0.5ml, 1ml, 1.5 ml and 2 ml was taken in different volumetric flask in following concentration, respectively. After that 5 ml of mixed solution (A+B) was added. The final volume was made 25 ml with distilled water.

Absorbance: The absorbance was taken in a spectrophotometer. At first spectrometer was made standard with 5 standard solutions. The absorbance of standard solution was taken. After that, the absorbance of sample solution was taken.

The absorbance of the sample was transformed into concentration. For measuring sample concentration, curve was drawn with the help of standard solution concentration. From the curve, the sample concentration was measured. The percentage of total phosphorus was measured by following formula-

Percentage of total phosphorus (%P) $= \frac{ppm \times 25 \times 50 \times 100}{Vol.\ taken\ for\ colour \times Wt.\ of\ soil \times 10^6}$

2.2.3.7 Determination of total Potassium (K)

The digestion solution prepared to measure P was also used to measure K by following the method as described by Piper (1950). Six standard solutions in ppm (0, 10, 20, 30, 50, and 100) were prepared using K_2SO_4. Absorbance was measured using a flame photometer at 766.5 nm. A standard curve was constructed using the absorbance of the six concentrations. The concentration of K in the samples was determined from this standard curve.

% of total potassium (K) = $\frac{ppm \times 50 \times 100}{Vol.\ taken\ for\ color \times wt\ of\ sample \times 10^6}$

2.2.3.8 Determination of total Sodium (Na)

The digestion solution prepared to measure P was also used to measure Na (Piper 1950). Six standard solutions (0.10, 20, 30, 50, and 100 ppm) were prepared using $NaClO_4$. Absorbance was measured using a flame photometer at 589 nm. The absorbance of the six concentrations was used to construct a standard curve from which the concentration of Na in samples was determined.

% of total sodium (Na) = $\frac{ppm \times 50 \times 100}{Vol.\ taken\ for\ color \times wt\ of\ sample \times 10^6}$

2.3 Determination of decomposition rates of Sal leaf litter

2.3.1 Experimental design for litter decomposition

To determine the decomposition rate of Sal leaf litter, a reciprocal experimental design was followed. In this design, leaf litter from each of the three forests was mixed with soils collected from the three selected forests. Three replicate pots were used for each treatment of leaf litter-soil mixture. Leaves from Singra National Park were mixed with the three selected forest soils. Similarly, leaves from Lalmai Sal forest and Madhupur Sal forest were mixed with the three forest soils (Figure 2.9). To determine the rate of decomposition of leaf litter, the pots were kept in a growth chamber for one year.

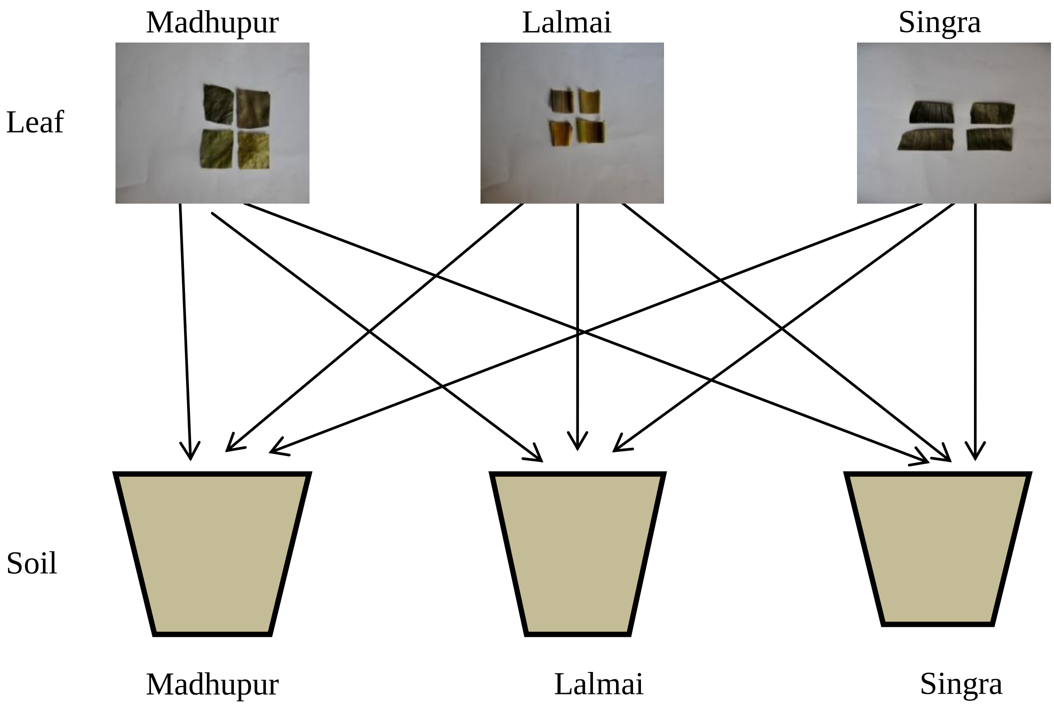
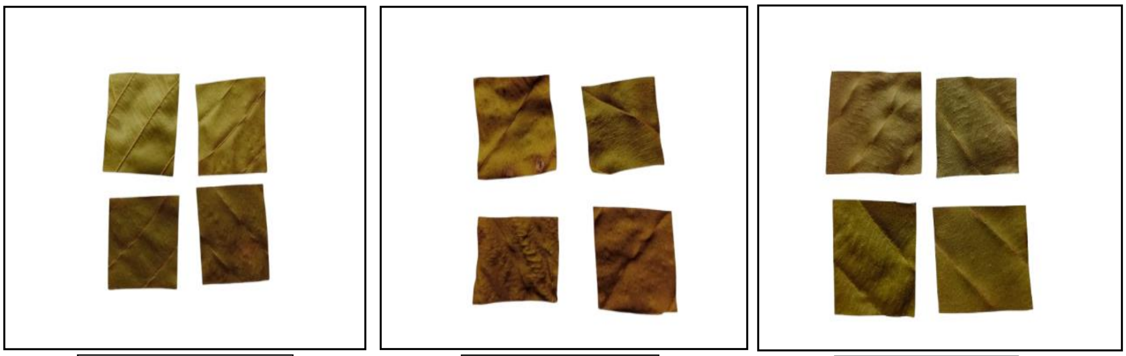


Figure 2.9: Reciprocal experimental design for the determination of leaf litter of Sal mixed reciprocally with the soil of the Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

2.3.1.1 Collection of leaf and soil samples for litter decomposition study

Fresh, mature and ungrazed leaves of Sal tree were collected from Madhupur Sal forest, Lalmai Sal forest, and Singra National Park. The collected leaves were packed in plastic bags and kept at air tight condition. Soil samples were then taken from the three selected forest locations where Sal leaves were collected. The collected soil was kept in plastic bags. The collected leaves and soils from the three forests were transported to the laboratory immediately. The leaves were dried in an oven at 80 °C for 24 h. Then, the leaves were cut into 2 cm × 2 cm pieces and thoroughly mixed with soil (Figure 2.10). To each pot (volume 500 ml) filled with soil collected from the forest; pieces of dried leaves weighing 0.2 g were added and mixed thoroughly. The pots were then covered with polyethylene bags to avoid contamination (Figure 2.11). Three replicated pots were used for each litter treatment. The pots were kept at room temperature for 12 months for incubation. Distilled water was added occasionally to keep the soil moisture constant in the pots. After incubation, the undecomposed leaves were removed from the soil to release the soil nitrogen content from the leaves.



Madhupur leaf   Lalmai leaf   Singra leaf

Figure 2.10: Sal leaves of Madhupur Sal Forest, Lalmai Sal Forest and Singra National Park.

Figure 2.11: Sal leaves intermixed with soil in Madhupur Sal Forest, Lalmai Sal Forest and Singra National Park.

2.3.2 Determination of nutrients in leaf

2.3.2.1 Determination of total nitrogen (N) in leaf

The total N content of leaves was measured by following Kjeldahl method (Black 1965). To measure the total N content in leaves, a 500 ml clean Kjeldahl flask was used into which 0.2 g of finely powdered leaves were added. Then, 2 ml of distilled water was added, shaken, and left for 20 min. 10 ml of concentrated H_2SO_4 was added and mixed thoroughly. The flask was heated in the digestion chamber over low heat for 15 minutes. When white H_2SO_4 vapor appeared, the flask was removed from the heater and 3 g of catalyst (digestion mixture) was added to increase the boiling point of the H_2SO_4 digestion and speed up the reaction. The flask was then placed on the heater and the temperature was increased. The digest was held for 4 hours until it was clear. It was then allowed to cool down. Once the digestive had cooled, it was diluted with distilled water and finally adjusted to a volume of 100 ml with distilled water in a volumetric flask. 10 ml of the extract was then distilled with 10 ml of 40% NaOH using an equal volume of NaOH using a micro Kjeldahl. The distillate was collected in 10 ml of 2% H_3BO_3 until the volume was approximately 50 ml. Approximately 60 ml of the distillate (ammonium borate) was collected in a 125 ml conical flask containing 10 ml of boric acid and mixed indicator. The distillate was then titrated against standard H_2SO_4. The endpoint was indicated by the pink color of the solution. At the same time, blind tests were performed for all chemicals except for the leaves.

Calculation:

1000 ml 1N H_2SO_4 = 1000 ml normal N = 14 g N

Or, 1 ml of 1N H_2SO_4 = 0.014 g N

% of total nitrogen $= \frac{(T-B)\times f \times .014\times 100\times 100}{W\times Volume\ of\ extract\ used}$

Where,

B = Amount in ml of N/100 H_2SO_4 required in titration of the blank experiment
T = Amount in ml of N/100 H_2SO_4 required in titration of the experiment with plant sample
f = Normality factor of N/100 H_2SO_4 (=0.00915 N)
W = Weight of sample

2.3.2.2 Determination of total phosphorus (P) content in leaf

The total P content of leaves was measured using the vanadomolybdic acid yellowing method (Jackson & L. 1973). Total phosphorus was measured in five steps: digestion, filtration, color development, preparation of standard solutions, and absorption using a spectrophotometer.

Digestion: For digestion, a 45 ml beaker was taken and rinsed with distilled water. Then, 0.2 g of finely chopped and air-dried leaves were taken. Next, 10 ml of nitric acid (HNO_3) was added to the beaker and placed on a heating plate. It was left on the heating plate until the liquid dried. After several repetitions, 5 ml of 70% perchloric acid ($HClO_4$) was added and placed on a hot plate to dry. After thorough drying, the cup was removed from the heating plate.

Filtration: After complete digestion, filtration was done. In the digestion beaker, distilled water was added and filtrated with filter paper and the final volume of filtration was 50 ml.

Colour development: A 25 ml volumetric flask was used for color development. 5 ml of the filtered sample was then placed in the volumetric flask. 5 ml of mixed solution (A+B) was then added. Distilled water was added to bring the final volume to 25 ml.

Standard solution preparation: Standard solutions were prepared in five different concentrations: 0, 1, 2, 3, and 4 ppm. In a 25 ml volumetric flask, 0 ml, 0.5 ml, 1 ml, 1.5 ml, and 2 ml were added to different volumetric flasks with the following concentrations: A + B. Then, 5 ml of mixed solution (A + B) was added. Distilled water was added to make the final volume 25 ml.

Absorbance: The absorbance was taken in a spectrophotometer. At first spectrometer was made standard with 5 standard solutions. The absorbance of standard solution was taken. After that the absorbance of sample solution was taken.

The absorbance of the sample was transformed into concentration. For measuring sample concentration, curve was drawn with the help of standard solution concentration. From the curve, the sample concentration was measured. The percentage of total P was measured by the following formula-

Percentage of total phosphorus (%P) = $\frac{ppm \times 25 \times 50 \times 100}{Vol. taken\ for\ colour \times Wt.\ of\ soil \times 10^6}$

2.3.2.3 Determination of total Potassium (K) content in leaf

The digest solution prepared for the determination of P was also used for the determination of K as described by Piper (1950). There were six standard solutions (0, 10, 20, 30, 50, 100) in ppm were prepared by using K_2SO_4. Absorbance was determined using a flame photometer at 766.5 nm. By using the absorbance of six concentrations, standard curve was drawn. From this standard curve, concentration of sample K was determined.

% of total potassium (K) = $\frac{ppm \times 50 \times 100}{Vol.\ taken\ for\ color \times wt\ of\ sample \times 10^6}$

2.3.2.4 Determination of total Sodium (Na)

The digest solution prepared for the determination of P was also used for the determination of Na (Piper & S. 1950). Five standard solutions (0,10, 20, 30, 50, and 100) in ppm were prepared by using sodium chlorate ($NaClO_4$). Absorbance was determined using a flame photometer at 589 nm. By using the absorbance of five concentrations, standard curve was drawn and from this standard curve, concentration of sample Na was determined.

% of total sodium (Na) = $\frac{ppm \times 50 \times 100}{Vol.\ taken\ for\ color \times wt\ of\ sample \times 10^6}$

2.3.2.5 Determination of total carbon (C)

For the determination of leaf total C, a modified method of Tyrin (1936) was used. It is a modification of the volumetric determination of leaf carbon with potassium dichromate ($K_2Cr_2O_7$) in strongly acid solution, leading to the formation of carbon-di-oxide (CO_2). The amount of oxygen consumed during the oxidation of C was calculated from the difference between the amount of dichromate taken and the amount remaining after oxidation; this is determined by the titration with a solution ferrous sulfate ($FeSO_4$. $7H_20$). The chemicals were prepared by following steps-

Potassium dichromate solution (.4 N):

40g of $K_2Cr_2O_7$ is dissolved in 1 L of distilled water and 1L of H_2SO_4 was carefully added to the solution in small portions with stirring so that excessive evolution of heat was avoided; this mixing should be done carefully mixed and stored in a flask with a ground stopper.

Ferrous sulfate solution (.4N):

For the preparation of ferrous sulfate solution 111.2g of ferrous sulfate crystals was dissolved in distilled water followed by an addition of 40 ml concentrated H_2SO_4 and diluting up to 1 L.

Phenylanthranilic acid (N-phenylanthranilic acid):

The indicator solution contains 0.2 g phenylanthranilic acid in 100 ml of 0.2 percent sodium carbonate (Na_2CO_3) solution.

For the determination of total leaf C, 0.02g of oven dried leaf sample was taken which was finely chopped. Then, 100 ml of conical flask was taken and the leaf was transferred to the conical flask. After that, 20 ml of potassium dichromate solution (.4 N) was added to the conical flask with the help of pipette. About 0.1 g of quartz was added to ensure steady boiling of the liquid and to protect the dichromate mixture from decomposition. A 4 cm diameter funnel was inserted into the neck of the conical flask, and the flask was placed on a hot plate or sand bath. The mixture was heated to boiling point and boiled for exactly 5 minutes. The flask was removed from the plate, and inner and outer surfaces of the funnel and the neck and walls of the flask are carefully washed down with about 10 ml of distilled water. The color of the liquid after the oxidation was completed should be yellow or greenish-brown. A greenish color of the liquid indicates insufficient oxidizing agent, and the analysis must be repeated with a smaller sample. The solution was therefore titrated with 0.4 N solution of ferrous sulfate using phenylanthranilic acid as the indicator. The titration was complete when the color changed from deep violet to bright green. Ferrous sulfate solution (T) required in the titration was recorded. After that, a blank experiment was run in the same way with all reagents except the leaf sample. Recording the amount of ferrous sulfate solution (B) required a blank experiment. From the data of blank experiment, the strength of $FeSO_4$ solution was determined.

Calculation:

Strength of potassium dichromate-

$V_1 \times S_1 = V_2 \times S_2$

Where,

V1= Volume of $K_2Cr_2O_7$

S_1= Strength of $K_2Cr_2O_7$

V_2= Volume of $FeSO_4$

S_2= Strength of $FeSO_4$

Strength of ferrous sulfate data collects from blank experiment.

Calculation of Carbon-

1 L of N $K_2Cr_2O_7$ solution = 1 L Ferrous sulfate solution= 3g organic C

1 ml N $K_2Cr_2O_7$ solution = 1 ml Ferrous sulfate solution = 0.003 g of C

Thus, the amount of C in leaf, expressed as percent, oxidized by N $K_2Cr_2O_7$ solution was calculated as follows-

Percent of total carbon (C) $= \frac{(B-T)\times f}{W} \times 0.003 \times 100$

Where,

B = Amount of N ferrous sulfate solution required in blank experiment (mL)

T = Amount of N ferrous sulfate solution required in experiment in leaf (mL)

f = Strength of ferrous sulfate solution in blank experiment

W = Weight of leaf taken (g)

2.3.2.6 Determination of mass loss rate

On the day after completion of incubation period of 12 months, the leaf litter that had not been decomposed was collected and rinsed thoroughly with distilled water to remove soil. Litter was then oven-dried at 60 ^{0}C for 24 h. The mass loss rate was calculated using the following formula and expressed as a percentage of initial mass before incubation:

Mass loss rate (%) = $\frac{W0-Wt}{W0} \times 100$

Where

W_0= Dried leaf litter weight before incubation

W_t= Dried leaf litter weight after incubation

2.3.2.7 Determination of phenolics

Phenolics were determined by following the standard method (Bärlocher and Graça 2005). A stock solution of 25 mg tannic acid in 100 ml 70% acetone was prepared. Then, 0, 0.2, 0.4, 0.6, 0.8, and 1.0 ml of stock solution were transferred into 6 Eppendorf tubes, and 1.0, 0.8, 0.6, 0.4, 0.2, and 0 ml of distilled water were added, respectively, and mixed with shaking. 5 ml of 2% Na_2CO_3 in 0.1 N NaOH was added and mixed and kept for 5 minutes. After 5 minutes, 0.5 ml of Folin-Ciocalteu reagent was added and mixed.

After 120 minutes, absorbance was measured at 760 nm. Tannic acid concentration was plotted against absorbance. The relationship was linear.

Leaves were dried and grinded to powder using liquid N, and 0.1 g was taken in an Eppendorf tube. Phenolics were extracted in 5 ml of 70% acetone for 1 hour at 4 °C. The extract was centrifuged (8000 rpm, 20 minutes). Then, 0.5 ml of the supernatant was taken and made volume up to 1 ml with distilled water. Na_2CO_3 and Folin-Ciocalteu reagents were added.

After 120 minutes, absorbance was measured at 760 nm. Based on the standard curve, the tannic acid equivalent per mg of leaf powder was determined. Three replicates were analyzed for the determination of phenolics in each leaf litter type.

2.3.2.8 Determination of leaf tannins

For the determination of tannin content standard protocol was followed (Bärlocher and Graça 2005). Leaves were dried and grinded to powder using liquid N. Then, 0.1 g powdered leaf was taken in a 50 ml Eppendorf tube and 5 ml extraction solution (50% methanol) was added. Tannins were extracted for 30 minutes at 4^0C. Then, 300 µl of sample was taken in a test tube by micropipette. Then, 200 µl distilled water was added to adjust total volume to 500 µl. After that, 7 ml solution 2 ($FeSO_4.7H_2O$ + HCl) was added to it and vortexed. A control experiment was done simultaneously using all the chemicals except leaf. Absorbance was measured using a spectrophotometer at 550 nm. Tubes were placed in water bath at 95 ^{0}C and incubated for exactly 50 minutes. Then, the tubes were cooled at room temperature before measuring absorbance again at 550 nm. Absorbance was calculated by subtracting the absorbance before heating from that after heating. Three replicates were analyzed for the determination of tannins in each leaf litter type.

2.3.2.9 Determination of mineralized nitrogen (N) in soil

Mineralized N in soil after incubation was determined by following the Kjeldahl method (Black 1965). For this purpose, 5 g of soil was taken into a 100-ml plastic bottle. Fifty ml of 1N KCl solution was added to it and shaken, and then it was left for 1 hour. Then, the samples were filtered with Whatman filter paper. Then, 10 ml of extract was distilled with 10 ml of 10% NaOH using a microKjeldahl distillation apparatus. 0.2 g of Devarda's alloy was added into the funnel, where samples and 10% NaOH were taken. The distillate was collected in 10 ml 2% H_3BO_3 until the volume was about 50 ml. About 60 ml volume of distillate (ammonium borate) was collected in a 125 ml conical flask containing 10 ml of boric acid with mixed indicator. Then, the distillate was titrated against the standard H_2SO_4. The end point was indicated by pink color of the solution. A blank experiment was done simultaneously using all the chemicals except soil.

Calculation:

1000 ml 1N H_2SO_4 = 1000 ml normal nitrogen = 14 g N

Or, 1 ml of 1N H_2SO_4 = 0.014 g N

% of available nitrogen = $\frac{(T-B)\times f\times 0.014\times 50\times 100}{W\times \text{Volume of extract used}}$

Where,

B = Amount in ml of N/100 H_2SO_4 required in titration of the blank experiment

T = Amount in ml of N/100 H_2SO_4 required in titration of the experiment with soil

f = Normality factor of N/100 H_2SO_4 (=0.00915 N)

W = Weight of soil

2.4 Seasonal Variation in Soil Bacterial Colony Counts

2.4.1 Determination of soil for bacterial colony counts

Soil samples for bacterial enumeration were obtained from three replicate quadrats inside the closed-canopy regions of Madhupur Sal Forest. At each quadrat, soil cores were extracted at three depth intervals (0–10 cm, 10–20 cm, and 20–30 cm) using a sterile stainless-steel auger to minimize cross-contamination. Samples from identical depths across quadrats were composited in sterile polyethylene bags, stored immediately at 4°C, and transported to the laboratory within 6 hours of collection. This sampling method allowed for detailed study of how bacterial communities change at different soil depths, considering variations in soil organic matter, moisture, and nutrients.

2.4.2 Culture of bacterial colonies

Nutrient agar medium was used to enumerate bacteria present in soil samples collected at a depth of 10 cm from three selected Sal forests. The pH was adjusted before the addition of agar and sterilization. The serial dilution plate technique was used to isolate the bacteria (Greenberg *et al*. 1998). One gram of soil sample was mixed with 100 ml of distilled water in a sterile conical flask and shaken well. This suspension was then used to make serial dilutions. One ml of this suspension was added to 9 ml sterile water to make a tenfold (1:10) dilution and further diluted up to 10^5-fold. Two plates were plated for each diluted sample. Using a pipette, 1 ml of each diluted sample was added to a sterile Petri dish. The molten agar medium was then poured into the Petri dish and mixed thoroughly by swirling first in one direction and then in the opposite direction. After the medium was solidified, the plates were inverted and incubated in an incubator (Memmert GmbH + Co KG 8540 Schwabach) at 37 °C for 48 h. After 48 hour of incubation, plates containing well-differentiated colonies were selected for enumeration. Selected plates were placed in a colony counter (Digital Colony Counter, DC-8OSK 1000086, Kayagaki, Japan). Colonies were counted and divided into three groups based on their different sizes, i.e. large, medium and small colonies.

2.4.3: Classification of bacterial colony counts

Bacterial colonies enumerated from soil samples were systematically classified into three morphotype groups—large (>3 mm diameter), medium (1–3 mm), and small (<1 mm)—based on visual assessment of size, edge morphology, elevation, and surface characteristics after 48 hours of incubation at 37°C (Figure 2.12). This size-based categorization served as a critical first-tier phenotypic screening tool to infer shifts in microbial community structure across soil depths (0–10 cm, 10–20 cm, 20–30 cm), as colony dimensions often correlate with bacterial life-history strategies and taxonomic identity. Large colonies typically represent fast-growing *r*-strategists (e.g., *Bacillus*, *Pseudomonas*), which dominate nutrient-rich topsoil layers, while small colonies indicate slow-growing oligotrophs or stress-tolerant taxa prevalent in deeper, resource-limited horizons (Santos *et al*. 2020, Sarker *et al*. 2023). The protocol aligns with standardized environmental microbiology methods (VanderGheynst *et al*. 2020), where morphotyping provides rapid, cost-effective insights into ecological guilds before molecular validation. In Madhupur Sal Forest soils, this approach revealed depth-stratified bacterial niches linked to organic carbon gradients—a pattern consistent with global forest ecosystems (Chen *et al*. 2021).

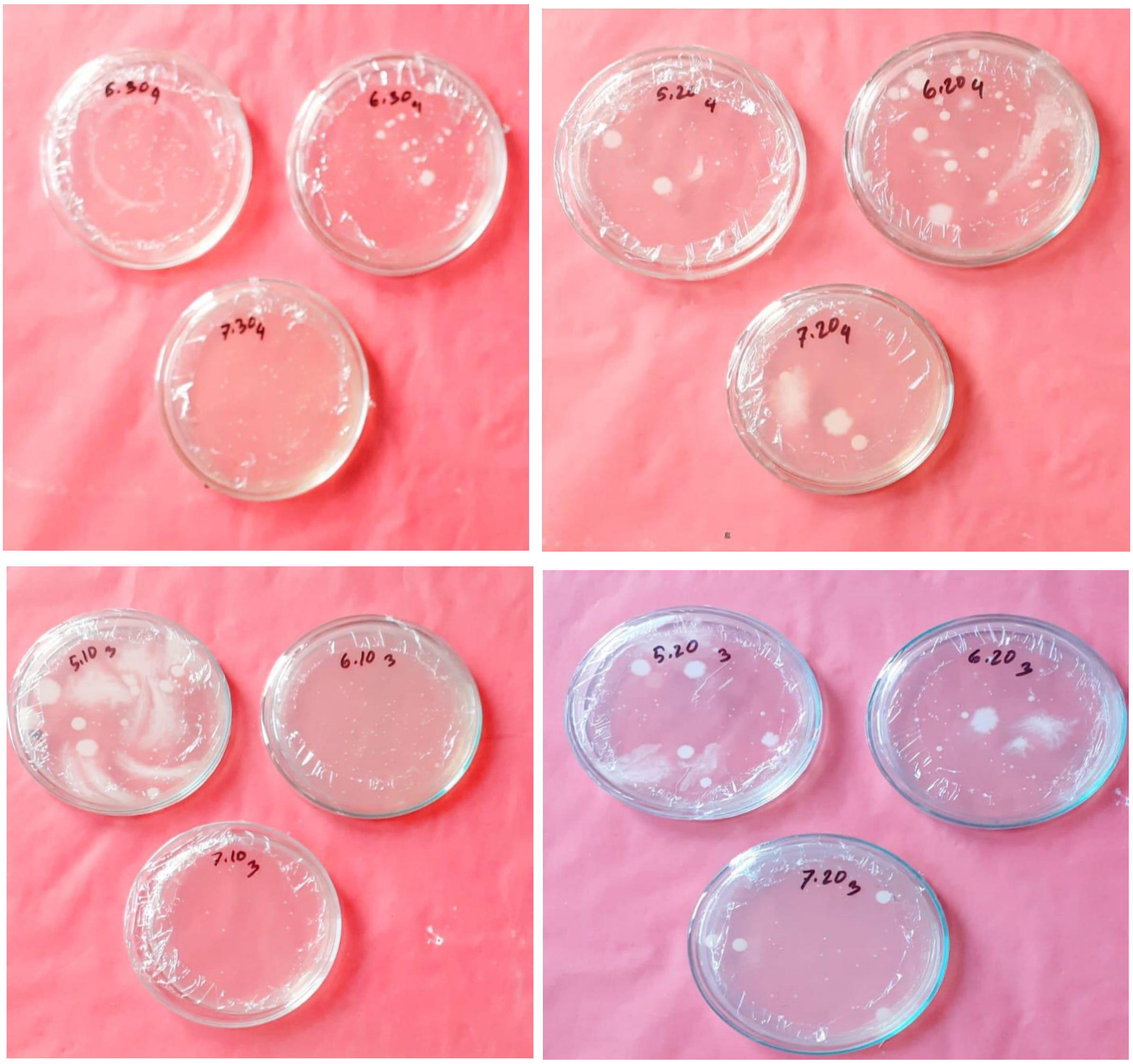


Figure 2.12: Photograph of Bacterial culture from Madhupur Sal Forest soil.

2.5 Statistical analysis

The effects of main factors and their interactions on dependent variables were examined by using ANOVA. A Turkey-Kramer HSD test was performed to test the significance level between mean values. Statistical analysis was performed using JMP 4.0 software (SAS Institute, Cary, NC, USA). Graphs were created using Prism-Graph Pad software (version 9, Arlington, USA).

CHAPTER 3

RESULTS

3.1 Vegetation structure of the selected Sal forests

3.1.1 Phytosociological analysis of selected Sal forests

3.1.1.1 Importance Value index (IVI) of the plant species of Madhupur Sal forest

The phytosociological association among plant species of Madhupur Sal forest are shown in Table 3.1. A total of 34 plant species were recorded during this season. Of the species recorded, 16 were trees, 7 were shrubs and 11 were herbs. Among the tree species, *S. robusta* Roxb. showed the highest IVI (129.21), followed by *Artocarpus lacucha* (20), and *Mallotus phillippensis* (17.01). *S. robusta* Roxb. was the most dominant. The rare species in this forest were *Azadirachta indica* (2.34), *Ficus hispida* (2.34), and *Aegle marmelos* L. (4.08). Among the shrubs, *Clerodendrum viscosum* appeared to be the most noteworthy with the highest IVI value (125.56) followed by *Glycosmis pentaphylla* (108.44), and *Randia dumetorum* (38.60). The rare species in this forest was *Abroma augustum* (6.93). Among the herbaceous species, *Commelina benghalensis* appeared to be the most noteworthy with the highest IVI value (76.00) followed by *Cyperus rotundus* (75.00), *Pteris* sp. (47.90) and *Curcuma zeoderia* Rosc. (29.64). The rare species of this forest were *Kyllinga brevifolia* Rottb. (5.95), *Ferula narthex* Boiss. (6.60) and *Dioscorea japonica* (6.94)

Table 3.1 Importance value index (IVI) of tree, shrub and herb species of Madhupur Sal forest in Bangladesh.

Sl. No.	Scientific Name	Local Name	Family	IVI
Trees				
1	*Shorea robusta* Roxb.	Sal	Dipterocarpaceae	129.21
2	*Artocarpus lacucha*	Deuya	Moraceae	20.00
3	*Mallotus phillippensis*	Raini/Sinduri	Euphorbiaceae	17.01
4	*Eugenia* sp.	Jaam	Myrtaceae	14.18
5	*Streblus asper* Lour.	Sheora	Moraceae	10.55
6	*Ziziphus oenoplia*	Bonboroi	Rhamnaceae	11.50
7	*Lagerstroemia speciosa*	Jarul	Lythraceae	10.31
8	*Dillenia pentagyna*	Bon chalta	Dilleniaceae	8.40
9	*Cassia fistula* L.	Sonalu	Fabaceae	8.14
10	*Eriobotrya japonica*	Loquat	Rosaceae	8.14
11	*Pterospermum acerifolium*	Khagor	Malvaceae	7.12
12	*Albizia procera*	Koroi	Mimosoideae	7.02
13	*Zizyphus mauritiana*	Bon Boroi	Rhamnaceae	4.43
14	*Aegle marmelos* L.	Bel	Rutaceae	4.08
15	*Ficus hispida*	Khoksha	Moraceae	2.34
16	*Azadirachta indica*	Neem	Meliaceae	2.34
Shrubs				
1	*Clerodendrum viscosum*	Vaat	Lamiaceae	125.56
2	*Glycosmis pentaphylla*	Dat majon/ Motkila	Rutaceae	108.44
3	*Randia dumetorum*	Modanphala	Rubiaceae	38.60
4	*Grewia asiatica*	Phalsa	Malvaceae	23.82
5	*Calamus viminalis*	Bet	Palmae	12.63
6	*Urena lobata*	Bon Okra	Malvaceae	7.90
7	*Abroma augustum*	Olot kombol	Malvaceae	6.93
Herbs				
1	*Commelina benghalensis*	Kanshira	Commelinaceae	76.00
2	*Cyperus rotundus*	Mutha ghas	Cyperaceae	75.00
3	*Pteris* sp.	Dheki shak	Pteridoideae	47.90
4	*Curcuma zeoderia* Rosc	Shothi	Zingiberaceae	29.64
5	*Adiantum* sp.	Mayur shikha	Pteridaceae	14.90
6	*Trifolium repens* L.	Ampin	Fabaceae	14.44
7	*Musa acuminata*	Bon kola	Musaceae	12.80
8	*Kalanchoe pinnata*	Patharkuchi	Crassulaceae	9.92
9	*Dioscorea bulbifera*	Bonalu	Dioscoreaceae	6.94
10	*Ferula narthex* Boiss.	Hing	Apiaceae	6.60
11	*Kyllinga brevifolia* Rottb.	Shabujnirbisa	Cyperaceae	5.95

3.1.1.2 Importance Value index (IVI) of the plant species of Lalmai Sal forest

The phytosociological relationships among plant species in Lalmai Sal forest are shown in Table 3.2. A total of 25 plant species were recorded from this forest. Of the species observed, 10 were trees, 4 were shrubs and 11 were herbs. Tree species included *S. robusta* Roxb. It showed the highest IVI value (114.75), followed by *Acacia auriculiformis* (38.63), *Eugenia jambolana* **(**28.91**)** and *Randia dumetorum* (25.70). The rare species in this forest were *Ziziphus oenoplia* (6.10), *Dillenia indica* (11.41) and *Tectona grandis* (14.10). Among shrubs, *Urena lobata* had the highest IVI value (98.00), followed by *Grewia nervosa* (85.21), and *Clerodendrum viscosum* (62.13). Among herbaceous species, *Cynodon dactylon* had the highest IVI value (90.00), followed by *Cyperus rotundus* (62.85), *Commelina benghalensis* (60.42) and *Curcuma zeoderia* (23.10). The rare species in this forest were *Smilax rotandifolia* (4.08), *Mimosa pudica* (4.60) and *Amphicarpaea bracteata* (5.15).

Table 3.2 Importance value index (IVI) of tree, shrub and herb species of Lalmai Sal forest in Bangladesh.

Sl. No.	Scientific Name	Local Name	Family	IVI
Trees				
1	*Shorea robusta* Roxb.	Sal	Dipterocarpaceae	114.75
2	*Acacia auriculiformis*	Akashmoni	Fabaceae	38.63
3	*Eugenia jambolana*	Bonjam	Myrtaceae	28.91
4	*Randia dumetorum*	Monkata	Rubiaceae	25.70
5	*Syzygium grande*	Jam	Myrtaceae	21.34
6	*Robinia pseudoacacia*	Black locust	Fabaceae	20.38
7	*Eriobotrya japonica*	Loquat	Rosaceae	17.87
8	*Tectona grandis*	Segun	Lamiaceae	14.92
9	*Dillenia indica*	Bonchalta	Dilleniaceae	11.41
10	*Ziziphus oenoplia*	Bonboroi	Rhamnaceae	6.10
Shrubs				
1	*Urena lobata*	Bon Okra	Malvaceae	98.00
2	*Grewia asiatica*	Phalsa	Malvaceae	85.21
3	*Clerodendrum viscosum*	Vaat	Lamiaceae	62.13
4	*Glycosmis pentaphylla*	Motkila/Dātan	Rutaceae	54.70
Herbs				
1	*Cynodon dactylon*	Durba	Poaceae	90.00
2	*Cyperus* sp.	Mutha ghas	Cyperaceae	62.85
3	*Commelina bengalensis*	Kanshira	Commelinaceae	60.42
4	*Curcuma zeoderia*	Shothi	Zingiberaceae	23.10
5	*Symphytum tuberosum*	Makardana	Boraginaceae	23.10
6	*Phlebodium aureum*	Neel Tara Fern	Polypodiaceae	12.77
7	*Dioscorea bulbifera*	Bonalu	Dioscoreaceae	8.09
8	*Kyllinga* sp.	Shabuj nirbisa	Cyperaceae	5.91
9	*Amphicarpaea bracteata*	Bon-badam	Fabaceae	5.15
10	*Mimosa pudica*	Lojjaboti	Fabaceae	4.60
11	*Smilax rotandifolia*	Kumari Lata	Smilacaceae	4.08

3.1.1.3 Importance Value index (IVI) of the plant species of Singra national forest

The phytosociological association among plant species in Singra Sal forest is shown in Table 3. A total of 26 plant species were recorded in this forest. Of the species recorded, 16 were trees, 3 were shrubs and 7 were herbs. Among the tree species, *S. robusta* Roxb. appeared to be the most dominant with the highest IVI value (86.74), followed by *Artocarpus lacucha* (54.70), *Mallotus phillippensis* (44.94), and *Randia dumetorum* (30.50). The rare species in this forest were *Zizyphus jujuba* (2.92), *Albizia lebbeck* L. (2.92), and *Eugenia* sp. (2.92). Among the shrubs, *Clerodendrum viscosum* appeared to be the most dominant with the highest IVI value (120.54) followed by *Glycosmis pentaphylla* (94.60), *Urena lobata* (84.90). Among the herbaceous species, *Cynodon dactylon* appeared to be the most dominant with the highest IVI value (117.73) followed by *Cyperus rotundus* (68.70), *Commelina benghalensis* (62.24) and *Musa acuminata* (19.55).

Table 3.3 Importance value index (IVI) of tree, shrub and herb species of Singra National forest in Bangladesh.

Sl. No.	Scientific Name	Local Name	Family	IVI
Trees				
1	*Shorea robusta* Roxb.	Sal	Dipterocarpaceae	86.74
2	*Artocarpus lacucha*	Deuya	Moraceae	54.70
3	*Mallotus phillippensis*	Raini/Sinduri	Euphorbiaceae	44.94
4	*Randia dumetorum*	Monkata	Rubiaceae	30.50
5	*Ficus hispida*	Khoksa	Moraceae	14.12
6	*Eriobotrya japonica*	Loquat	Rosaceae	13.23
7	*Cassia fistula* L.	Sonalu	Fabaceae	9.70
8	*Streblus asper* Lour.	Sheora	Moraceae	8.90
9	*Trewia polycarpa* L.	Pithalu	Euphorbiaceae	8.10
10	*Zizyphus mauritiana*	Bon Boroi	Rhamnaceae	5.70
11	*Dillenia pentagyna*	Bon chalta	Dilleniaceae	5.40
12	*Lagerstroemia speciosa*	Jarul	Lythraceae	5.40
13	*Aegle marmelos* L.	Bel	Rutaceae	4.10
14	*Eugenia* sp.	Jaam	Myrtaceae	2.92
15	*Albizia lebbeck* L.	Koroi	Mimosoideae	2.92
16	*Zizyphus jujuba*	Kulboroi	Rhamnaceae	2.92
Shrubs				
1	*Clerodendrum viscosum*	Vaat	Lamiaceae	120.54
2	*Glycosmis pentaphylla*	Motkila/Daton	Rutaceae	94.60
3	*Urena lobata*	Bon Okra	Malvaceae	84.90
Herbs				
1	*Cynodon dactylon*	Durba	Poaceae	117.73
2	*Cyperus* sp.	Mutha ghas	Cyperaceae	68.70
3	*Commelina benghalensis*	Kanshira	Commelinaceae	62.24
4	*Musa acuminata*	Bon kola	Musaceae	19.55
5	*Dioscorea bulbifera*	Bonalu	Dioscoreaceae	12.70
6	*Pteris* sp.	Dheki shak	Pteridoideae	12.30
7	*Kyllinga brevifolia* Rottb.	Shabuj nirbisa	Cyperaceae	6.90

3.1.2 Vegetation structure of selected Sal forests in Bangladesh

3.1.2.1 Diversity indices of the selected Sal forests:

A total of 43 plant species were listed from 19 quadrats placed randomly at each of the selected forests namely Madhupur Sal forest, Lalmai Sal forest and Singra National Park. The mean value of the number of species per quadrat was at Singra National Park 14.80 ±1.53 followed by Madhupur Sal forest (14.44 ±0.87) and Lalmai sal forest (13.60 ±1.44). In Madhupur Sal forest, the mean species richness per quadrat was different for different growth forms such as trees (7.56 ± 0.84), shrubs (3.44 ± 0.38) and herbs (3.44 ± 0.71), in Lalmai Sal forest those were for trees 8.60 ± 1.20, for shrubs 2.80 ± 0.50 and for herbs 5.00 ± 0.71. The species richness per quadrat in Singra National forest was also different for different growth froms such as for trees 8.60 ± 1.03, for shrubs 3.00 ± 0.00 and for herbs 3.20 ± 0.66 (Table 3.4).

Table 3.4 Species richness and Shannon-Wiener index obtained in the selected Sal forests of Bangladesh

Parameters	Madhupur Sal forest	Lalmai Sal forest	Singra Sal forest	F-ratio	P value
Total species richness	14.44±0.87	13.60±1.44	14.80±1.53	0.22	0.81
Tree species richness	7.56±0.84	5.80±1.20	8.60±1.03	1.61	0.23
Shrub species richness	3.44±0.38	2.80±0.50	3.00±0.00	0.80	0.466
Herb species richness	3.44±0.71	5.00±0.71	3.20±0.66	1.47	0.258
Shannon-Wiener Index	2.58±0.09	2.30±0.07	2.43±0.19	1.61	0.231

In terms of tree species richness, the value was higher in Singra National forest 14.80 ±1.53 than in Madhupur and Lalmai Sal forests with the values 7.56±0.84 and 5.80±1.20, respectively. However, no significant difference in tree species richness appeared among the three forests. Thus, in terms of shrubs, herbs and total species, there was no significant difference appeared among the three forests.

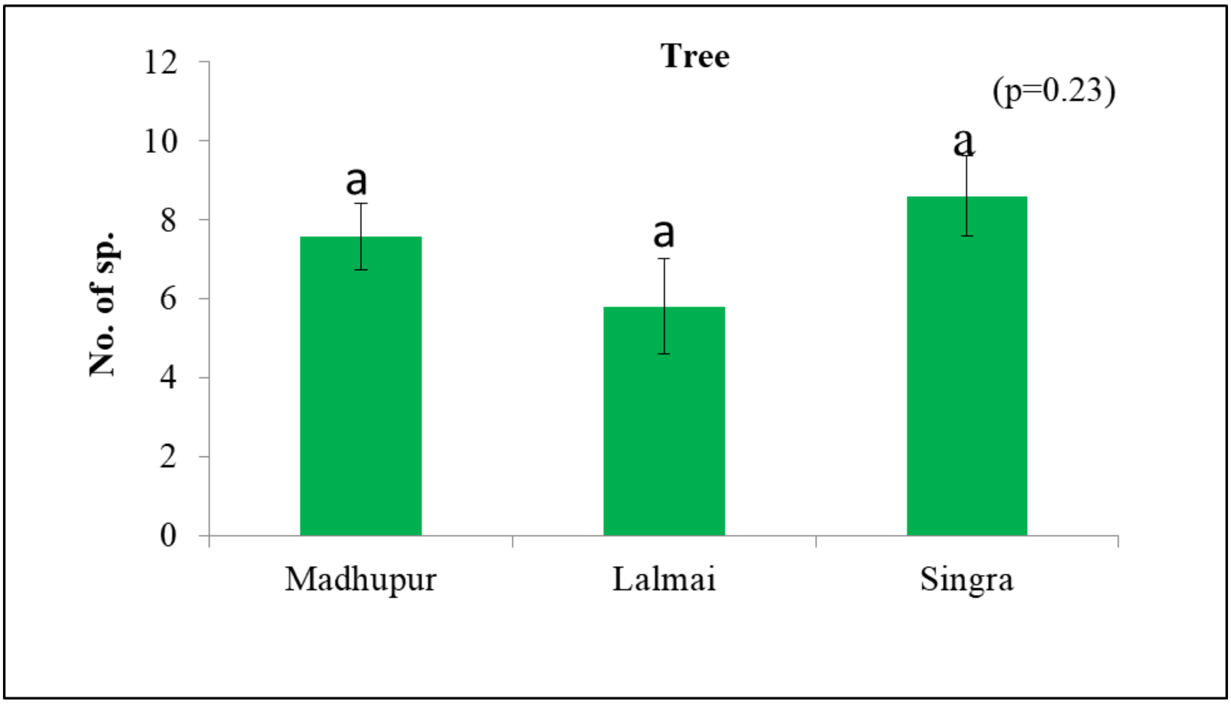


Figure 3.1: The species richness of the plant growth forms of trees per quadrat in Madhupur Sal Forest, Lalmai Sal Forest, and Singra National Park selected for the present study.

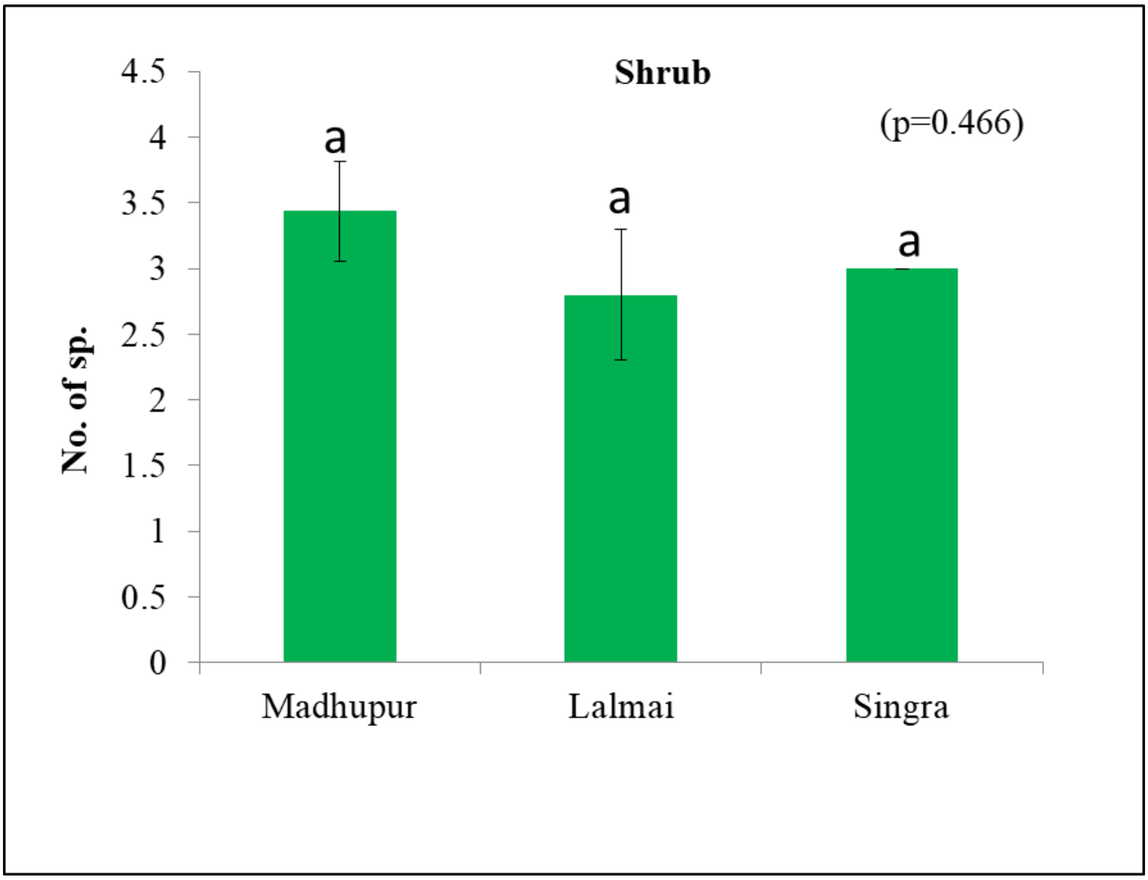


Figure 3.2: The species richness of the plant growth forms of shrubs per quadrat in Madhupur Sal Forest, Lalmai Sal Forest, and Singra National Park selected for the present study.

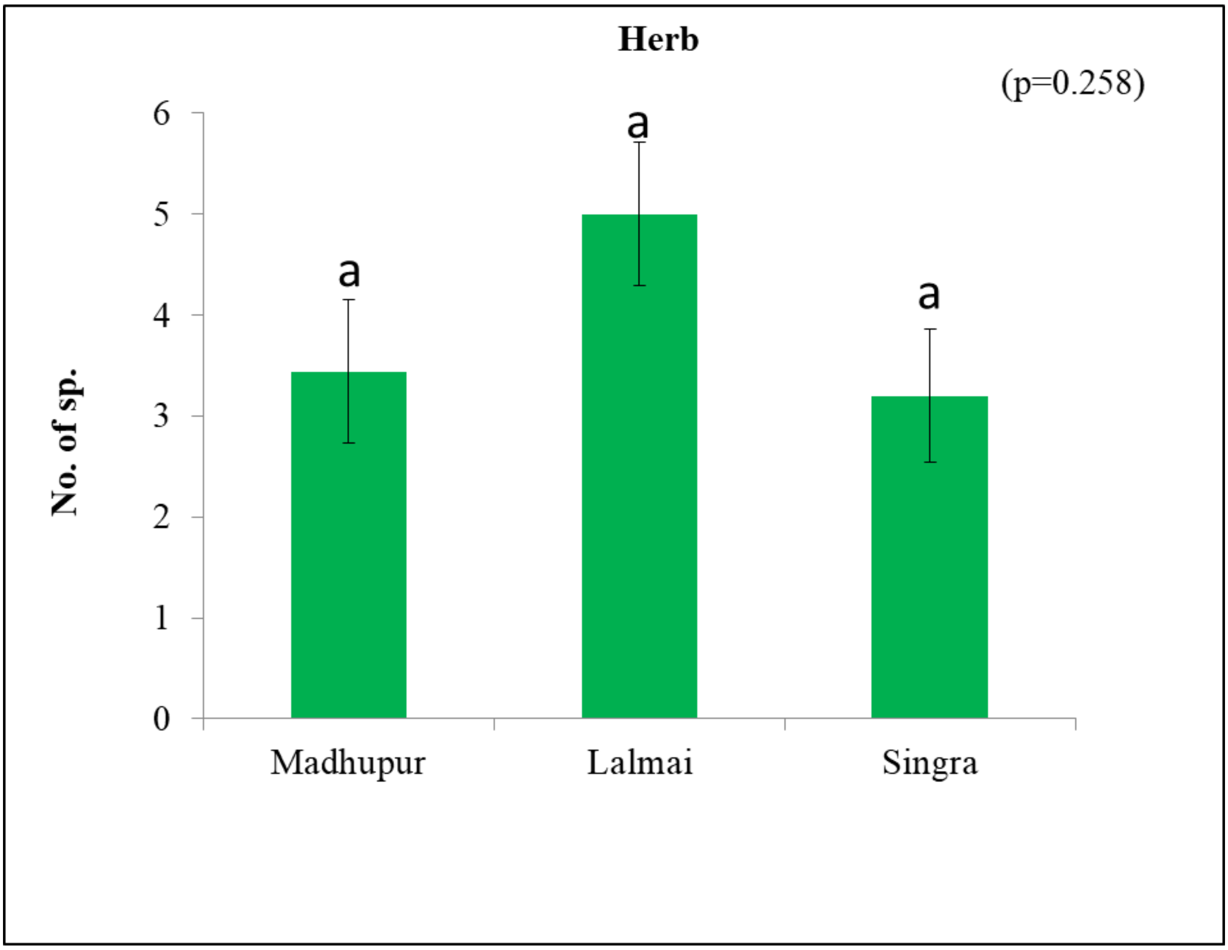


Figure 3.3: The species richness of the plant growth forms of herbs per quadrat in Madhupur Sal Forest, Lalmai Sal Forest, and Singra National Park selected for the present study.

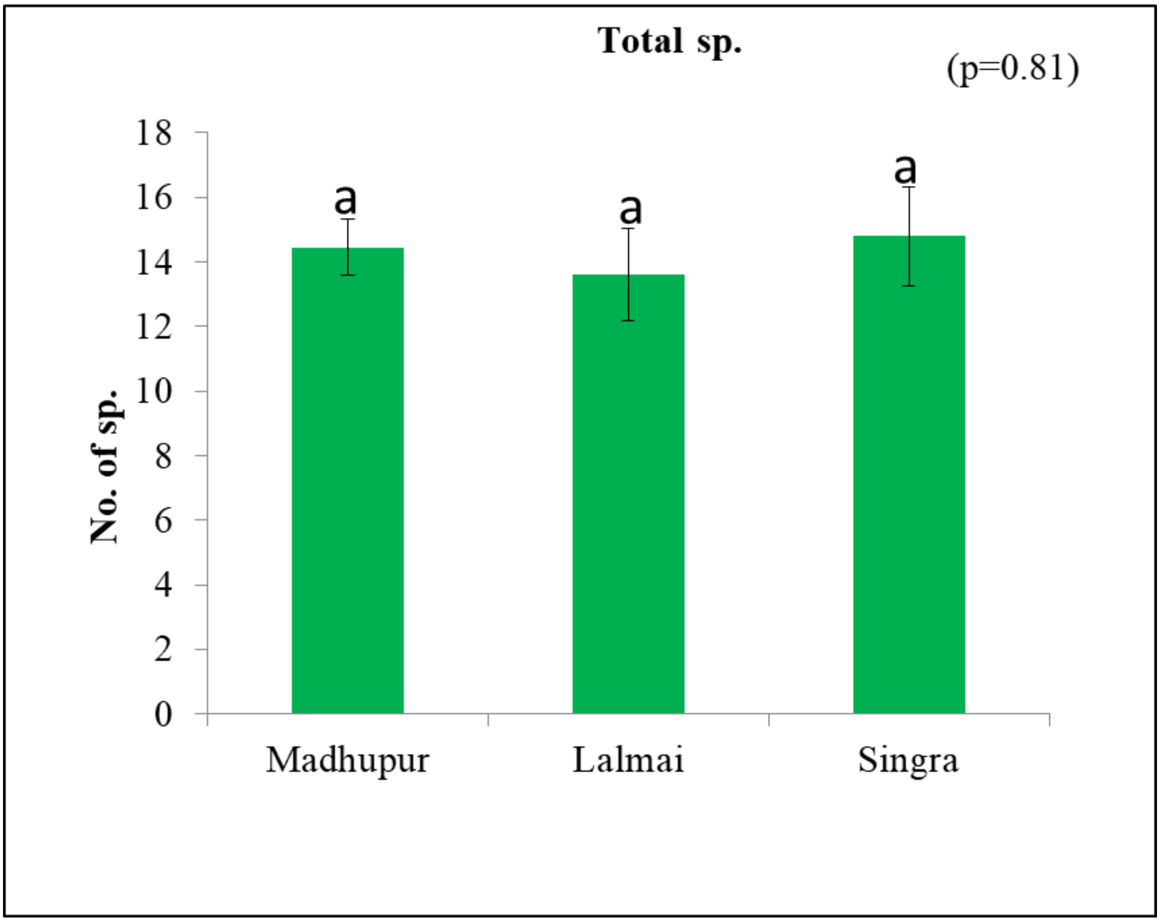


Figure 3.4: The species richness of the plant growth forms of the total species per quadrat in Madhupur Sal Forest, Lalmai Sal Forest, and Singra National Park selected for the present study.

3.1.2.2 Shannon Diversity Index

There was no significant difference in Shannon-Weiner diversity index among the three selected forests although the value was relatively lower in Lalmai Sal forest (2.30±0.07) than the other two forests (Figure 3.5).

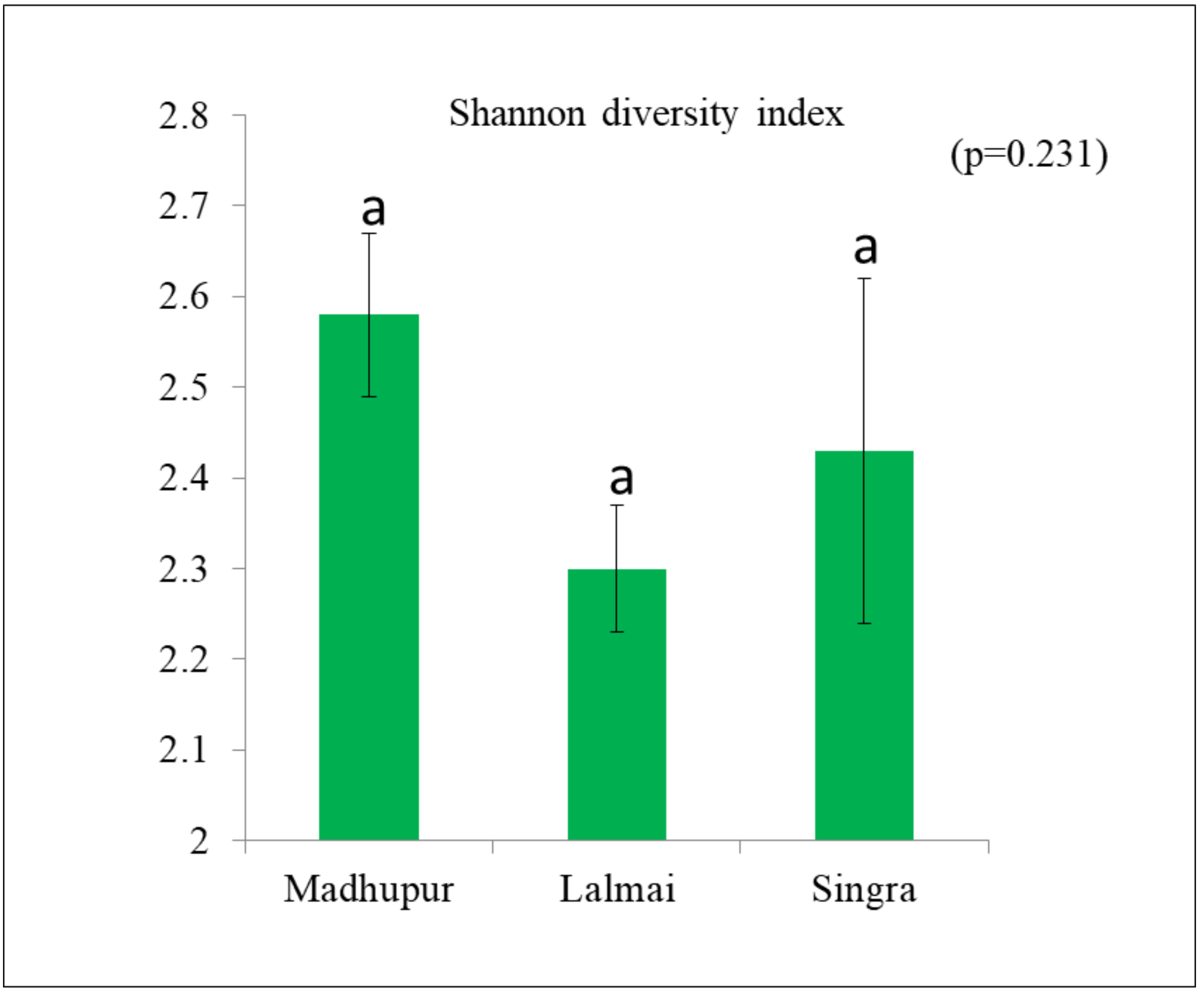


Figure 3.5: The Shannon-Wiener Diversity Index for plant species of Madhupur Sal forest, Lalmai Sal forest and Singra National forest.

3.1.2.3 Diameter at Breast Height (DBH)

Comparison of DBH of selected Sal plants from Madhupur Sal forest, Lalmai Sal forest and Singra National Park was shown in Figure 3.6. There was significant difference in DBH among the three Sal forests. The mean DBH value was significantly lower in Madhupur Sal forest than the other two forests. Mean DBH value of Sal plant was significantly (p = 0.022) higher in Lalmai Sal forest (38.84±2.12 cm) and Singra National forest **(**37.36±1.97 cm) than that of the Madhupur Sal forest **(**30.72±1.93 cm). These results indicated that the trees of the Singra Sal forest and Lalmai Sal forests were older than the Madhupur forest.

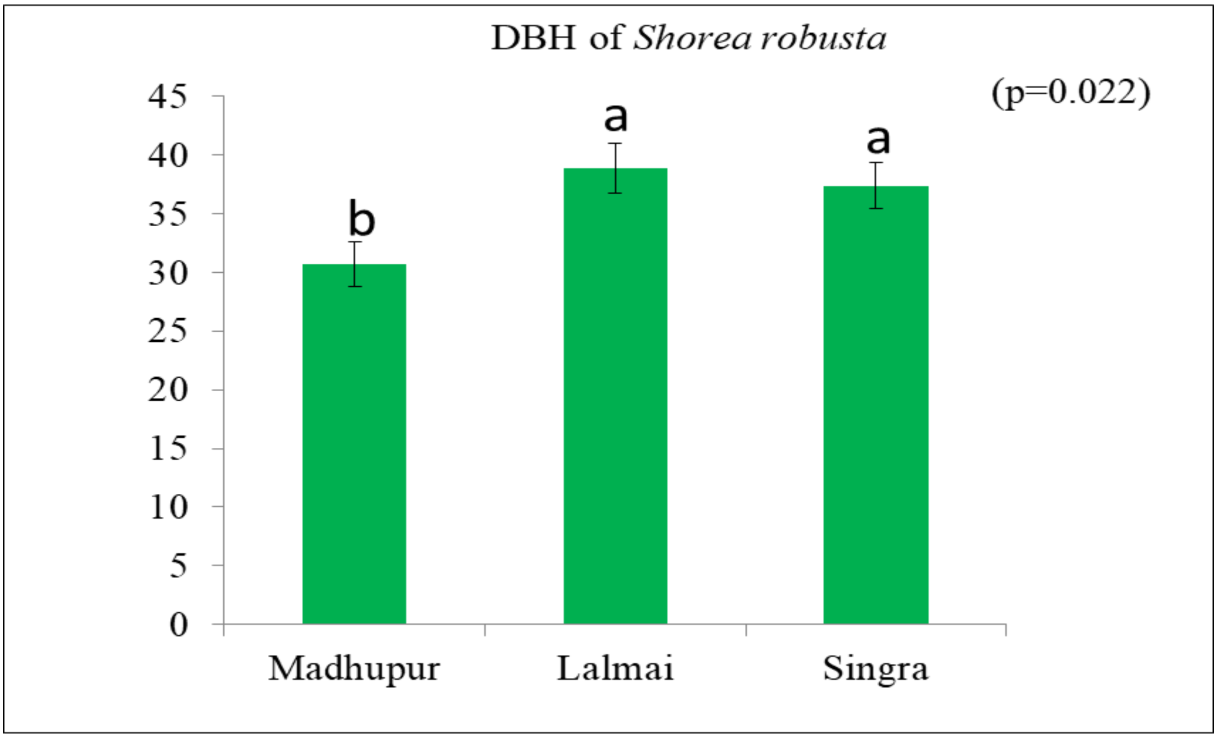


Figure 3.6: DBH (Diameter at Breast Height) of *Shorea rabusta* Gaertn. of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.2 Comparison of plant biomass among the selected Sal forests

3.2.1 Biomass of adult tree

3.2.1.1 Aboveground, belowground and total woody biomass of adult tree

The total biomass of woody plants in the Madhupur Sal Forest, Lalmai Sal forest and the Singra National Park showed spatial differences among the 19 quadrats (Figure 3.7). The mean value of total biomass of adult woody plants in Madhupur Sal forest was 652.80±76.63 t/ha, the mean value of total biomass of adult woody plants in Lalmai Sal forest was 1054.40±121.70 t/ha and that of Singra National Park was 991.34±113.04 t/ha. The above-ground biomass of woody plants in the studied quadrats ranged from 652.80 to 1054.40 t/ha. In terms of above-ground biomass of adult trees, the three forests showed significant differences ($p < 0.0161$) and Madhupur forest showed the lowest value compared to the other two forests.

Similarly, the total belowground biomass of woody plants was 106.70±11.74 t/ha in Madhupur Sal forest, and that was 175.80±21.20 t/ha in Lalmai Sal forest and that of 154.20±17.20 t/ha was in the Singra National Park (Figure 3.8). The belowground biomass of woody plants in the studied quadrats ranged from 106.70 to 175.80 t/ha. In case of belowground biomass of adult trees, the three forests showed significant differences ($p < 0.0146$) and Madhupur forest showed the lowest value compared to the other two forests.

Thus, the total biomass (ATB=AGB + BGB) of adult trees in the three selected forests was as 759.50±88.40 t/ha Madhupur Sal forest, 1230.20±142.80 t/ha in Lalmai Sal forest and 1145.53±130.21 t/ha in Singra National Park (Figure 3.9). The above and below ground biomass of woody plants in the studied quadrats ranged from 759.50 to 1230.20 t/ha. In terms of total adult tree biomass of the three forests showed significant differences ($p < 0.0159$) and Madhupur forest showed the lowest value compared to the other two forests.

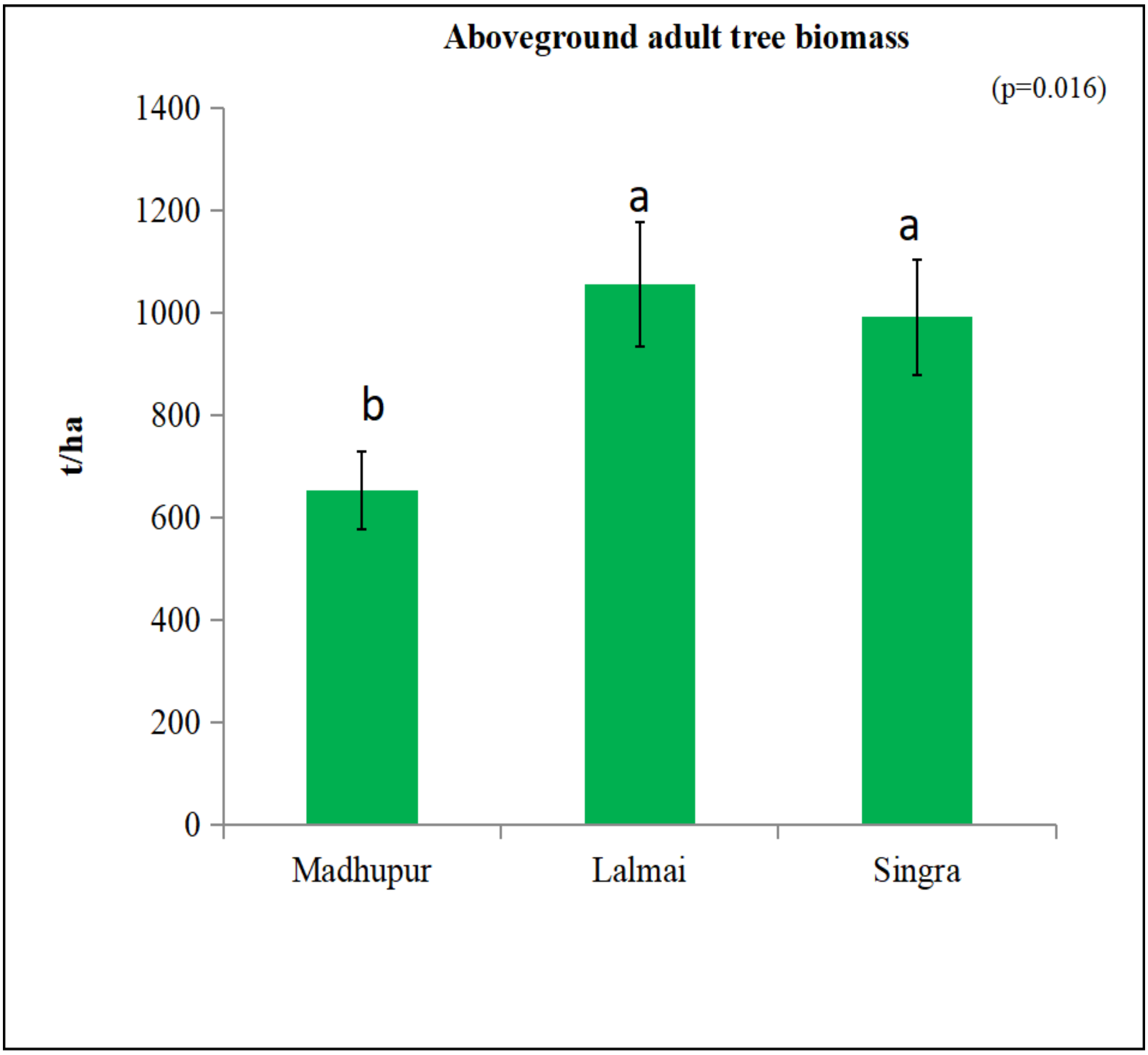


Figure 3.7: Biomass (t/ha) of adult tree (Aboveground) plants of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest.

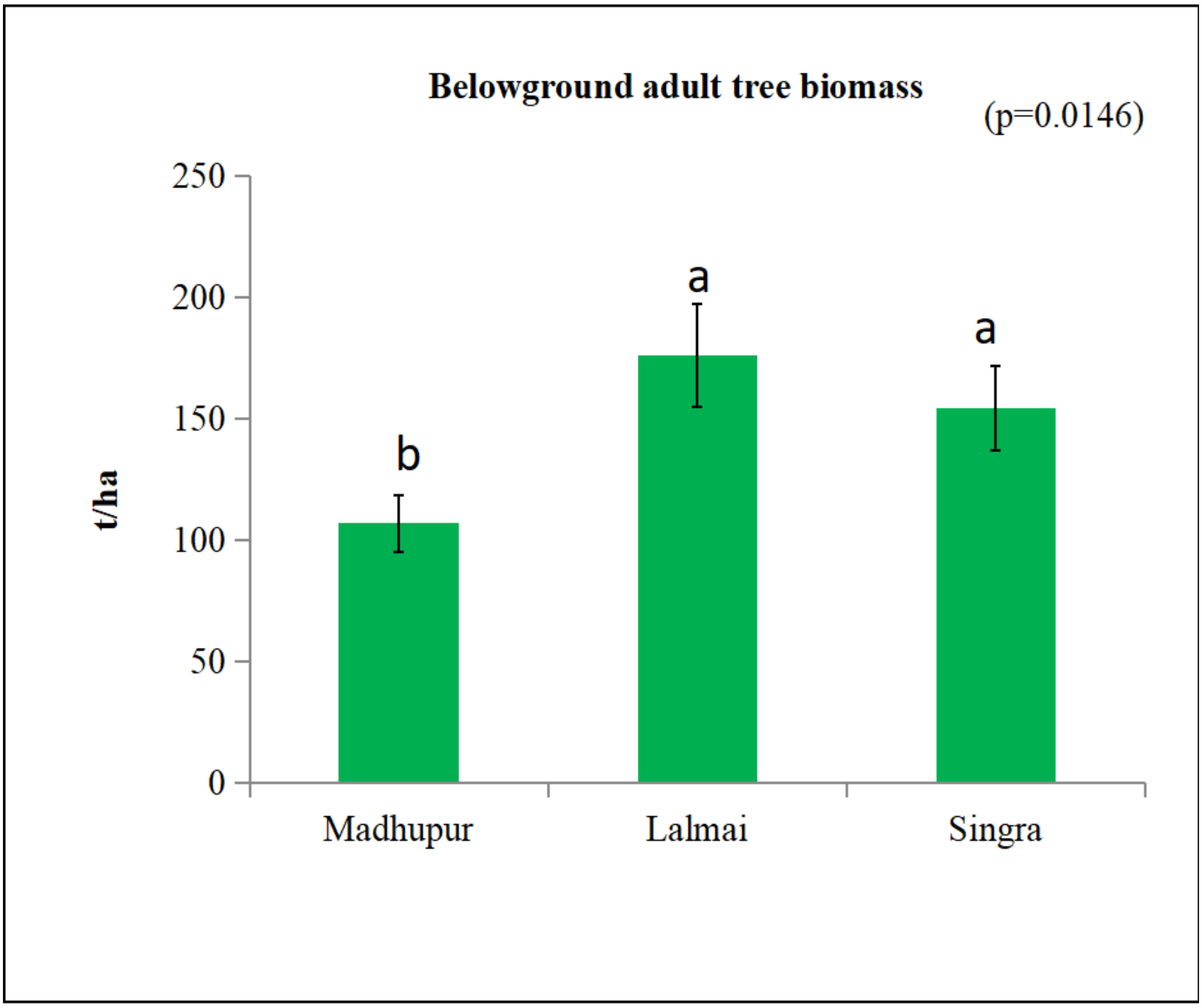


Figure 3.8: Biomass (t/ha) of adult tree (Belowground) plants of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest.

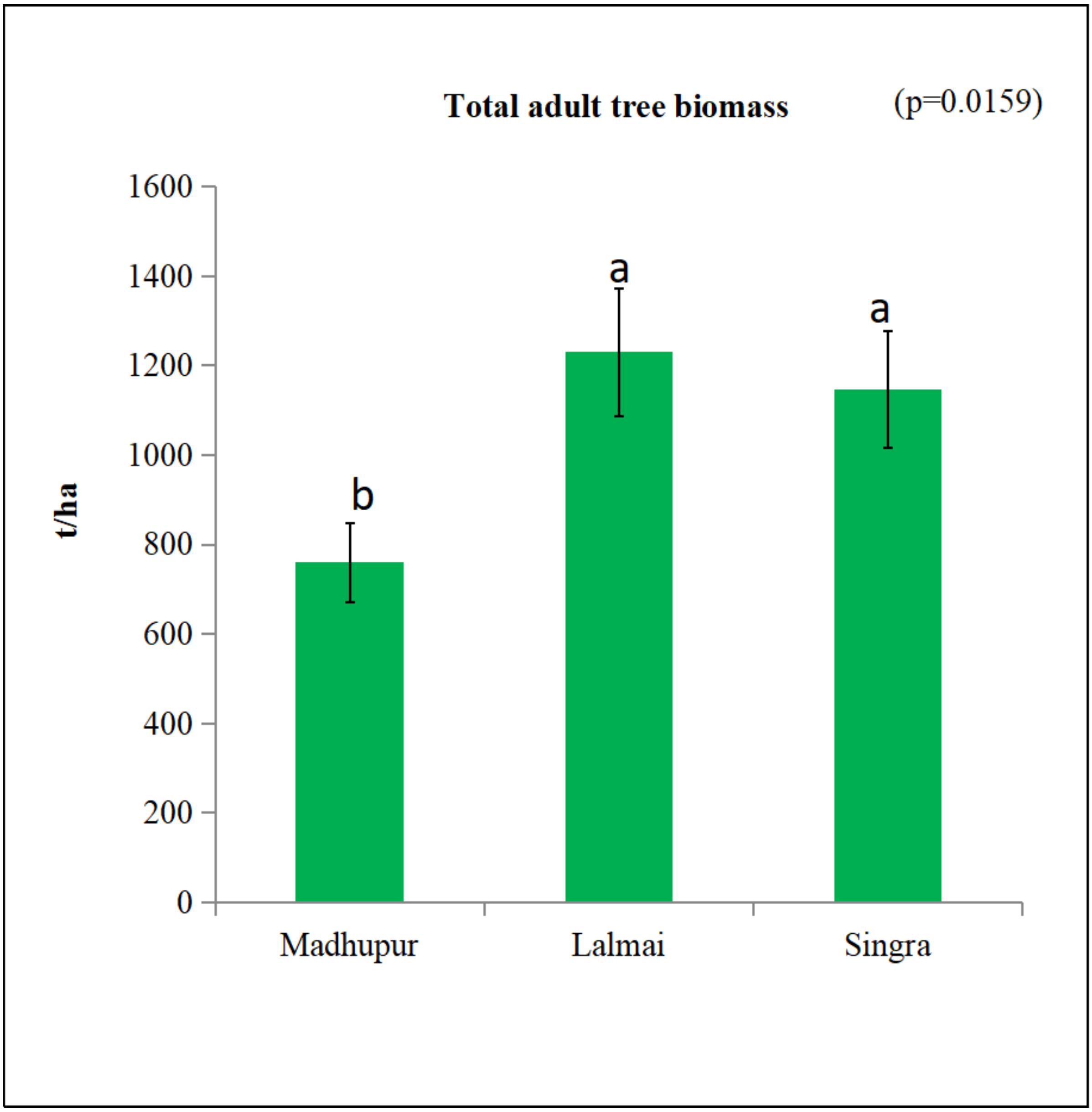


Figure 3.9: Biomass (t/ha) of adult tree (Total) plants of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest.

3.2.2 Biomass of juvenile tree

The total biomass of woody plants in Madhupur Sal Forest, Lalmai Sal forest and Singra National Park showed spatial differences among them. The mean value of the total biomass of juvenile woody plants in Madhupur Sal forest was 28.24±4.04 t/ha whereas in Lalmai Sal forest it was 8.32±1.43 t/ha and in Singra National Park it was 66.00±12.20 t/ha. The above-ground biomass of woody plants in the studied quadrats ranged from 8.32 to 66.00 t/ha. In terms of aboveground biomass of juvenile trees, the three forests showed significant differences ($p < 0.0001$. Singra National Park showed the highest value compared to the other two forests (Figure 3.10).

Similarly, the total belowground biomass of juvenile woody plants in Madhupur Sal forest was 7.34±1.05 t/ha, whereas in Lalmai Sal forest it was 2.20±0.37 t/ha and in Singra National Park the biomass of juvenile woody plants it was 17.20±3.20 t/ha. The belowground biomass of woody plants in the studied quadrats ranged from 2.20 to 17.20 mg/ha. In terms of belowground biomass of juvenile trees, the three forests showed significant differences ($p < 0.0001$) and Lalmai forest showed the lowest value compared to the other two forests (Figure 3.11).

Thus, the total biomass of juvenile trees (JTB=AGB + BGB) in the three selected forests was 40.80±4.52 t/ha in Madhupur Sal forest, 10.50±1.80 t/ha in Lalmai Sal forest and 83.14±15.31 t/ha in Singra National Park. In terms of aboveground and belowground biomass of woody plants in the studied quadrats, the total biomass of juvenile trees in the three forests showed significant differences ($p < 0.0001$) and Lalmai forest showed the lowest value compared to the other two forests (Figure 3.12).

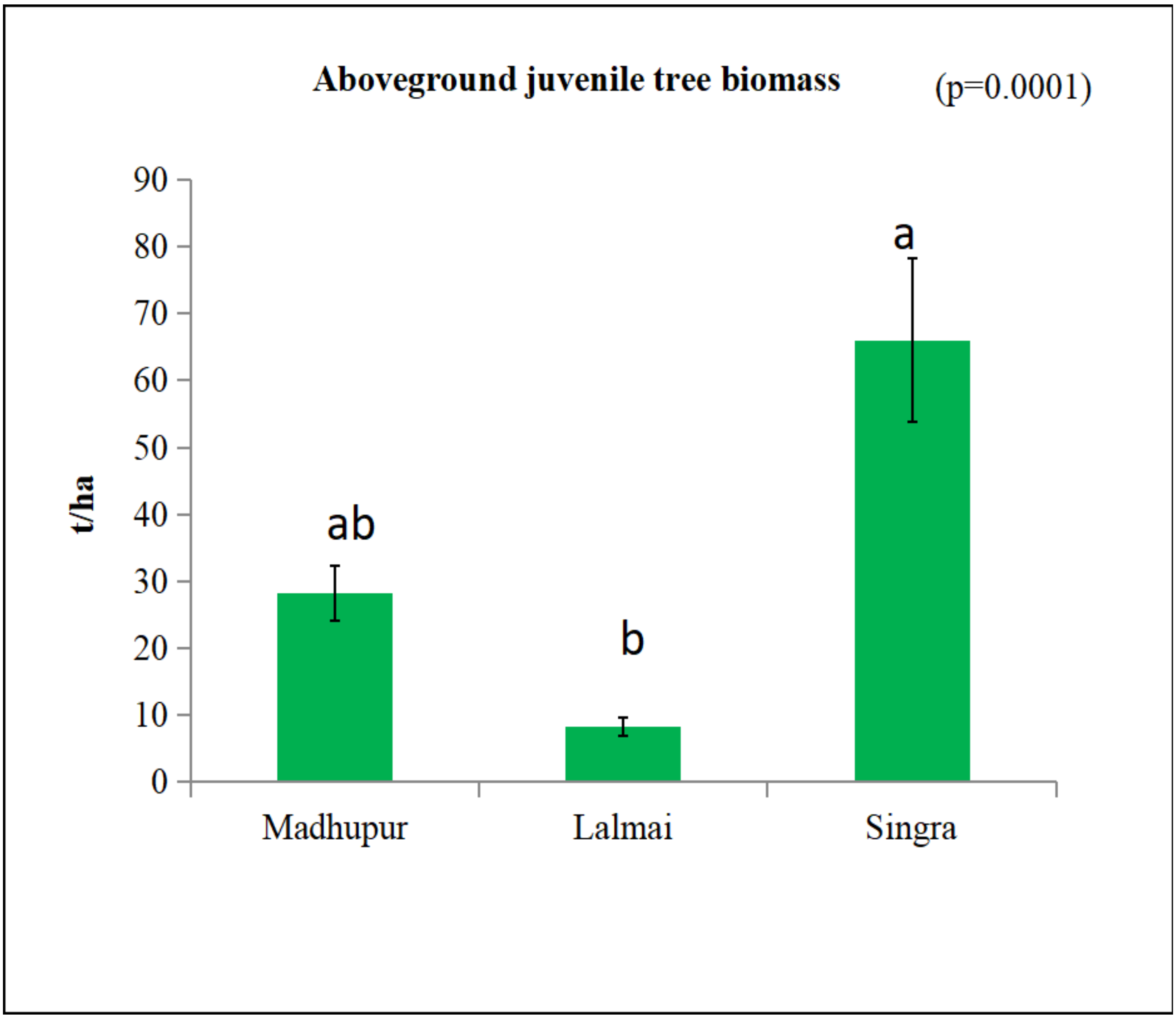


Figure 3.10: Aboveground Biomass (t/ha) of juvenile plants of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest.

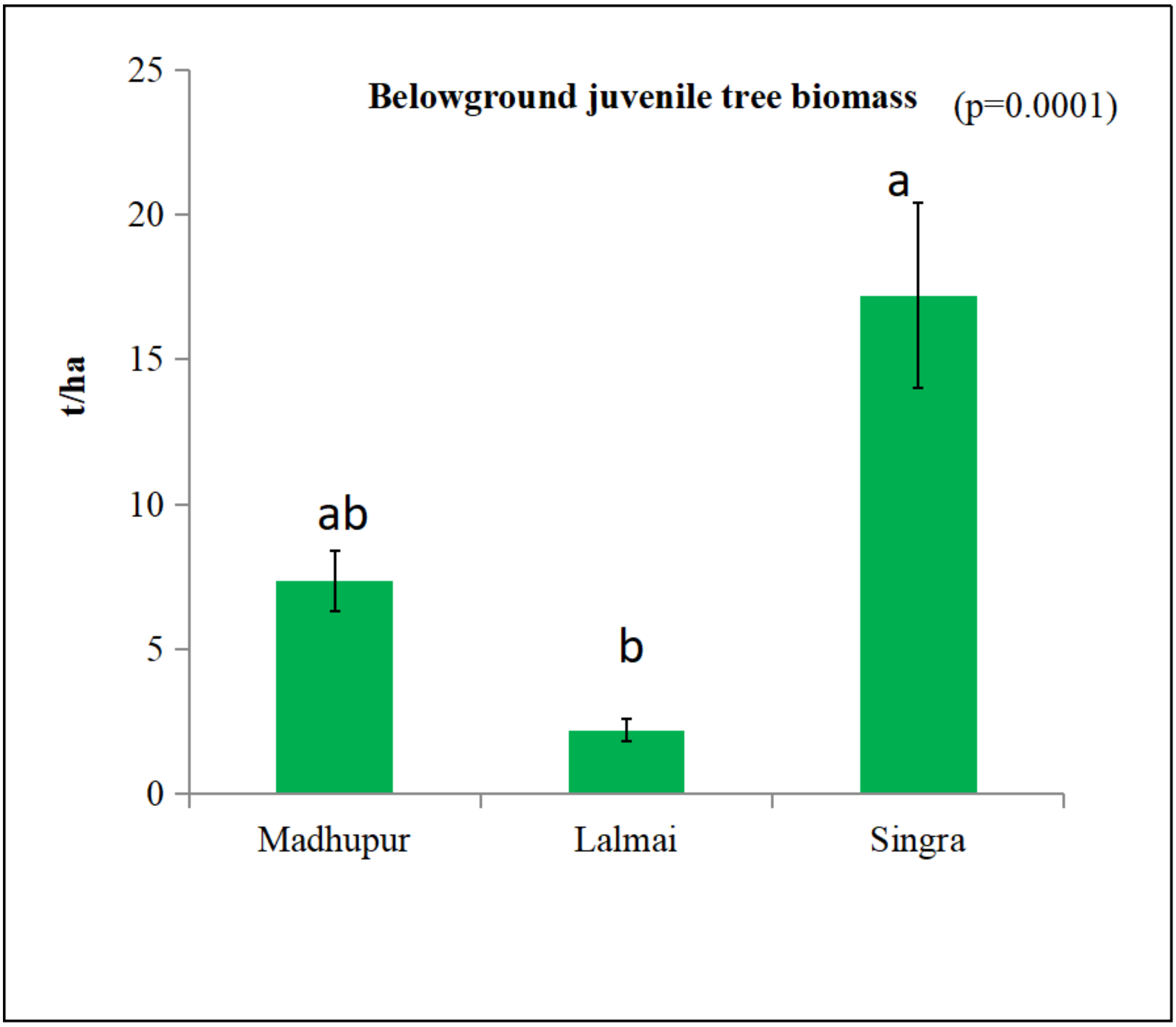


Figure 3.11: Belowground Biomass (t/ha) of juvenile plants of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest.

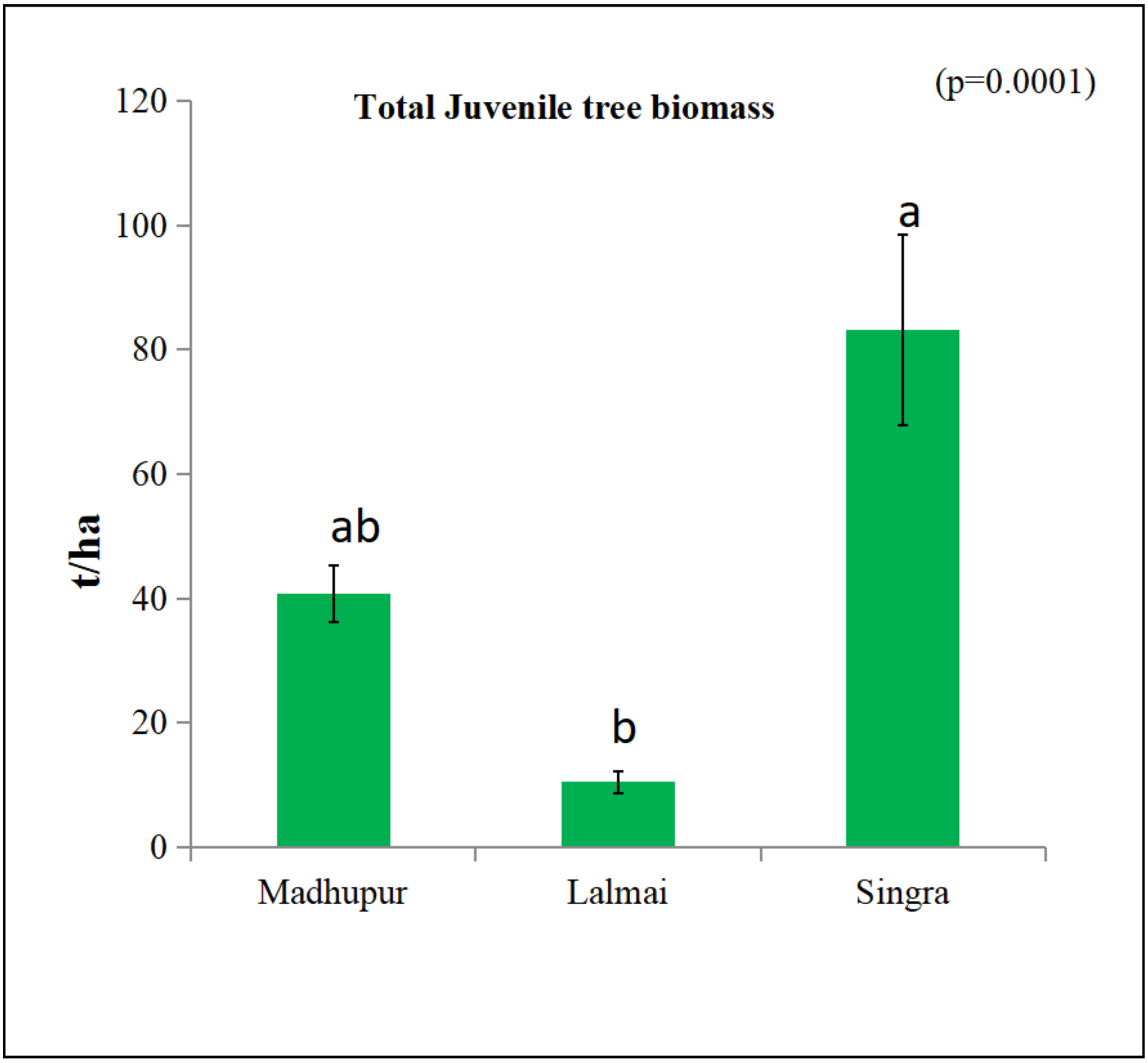


Figure 3.12: Total Biomass (t/ha) of juvenile plants of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest.

3.2.3 Biomass of Total Woody plant

The total biomass of juvenile plants and adult woody plants in tropical deciduous Madhupur Sal Forest, Lalmai Sal Forest and Singra National Park showed spatial differences among 19 quadrats (Figure 3.13). The average value of total biomass of juvenile and adult woody plants in the tropical deciduous Madhupur Sal Forest was (800.21±86.63) t/ha, the average value of total biomass of juvenile and adult woody plants in the Lalmai Sal Forest was (1240.64±143.94) t/ha and the average value of total biomass of juvenile and adult woody plants in the tropical dry deciduous Singra National Park was (1228.70±140.21) t/ha. The above- and below-ground biomass of juvenile and adult woody plants in the studied quadrats ranged from 800.21 to 1240.64 t/ha.

In terms of aboveground and belowground biomass of juvenile and adult woody plants, the three forests showed significant differences ($p < 0.0170$) and Lalmai Sal forest showed the highest value compared to the other two forests.

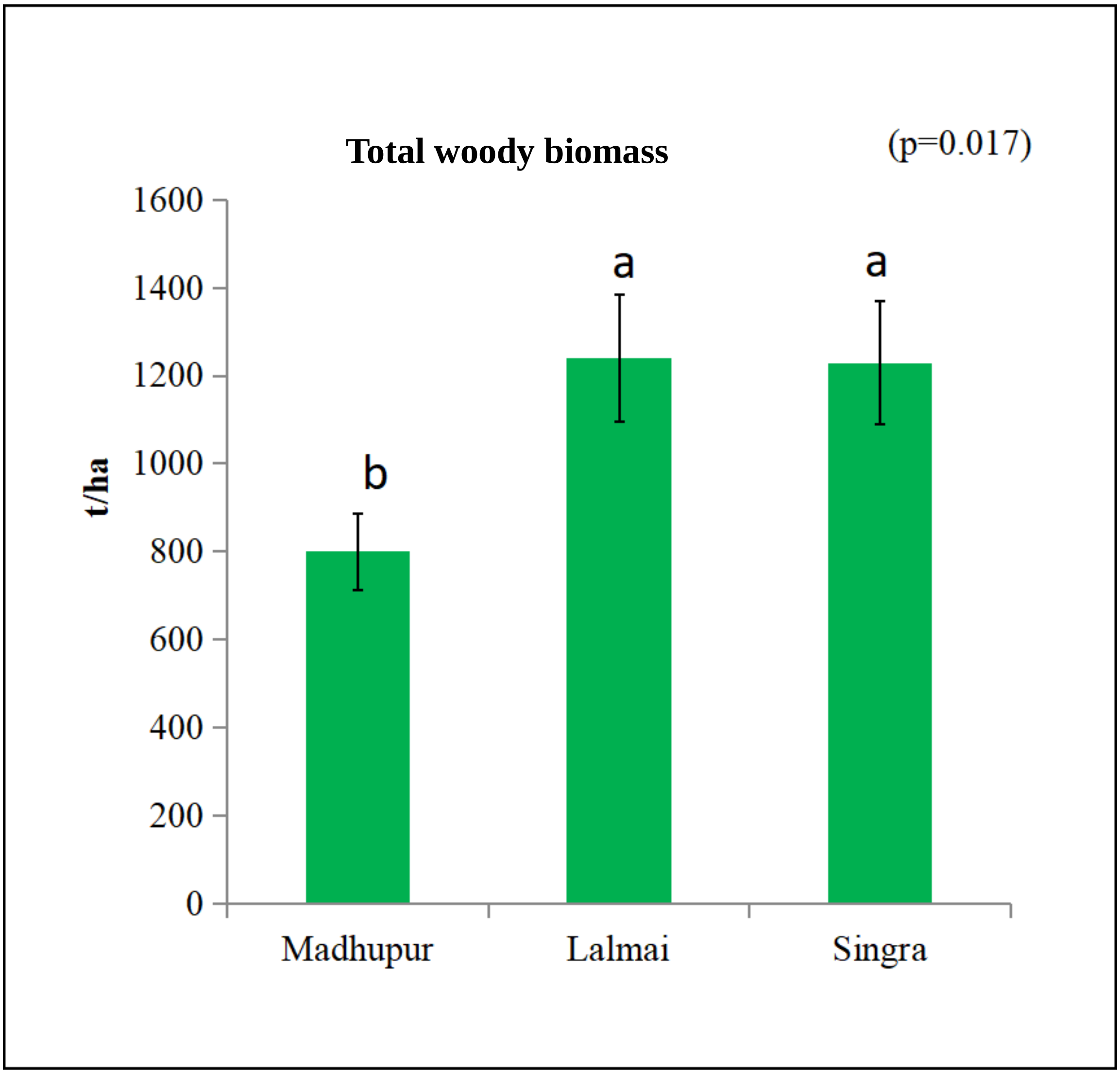


Figure 3.13: Total woody biomass (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest.

3.2.4 Biomass of Fine Root and Litter

Significant effects of forest and soil depth on total fine root biomass were observed in Madhupur Sal forest, Lalmai Sal forest and Singra National Park (Figure 3.14). The highest value was found at 10 cm depth and the lowest at 30 cm depth across these three forests. Madhupur forest showed the highest value among three depths. On the other hand, in terms of litter biomass on the forest floor, significant forest effects was observed on litter biomass in Madhupur Sal forest, Lalmai Sal forest and Singra National Park (Figure 3.15). Lalmai Sal Forest showed significantly the lowest values compared to the other two forest sites.

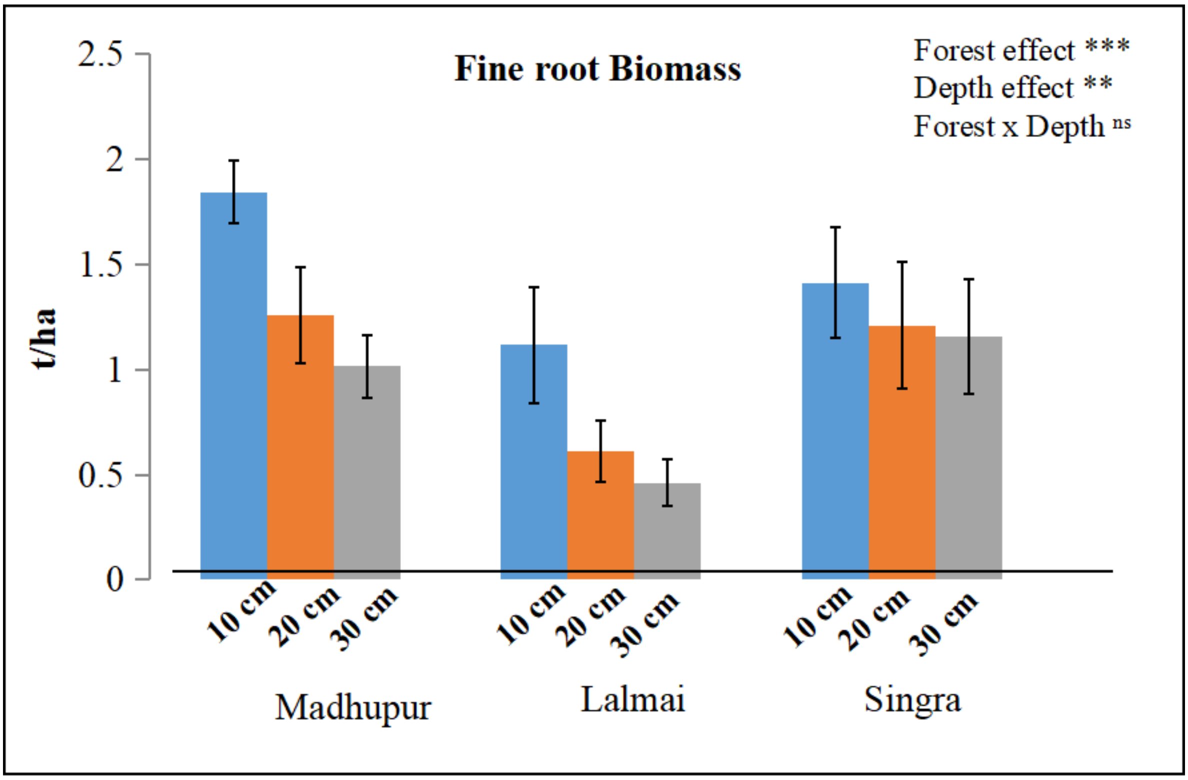


Figure 3.14: Fine root biomass (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

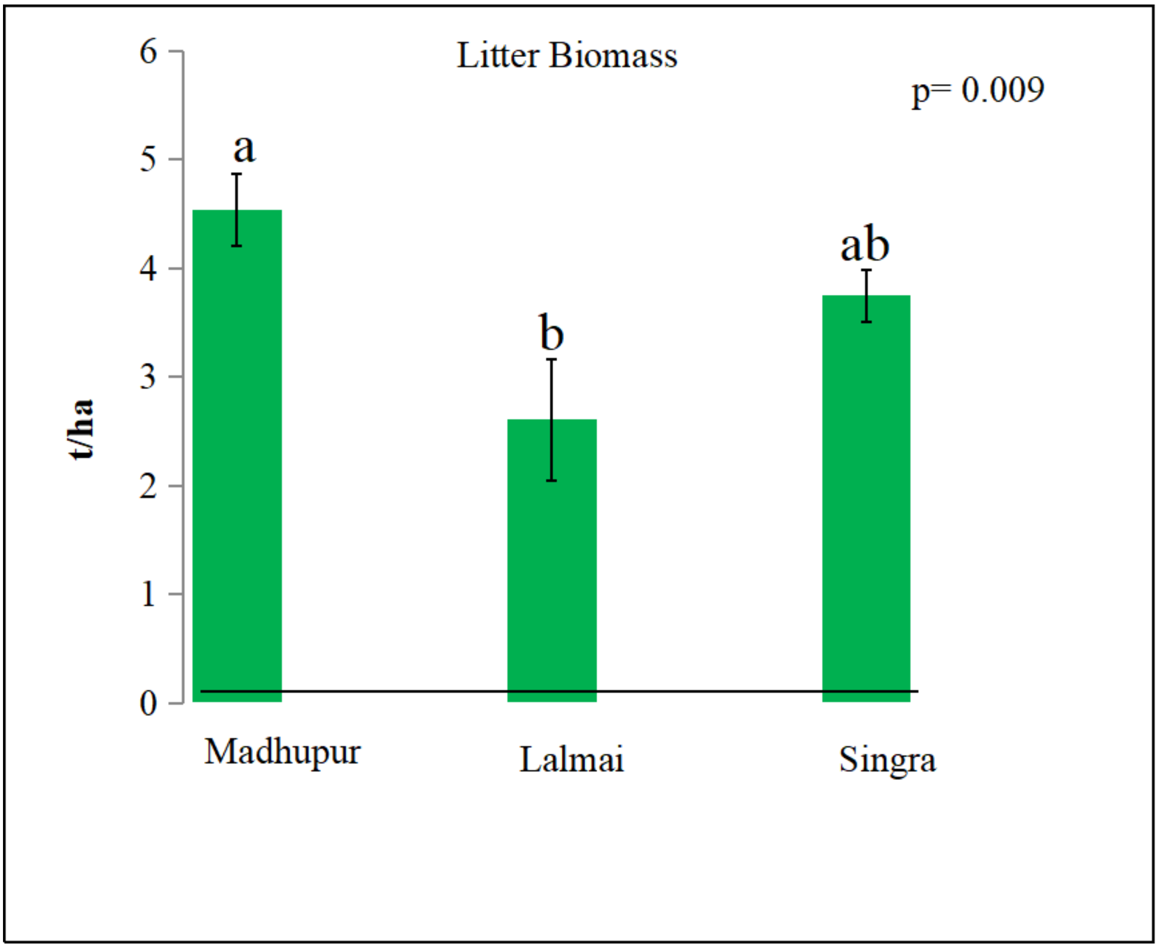


Figure 3.15: Litter biomass (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

3.2.5 Comparison of biomass C among the selected Sal forests

3.2.5.1 Adult tree C

The total C of woody plants in the Madhupur Sal forest, Lalmai Sal forest and Singra National Park showed spatial differences in the studied 19 quadrats (Figure 3.16). The average aboveground C value of adult woody plants in Madhupur Sal forest was 290.70±34.12 t/ha, that in the Lalmai Sal Forest it was 469.51±54.20 t/ha and in Singra National Park it was 441.45±50.34 t/ha. The aboveground C of woody plants in the studied quadrats ranged from 290.70 to 469.51 t/ha. In terms of aboveground C of adult trees, the three forests showed significant differences ($p < 0.0161$) and Lalmai Sal forest showed the highest value compared to the other two forests.

Similarly, the total belowground C of adult woody plants in Madhupur Sal forest was 47.50±5.23 t/ha, in Lalmai Sal forest 78.30±9.43 t/ha and in Singra National Park it was 68.66±7.65 t/ha (Figure 3.17). The amount of belowground C of woody plants in the studied quadrats ranged from 47.50 to 78.30 mg/ha. In terms of belowground C of adult trees, the three forests showed significant differences ($p < 0.0146$) and Lalmai forest showed the highest value compared to the other two forests.

Therefore, the total C (ATC=AGC + BGC) of adult trees in the three selected forests was 338.20±39.35 tons/ha in Madhupur Sal forest, 547.80±63.60 tons/ha in Lalmai Sal forest and 510.10±57.98 t/ha in Singra National Park (Figure 3.18). In terms of aboveground and belowground C of woody plants in the studied quadrats, the total C of adult trees in the three forests showed significant differences ($p < 0.0159$) and Lalmai forest it showed the highest value compared to the other two forests.

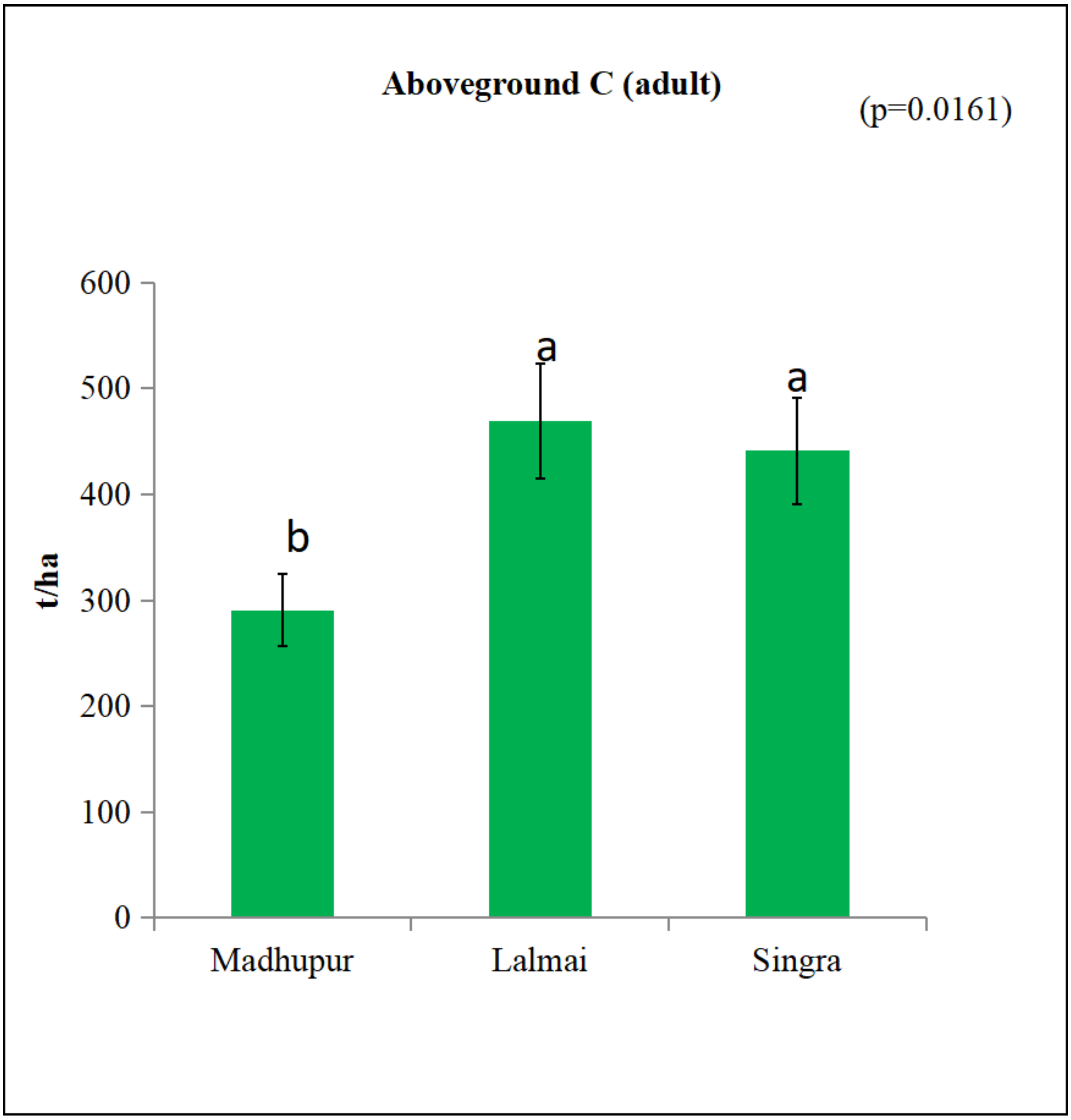


Figure 3.16: Carbon density (t/ha) of adult tree plants (Aboveground) of the Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

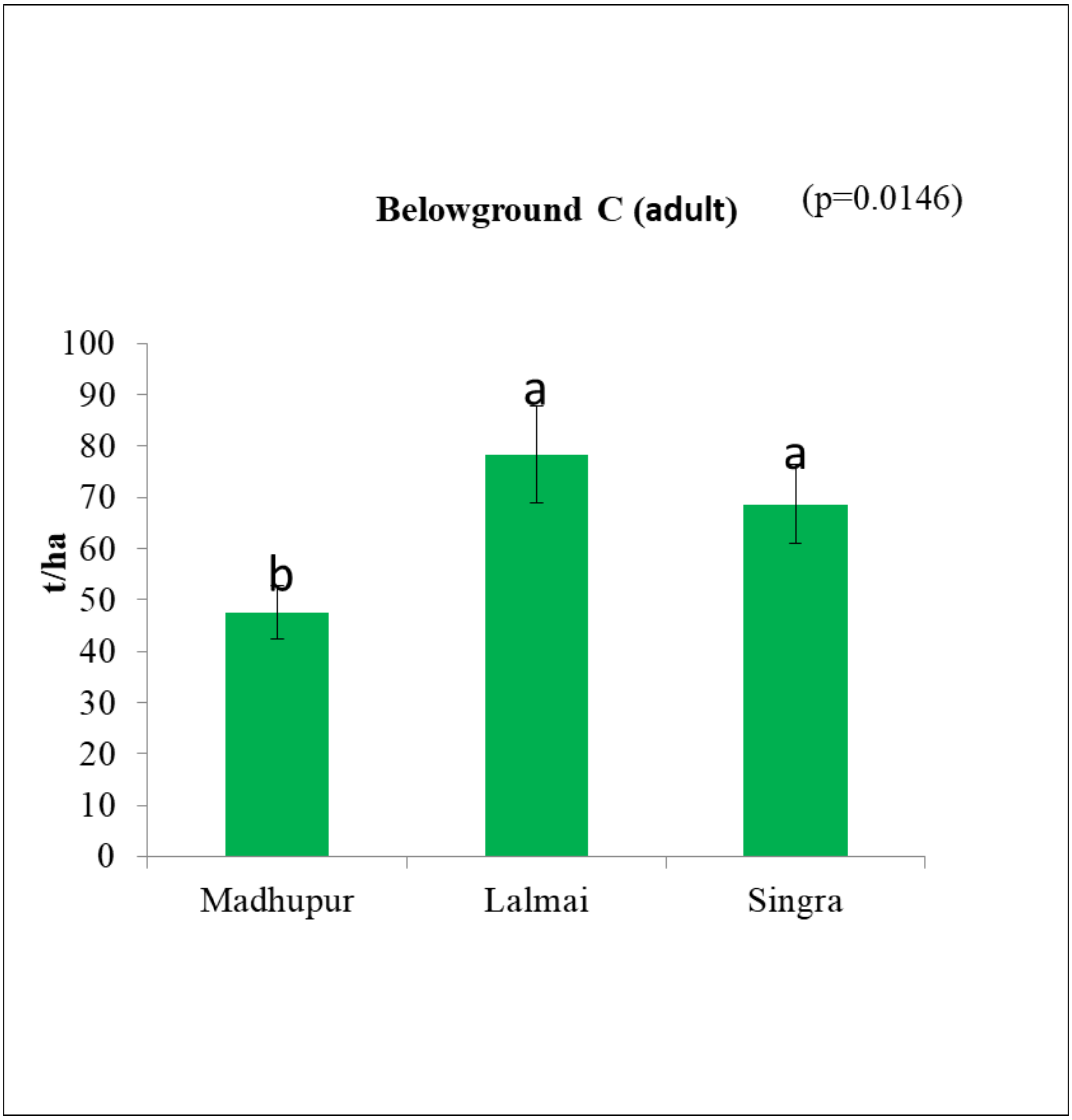


Figure 3.17: Carbon density (t/ha) of adult tree plants (Belowground) of the Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

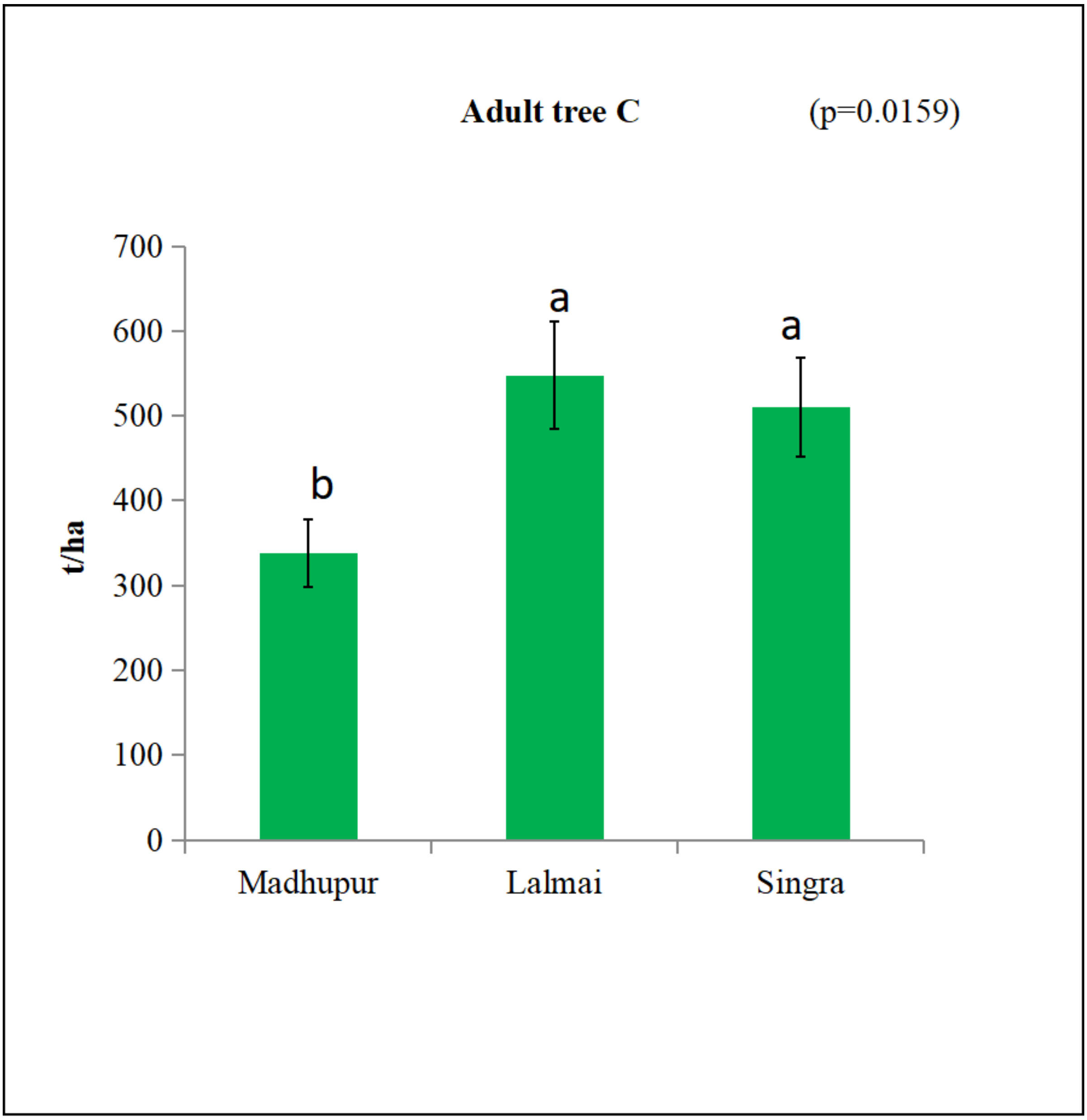


Figure 3.18: Carbon density (t/ha) of adult tree plants of the Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

3.2.5.2 Juvenile tree Carbon

The total C of woody plants in the Madhupur Sal forest, Lalmai Sal forest and Singra National Park showed spatial differences among them (Figure 3.19). The average aboveground C value of juvenile woody plants in Madhupur Sal forest was 12.57±1.80 t/ha, in the Lalmai Sal Forest it was 3.71±0.64 t/ha and in the Singra National Park it was 29.38±5.41 t/ha. The aboveground C of woody plants in the studied quadrats ranged largely from 3.71 to 29.38 t/ha. In terms of aboveground C of juvenile trees, the three forests showed significant differences ($p < 0.0001$) and Lalmai Sal forest showed the lowest value compared to the other two forests.

Similarly, total belowground C of juvenile woody plants in Madhupur Sal forest was 3.30±0.47 t/ha, in Lalmai Sal forest was 0.96±0.17 t/ha and in Singra National Park it was 7.64±1.41 t/ha. The amount of belowground C of woody plants in the studied quadrat ranged from 0.96 to 7.64 t/ha. In terms of belowground C of juvenile trees, the three forests showed highly significant differences ($p < 0.0001$) and Lalmai forest showed the lowest value compared to the other two forests (Figure 3.20). The total C (ATC=AGC + BGC) of juvenile trees in the three selected forests was 15.84±2.27 tons/ha in Madhupur Sal forest, 4.67±0.80 tons/ha in Lalmai Sal forest and 37.02±6.82 tons/ha in Singra National Park. In terms of aboveground and belowground C of woody plants in the studied quadrat, the total C of juvenile trees in the three forests showed highly significant differences ($p < 0.0001$) and Singra National Park it showed the highest value compared to the other two forests (Figure 3.21).

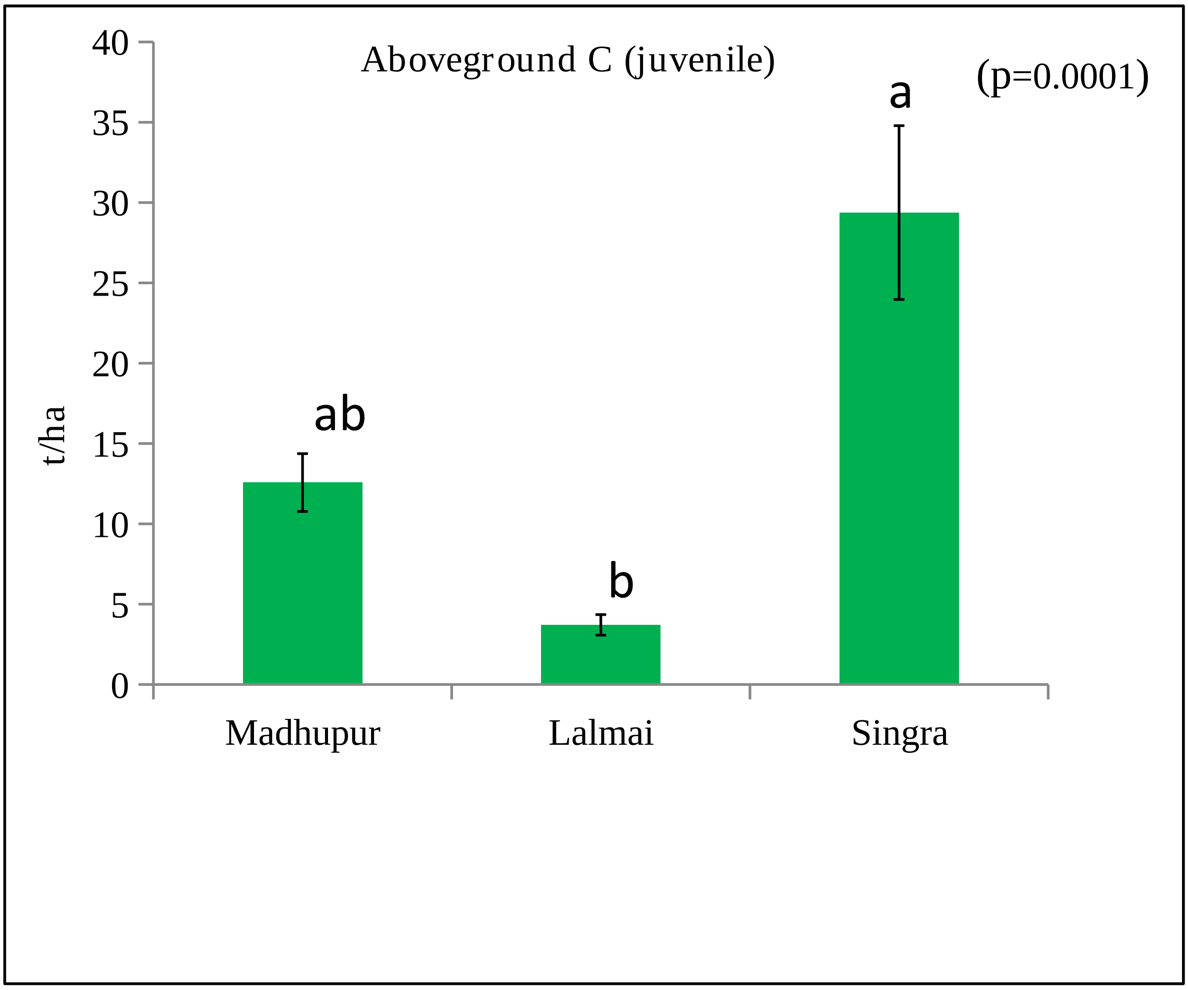


Figure 3.19: Carbon density (t/ha) of the aboveground (juvenile) tree plants of the Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

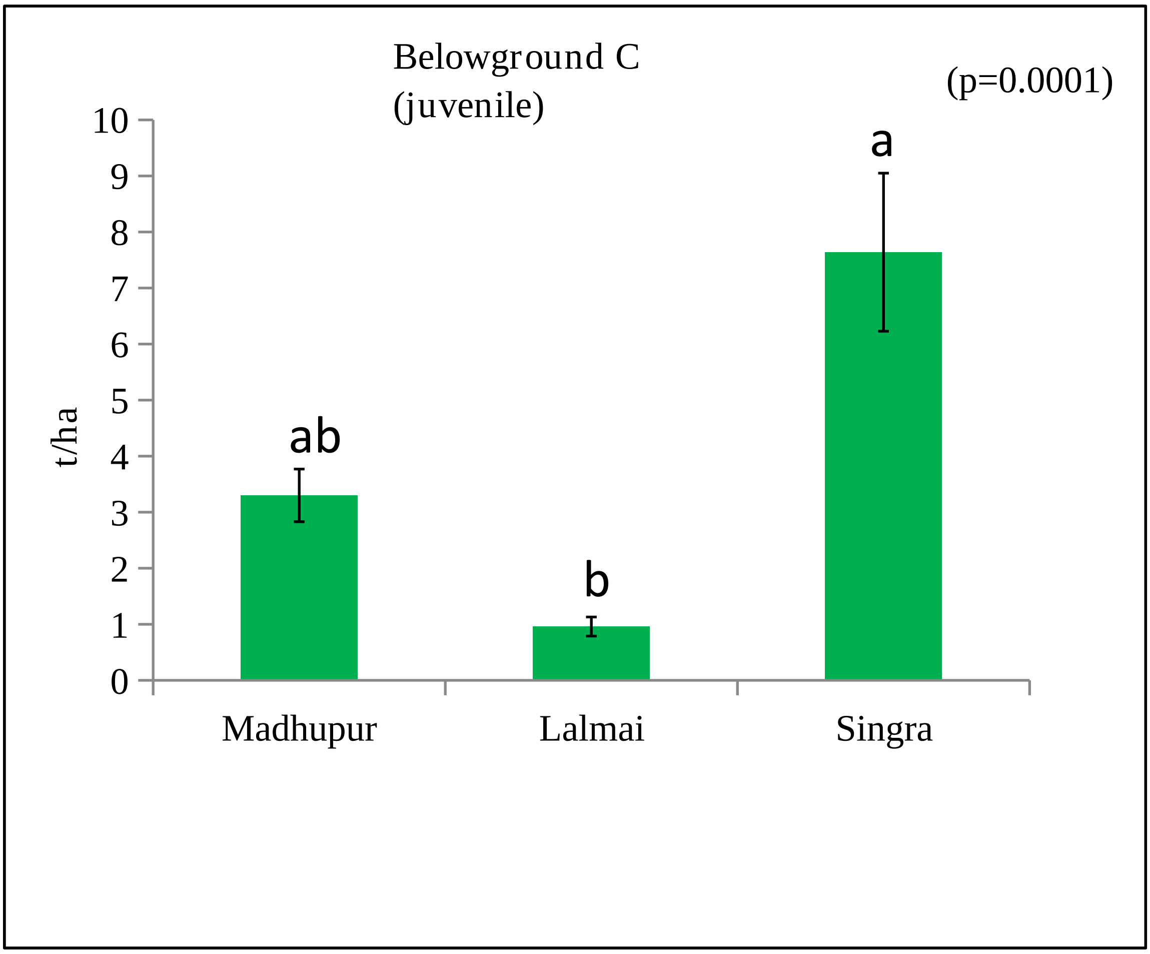


Figure 3.20: Carbon density (t/ha) of the belowground (juvenile) tree plants of the Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

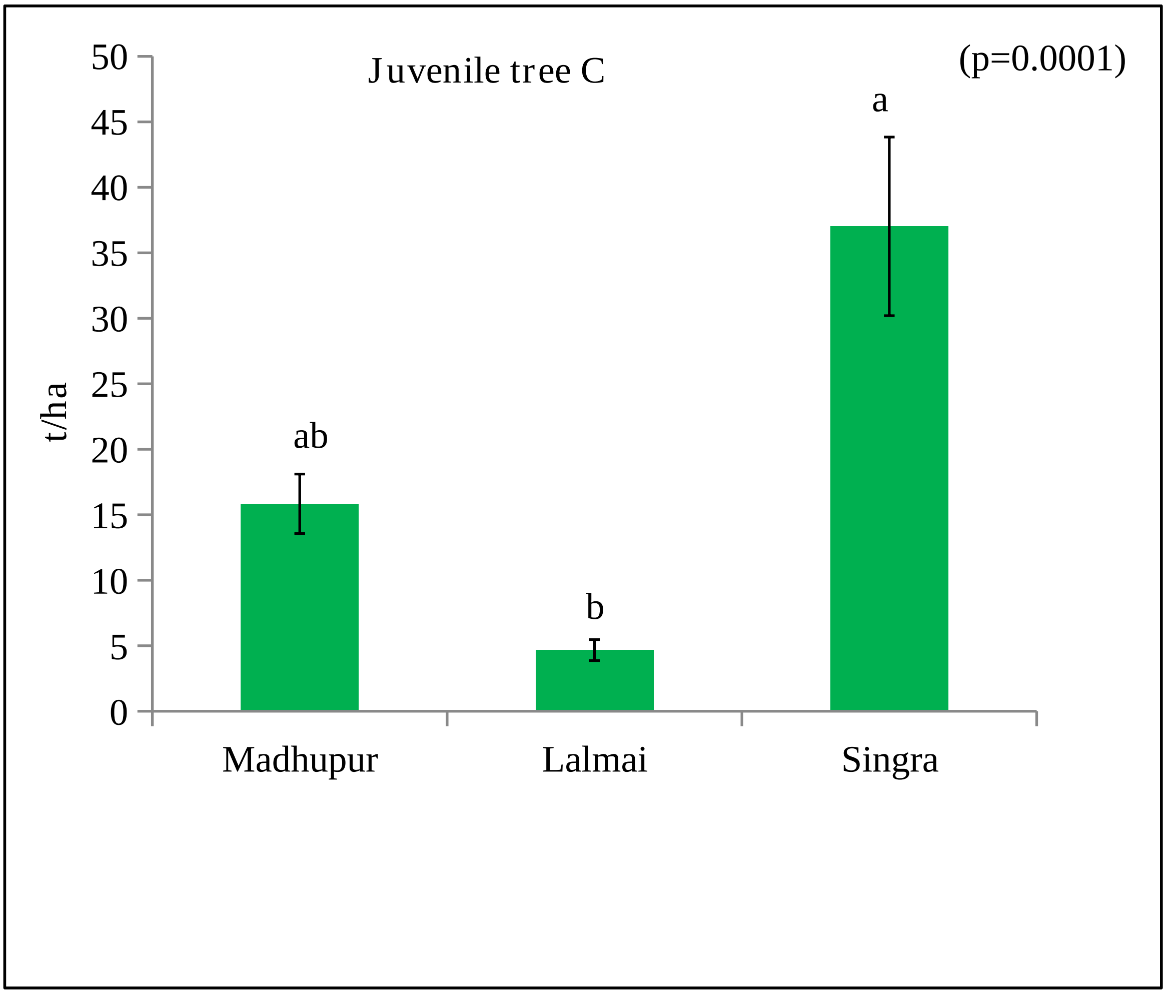


Figure 3.21: Carbon density (t/ha) of the Juvenile tree plants of the Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.2.5.3 Total woody Carbon

The total C of juvenile plants and adult woody plants in tropical deciduous Madhupur Sal forest, Lalmai Sal forest and Singra National Park showed spatial differences among the selected 19 quadrats (Figure 3.22). The average value of total C of adult and juvenile woody plants in Madhupur Sal forest was 354.03±38.43 t/ha, in Lalmai Sal forest was 552.46±64.09 t/ha and in Singra National Park was 547.13±62.43 t/ha. The above- and below-ground C of juvenile and adult woody plants in the studied quadrats ranged from 354.03 to 552.46 t/ha. In terms of aboveground and belowground C of juvenile and adult woody plants, the three forests showed significant differences ($p < 0.0156$) and Lalmai Sal forest showed the highest value compared to the other two forests.

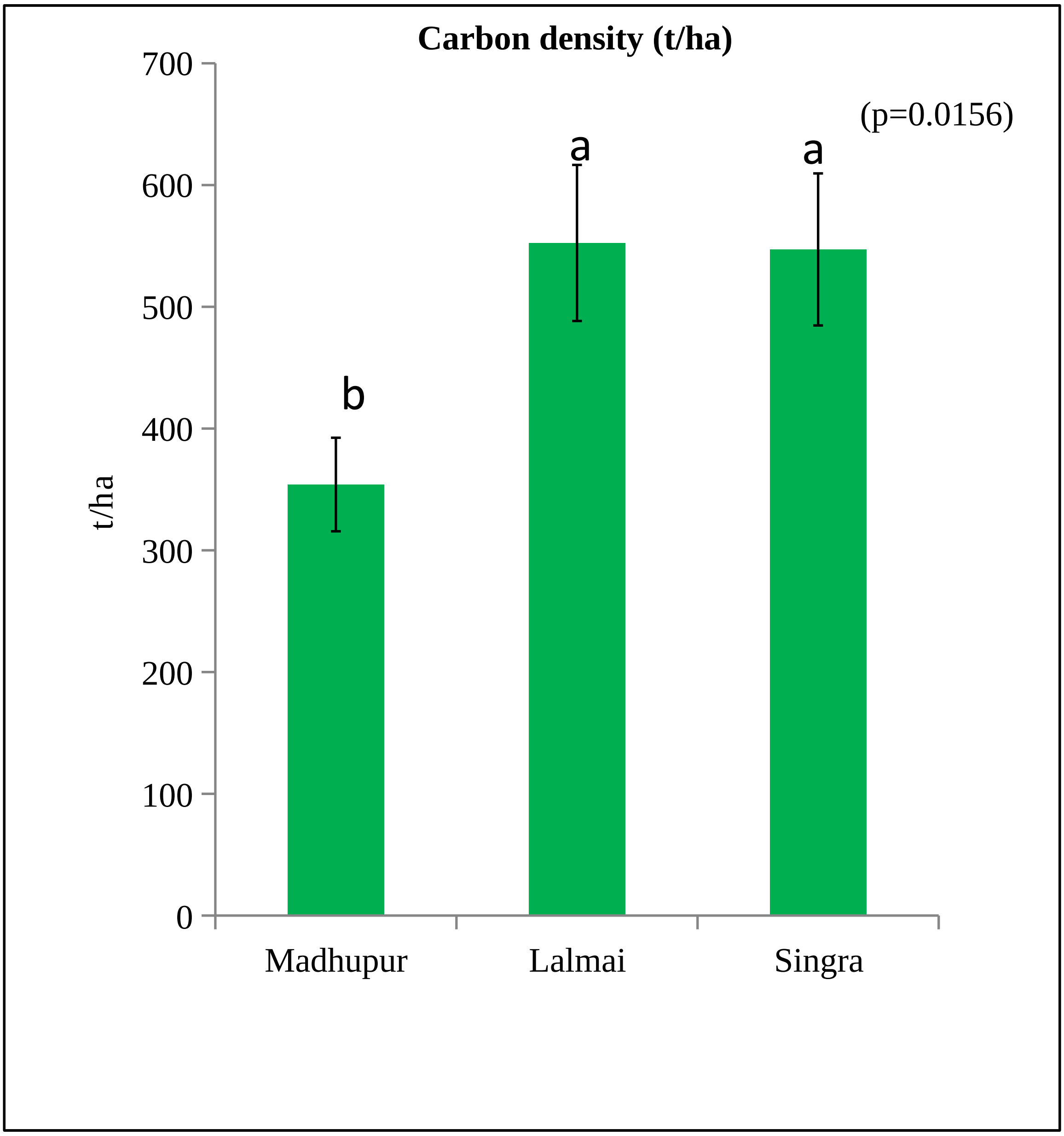


Figure 3.22: Carbon density (t/ha) of total woody plants of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.2.6 Comparison of C pools of selected Sal forests in Bangladesh

3.2.6.1 Total litter C of the three forests

The aboveground litter carbon in Madhupur Sal forest was 1243.93±167.98 t/ha, in Lalmai Sal forest was 466.43±222.23 t/ha and in Singra National Park it was 828.04±97.44 t/ha (Figure 3.23). The aboveground litter carbon stock in the studied forests ranged from 466.43 to 1243.93 t/ha. In terms of litter carbon pool, the three forests showed significant differences ($p < 0.020$) and Lalmai forest showed the lowest value compared to the other two forests.

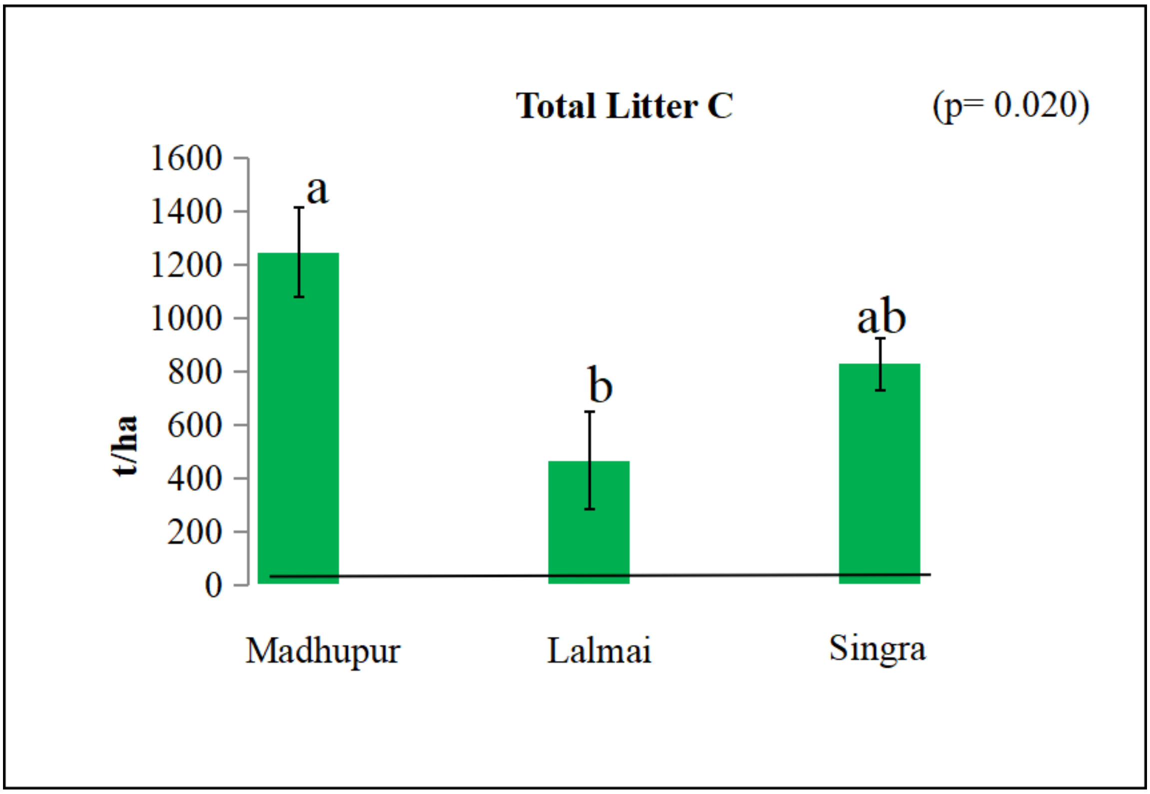


Figure 3.23: Total litter C contents in different pools of Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

3.2.6.2 Total root C and Total soil C

Significant effects of forest ($p < 0.01$) and soil depth ($p < 0.01$) were observed on total fine root carbon in Madhupur Sal forest, Lalmai Sal forest and Singra National Park (Figure 3.24). The highest value among these three forests was found at 10 cm depth and the lowest at 30 cm depth. Madhupur Forest showed the highest value among all three depth categories. On the other hand, in case of total soil carbon, a significant effect of forest ($p < 0.0001$) was observed on total soil carbon in Madhupur Sal forest, Lalmai Sal forest and Singra National Park, and no significant effect of soil depth was observed. (Figure 3.25). Singra forest showed the significantly higher value compared to the other two forests. Although there was no significant effect of depth, the value was higher in 10 cm among all these three forests.

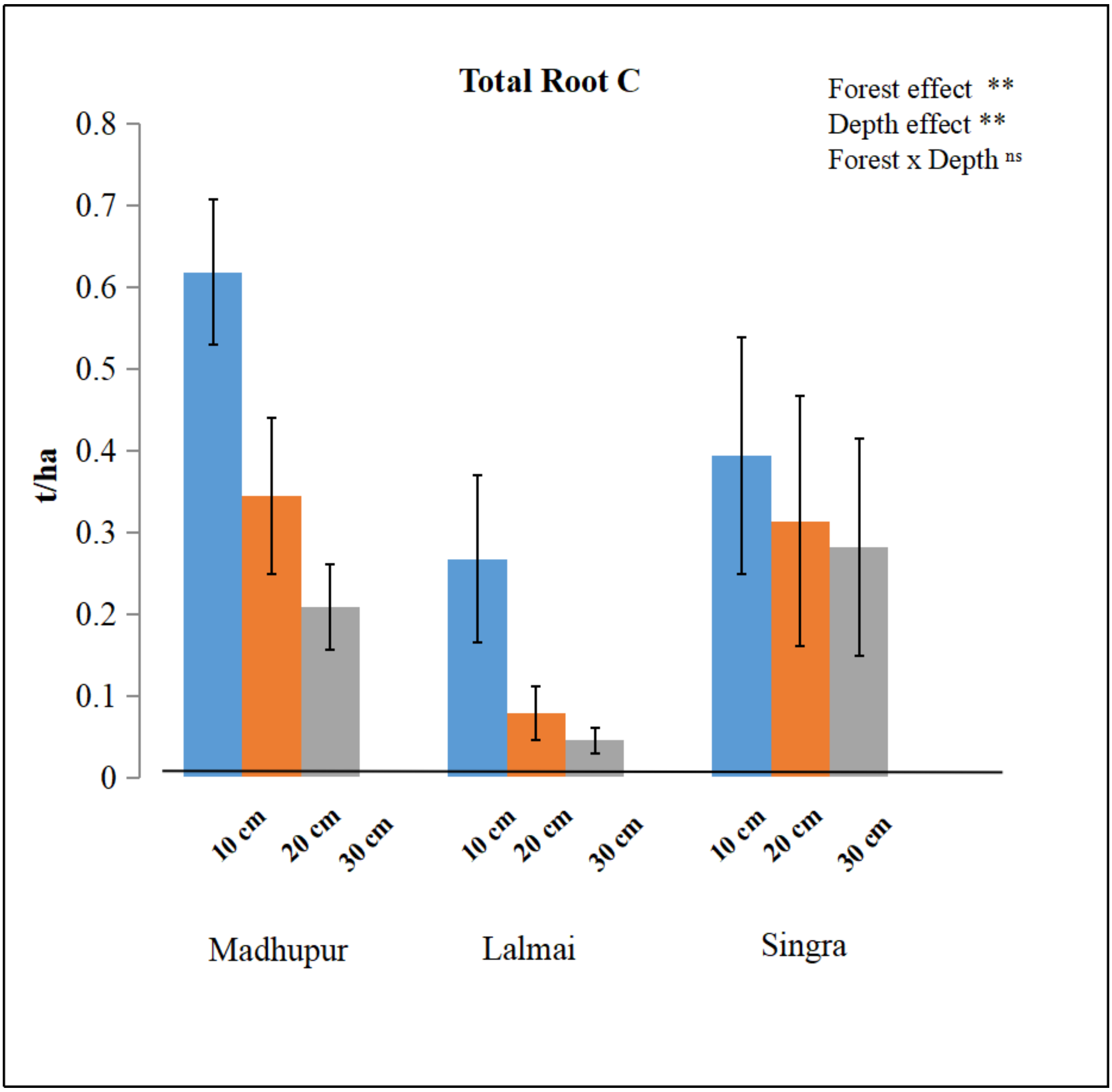


Figure 3.24: Total root C contents in different pools of Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

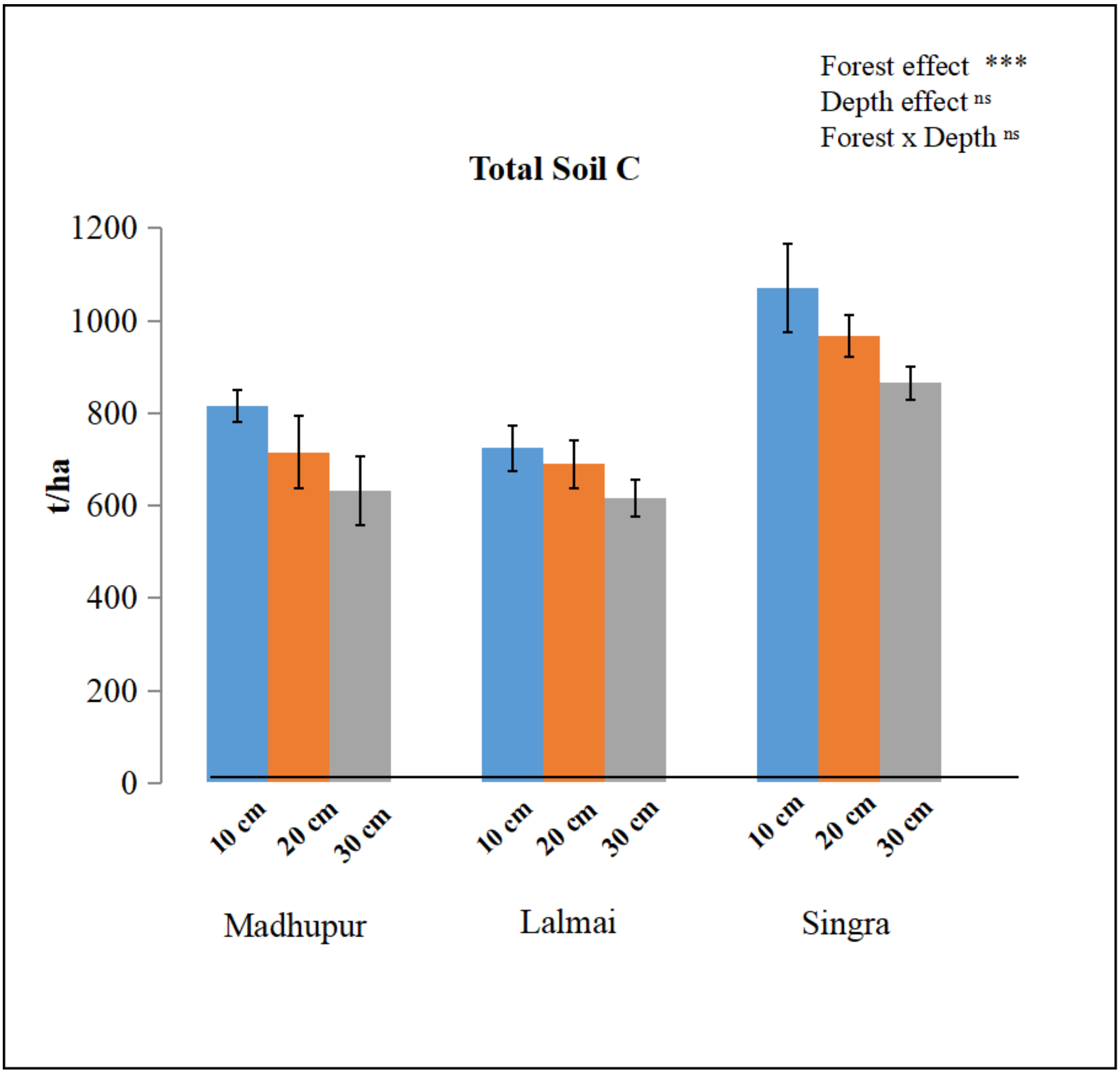


Figure 3.25: Total soil C contents in different pools of Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

3.2.7 Comparison of Organic C contents among the selected Sal forests

3.2.7.1 Soil Organic C

There was a significant effect of forest ($p < 0.0001$) on soil organic carbon. (Figure 3.26). Singra Forest showed the significantly higher value compared to the other two forests. Although there was no significant effect of depth but the mean value was higher in 10 cm and lower in 30 cm among the three forests.

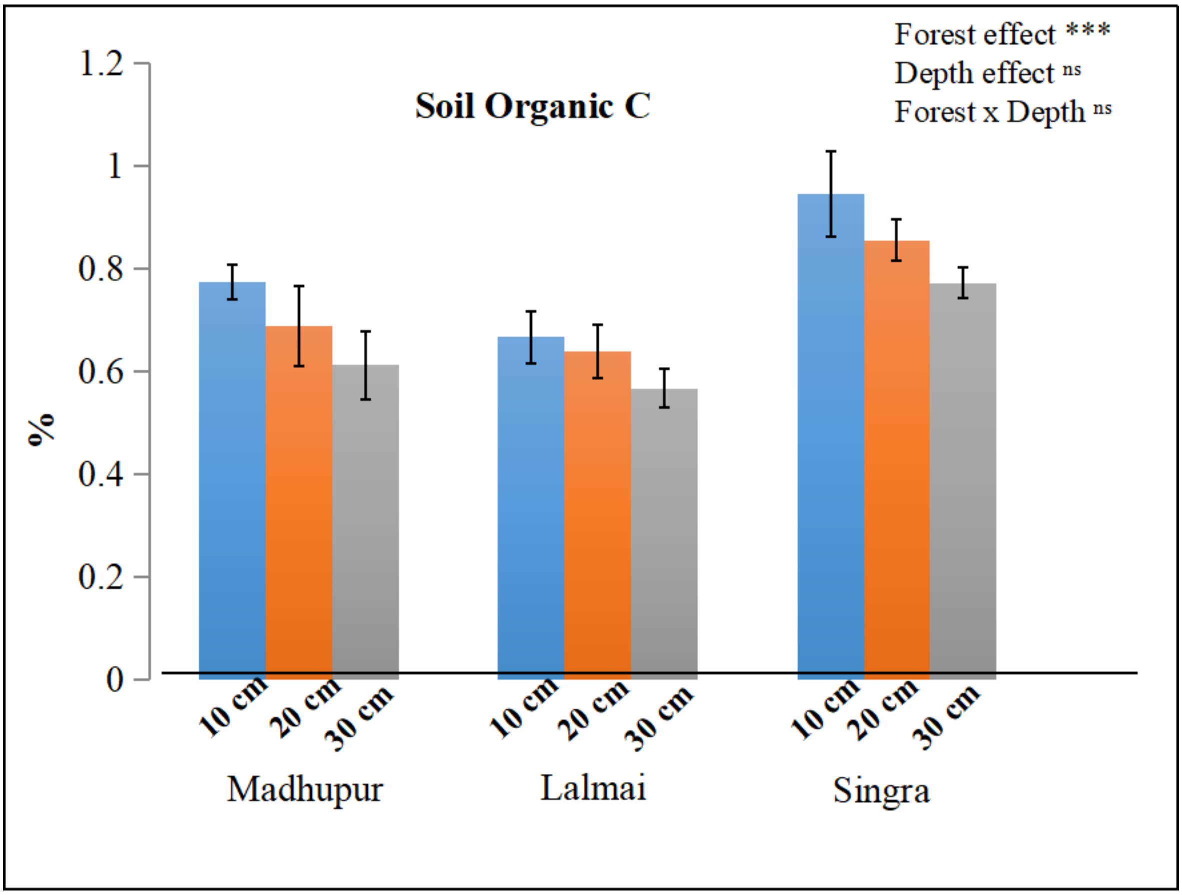


Figure 3.26: Soil organic C (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

3.2.7.2 Root Organic C

In case of fine root organic C (%), significant effects of forest ($p < 0.0001$) and soil depth ($p < 0.01$) on fine root organic C was observed in Madhupur Sal forest, Lalmai Sal forest and Singra National Park (Figure 3.27). The highest value among these three forests was found at 10 cm depth, and the lowest value was found at 30 cm depth. Madhupur forest showed the highest values among all three forests.

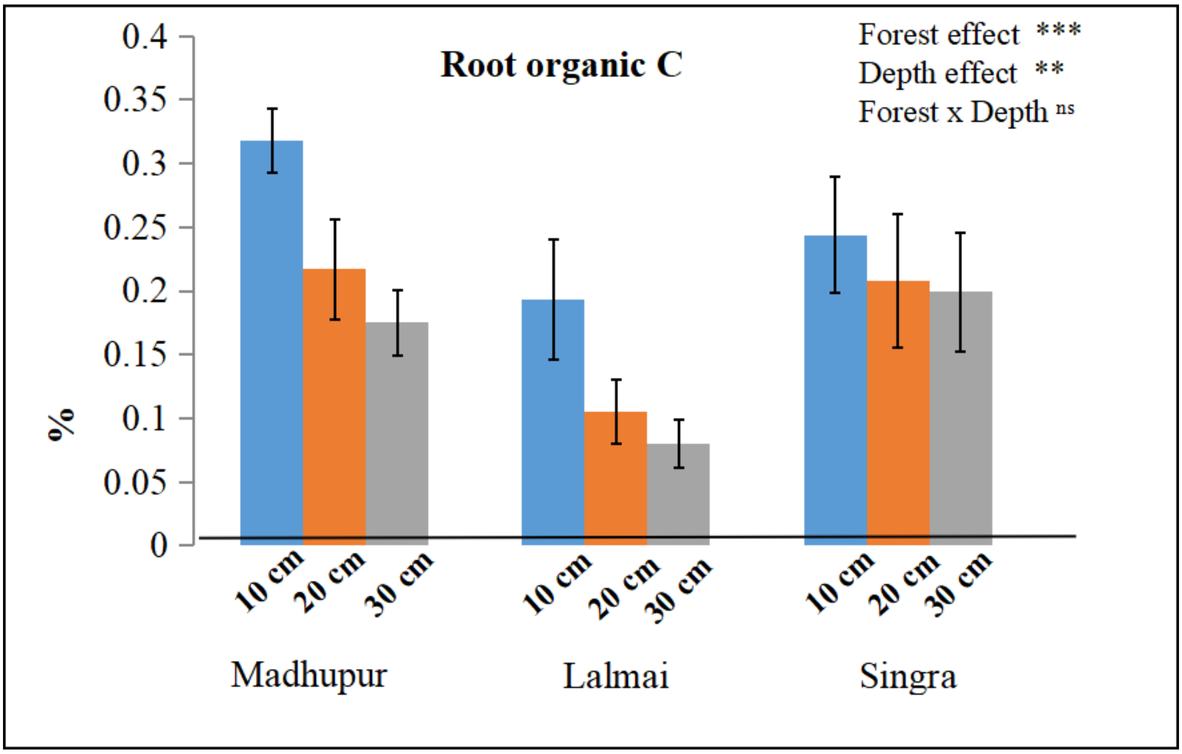


Figure 3.27: Root organic carbon (C) % of Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

3.2.7.3 Litter Organic C

Madhupur Sal forest, Lalmai Sal forest and Singra National Park showed significant differences in litter organic C (Figure 3.28). Madhupur Sal Forest showed the highest value compared to other two forests and Lalmai Sal forest showed the lowest value.

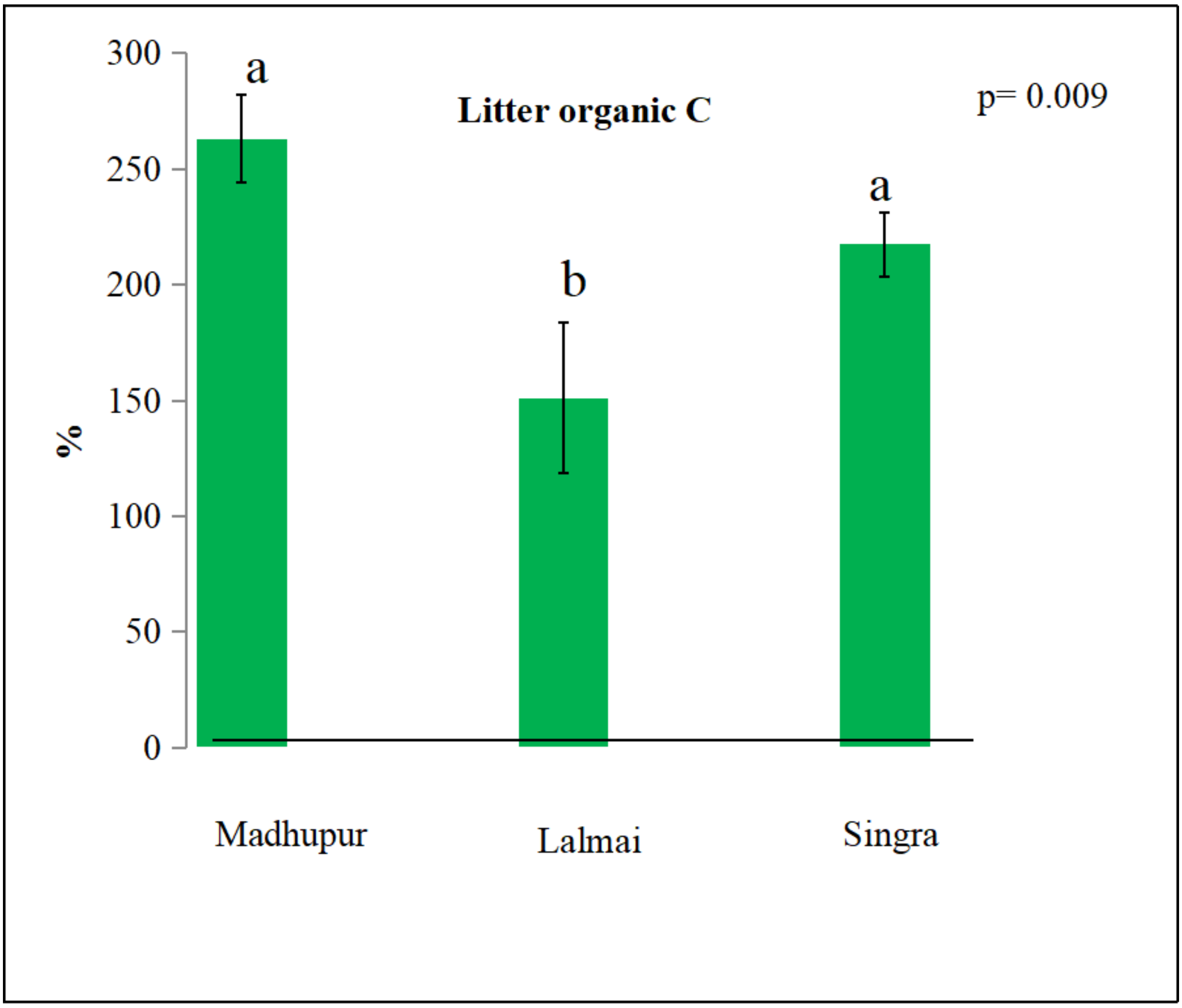


Figure 3.28: Mean values of litter organic C (%) in Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

3.2.8 Comparison of soil properties among the selected Sal forests

3.2.8.1 Soil pH

Two-way ANOVA statistics for soil pH were shown in Table 3.5. Two-way ANOVA was applied to test the relative influence of forest, soil, and their interaction on soil parameters. Soil pH was significantly affected by forest ($p < 0.0001$) and soil depth ($p < 0.011$) (Figure 3.29). However, soil pH was not significantly affected by their interaction. Among the three forests, the highest pH was found at 10 cm soil depth in Madhupur forest (5.92±0.3) and the lowest value of that was found at 20 cm soil depth in Lalmai forest (4.86±0.07). The lowest pH value in Lalmai Sal forest at 20 cm depth (4.86±0.07) indicated that the soil in Lalmai Sal forest was more acidic.

Table 3.5 Mean Value of different soil parameters of deciduous forest in Bangladesh.

Soil parameter	Lalmai Sal forest			Singra Sal forest			Madhupur Sal forest			P-Value
	10 cm	20 cm	30 cm	10 cm	20 cm	30 cm	10 cm	20 cm	30 cm	
pH	4.91±0.088	4.86±0.072	5.065±0.055	5.553±0.095	5.683±0.083	5.774±0.058	5.917±0.300	5.463±0.158	5.767±0.099	< 0.0001
Moisture(%)	19.337±1.640	19.889±1.873	19.458±0.988	13.879±1.270	14.041±0.960	15.124±0.707	23.093±0.830	24.873±0.910	26.418±1.671	< 0.0001
Conductivity	30.315±2.843	24.439±1.887	18.715±1.640	28.069±3.090	20.158±2.714	14.548±1.259	18.300±4.549	35.367±18.620	12.457±1.272	0.088
Organic C	0.667±0.050	0.639±0.052	0.568±0.038	0.946±0.084	0.856±0.040	0.773±0.030	0.774±0.034	0.689±0.077	0.613±0.066	< 0.0001
Bulk density	1.092±0.015	1.087±0.016	1.089±0.009	1.133±0.014	1.131±0.011	1.119±0.008	1.056±0.007	1.041±0.008	1.028±0.013	0.024
Total carbon	724.54±49.32	690.07±51.59	617.13±40.40	1071.14±95.27	966.82±45.99	865.27±36.02	816.65±34.81	715.98±78.14	631.67±74.80	< 0.0001
Avl. N	0.039±0.005	0.031±0.003	0.026±0.002	0.030±0.002	0.028±0.002	0.027±0.002	0.019±0.001	0.018±0.003	0.018±0.002	< 0.0001
Total P	0.029±0.003	0.026±0.003	0.024±0.003	0.046±0.004	0.039±0.004	0.037±0.004	0.052±0.006	0.015±0.001	0.016±0.001	0.0005

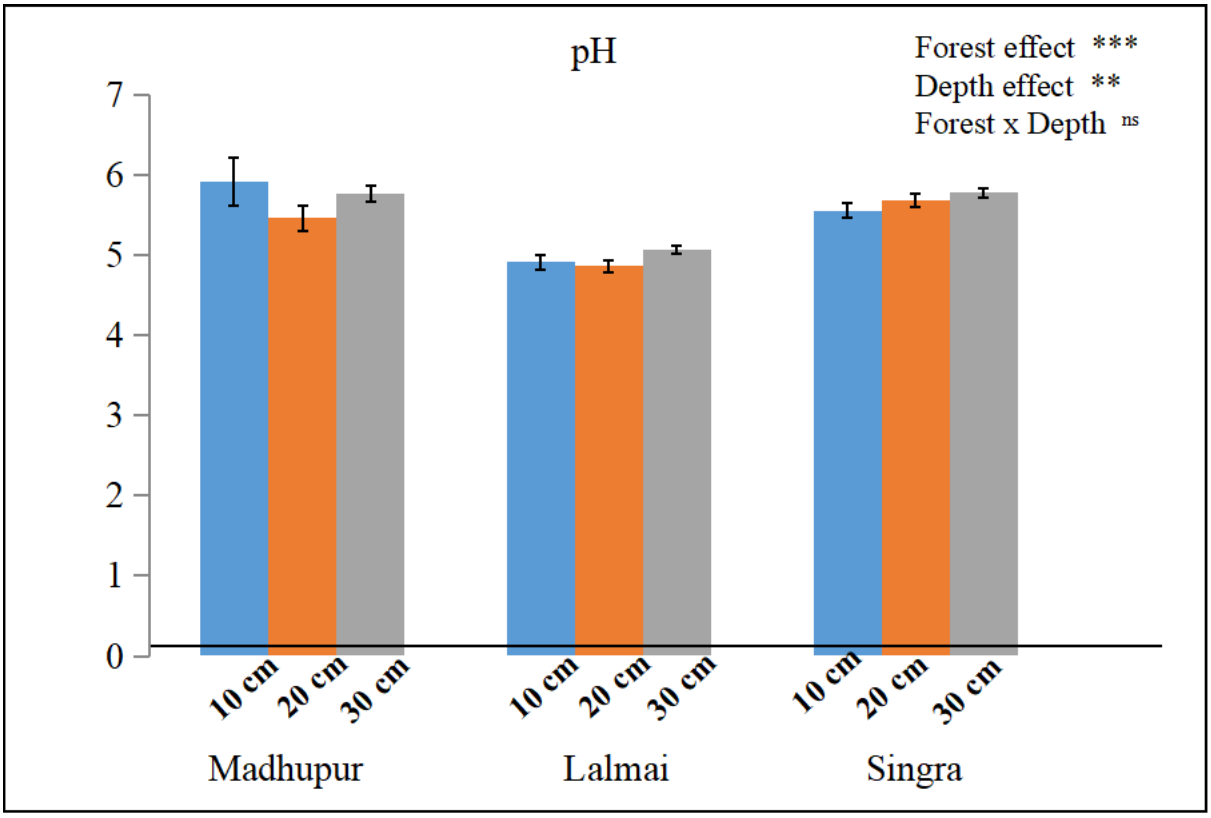


Figure 3.29: Mean pH value of the soil of Madhupur Sal forest, Lalmai Sal forest and Singra National Park.

3.2.8.2 Soil Moisture

Two-way ANOVA statistics on the effects of forest, depth and their interaction on soil moisture are shown in Table 3.5. Two-way ANOVA was applied to test the relative effects of forest, soil and soil depth on their interactions on the parameters. Forest significantly affected ($p < 0.0001$) the soil moisture among the three (Figure 3.30). But soil moisture was not significantly affected by their soil depth and interaction. Among the three forests, the highest soil moisture was found at 30 cm depth of soil in Madhupur forest (26.41 ±1.67**)** and the lowest soil moisture value was found at 10 cm depth in Singra National Park (13.88 ±1.27). These results indicate that soil of Singra National Park was dry.

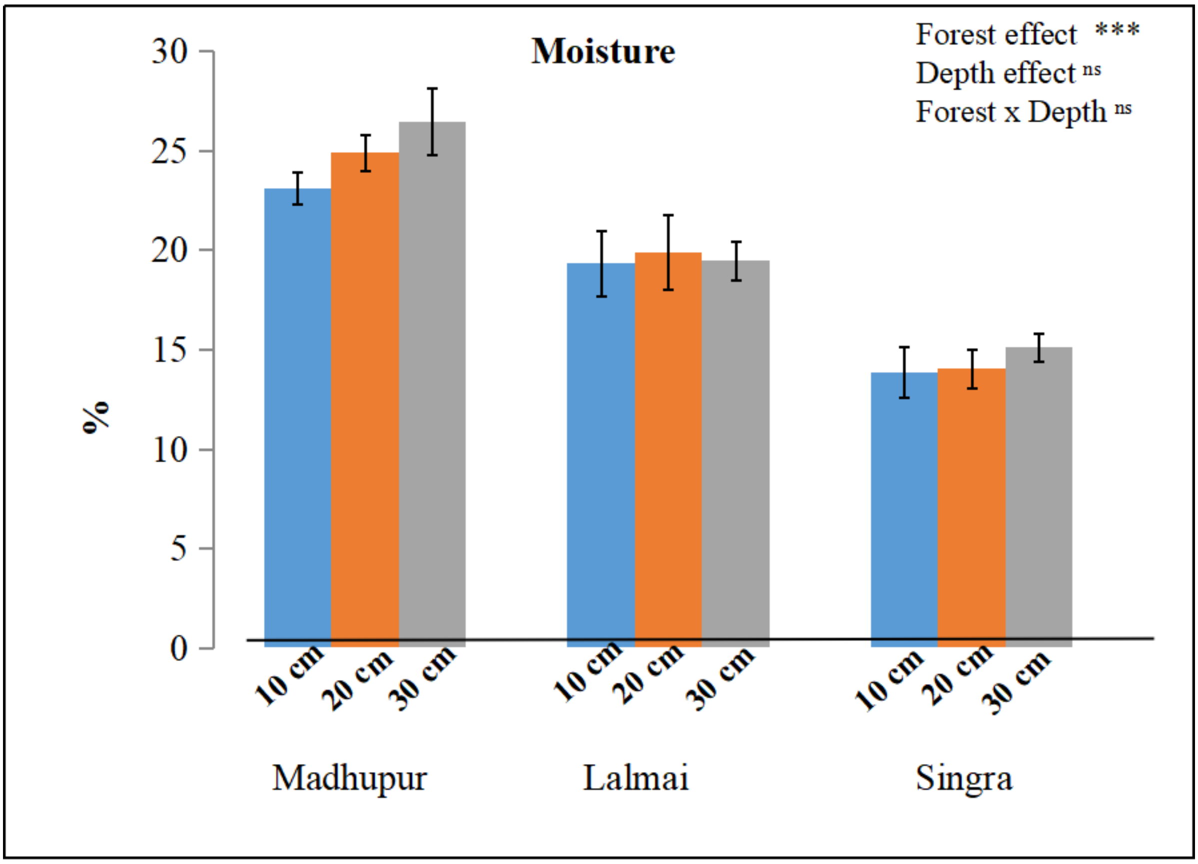


Figure 3.30: Mean value of soil moisture content (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.2.8.3 Electrical conductivity

Data showed that depth significantly ($p < 0.001$) affected the soil electrical conductivity, although the effects of forest and interactions between forest and depth were not significant. The mean values of the effects of forest, soil depth and their interaction on soil electrical conductivity of Madhupur Sal forest, Lalmai Sal forest and Singra National Park were shown in Figure 3.31. Among the three forests, the highest soil electrical conductivity was found in Lalmai Sal forest at 10 cm depth (30.31 ± 2.84 µS/cm) and the lowest value was found in Madhupur Sal forest at 30 cm depth (12.45 ± 1.27 µS/cm).

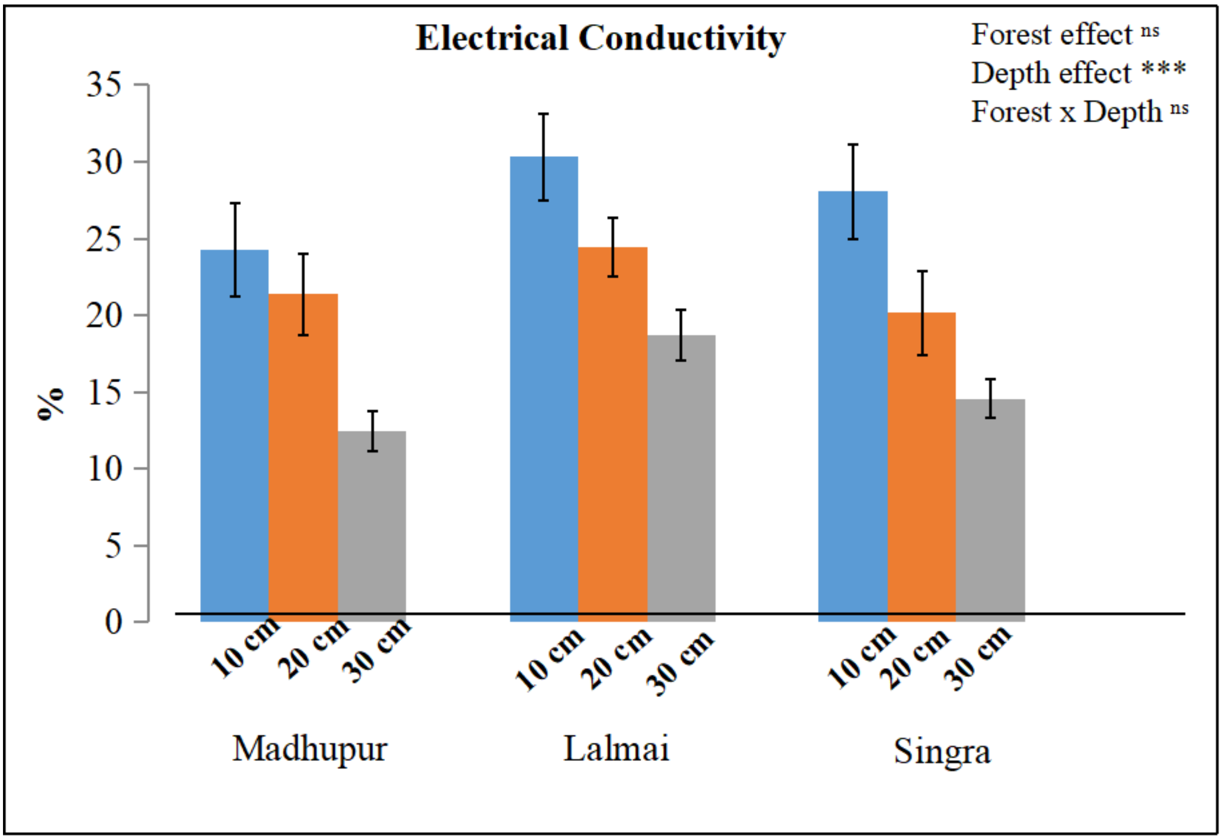


Figure 3.31: Mean values of soil electrical conductivity (%) of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

3.2.8.3 Bulk Density

The mean values of the effects of forest, soil depth and the interaction between these two factors on soil bulk density of Madhupur Sal forest, Lalmai Sal forest and Singra National Park were shown in Figure 3.32. Soil depth and interaction between forest and soil had no significant effect on soil bulk density. However, forest type showed significant effects on soil bulk density ($p < 0.01$). Among the three forests, Singra National Park had the highest value of soil bulk density at 10 cm depth **(**1.133± 0.014 g/cm^3) and Madhupur Sal Forest had the lowest soil bulk density value at 30 cm depth (1.028± 0.013 g/cm^3).

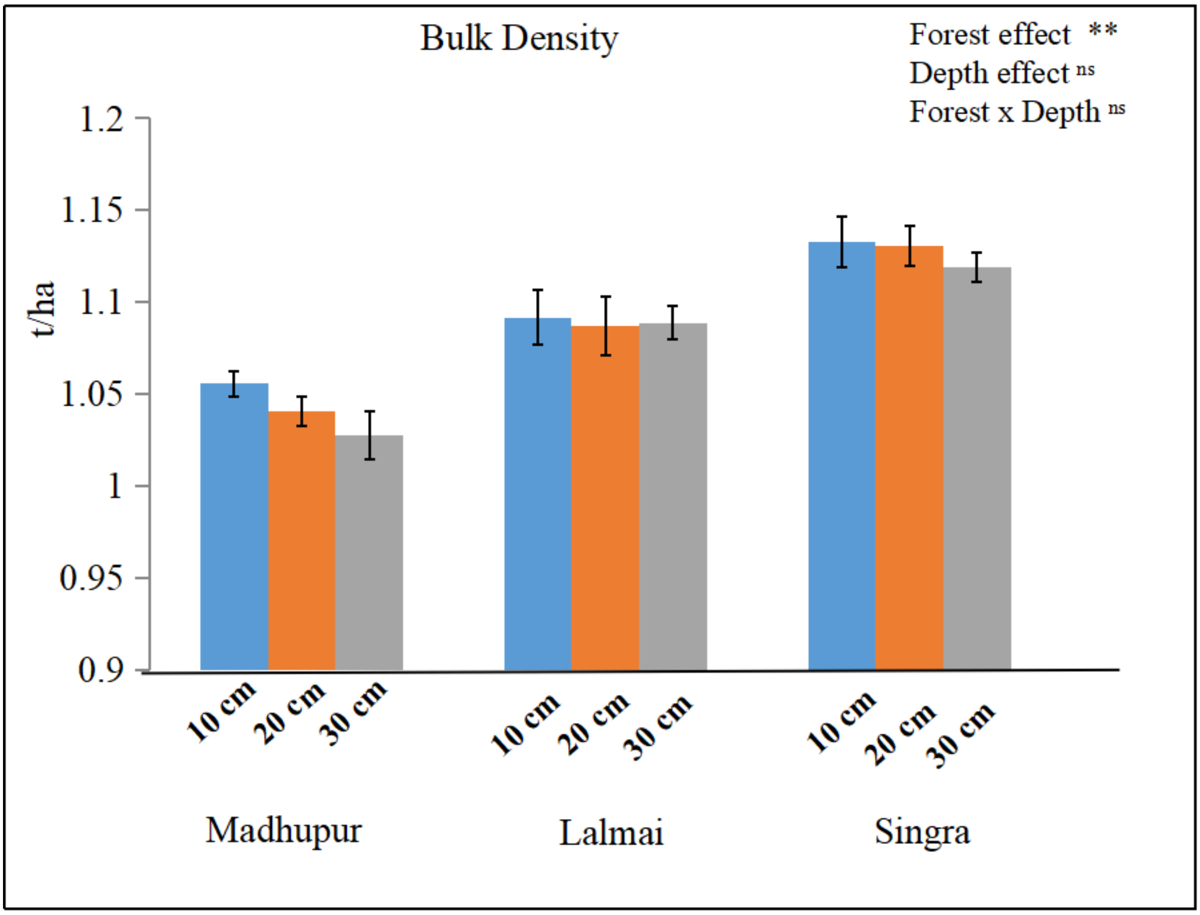


Figure 3.32: Mean values of soil bulk density (g/cm^3) of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

3.2.8.4 Available soil N

ANOVA statistics showed that forest had significant effect ($p < 0.001$) on soil available N although there were no significant effects of soil depth and interaction between forest and depth. The mean values of the effects of forest, soil depth and the interaction of forest and soil depth on soil available N in Madhupur Sal forest, Lalmai Sal forest and Singra National Park were shown in Figure 3.33. The highest value of available N was observed in the Lalmai forest followed by Singra National Park and Madhupur Sal forest.

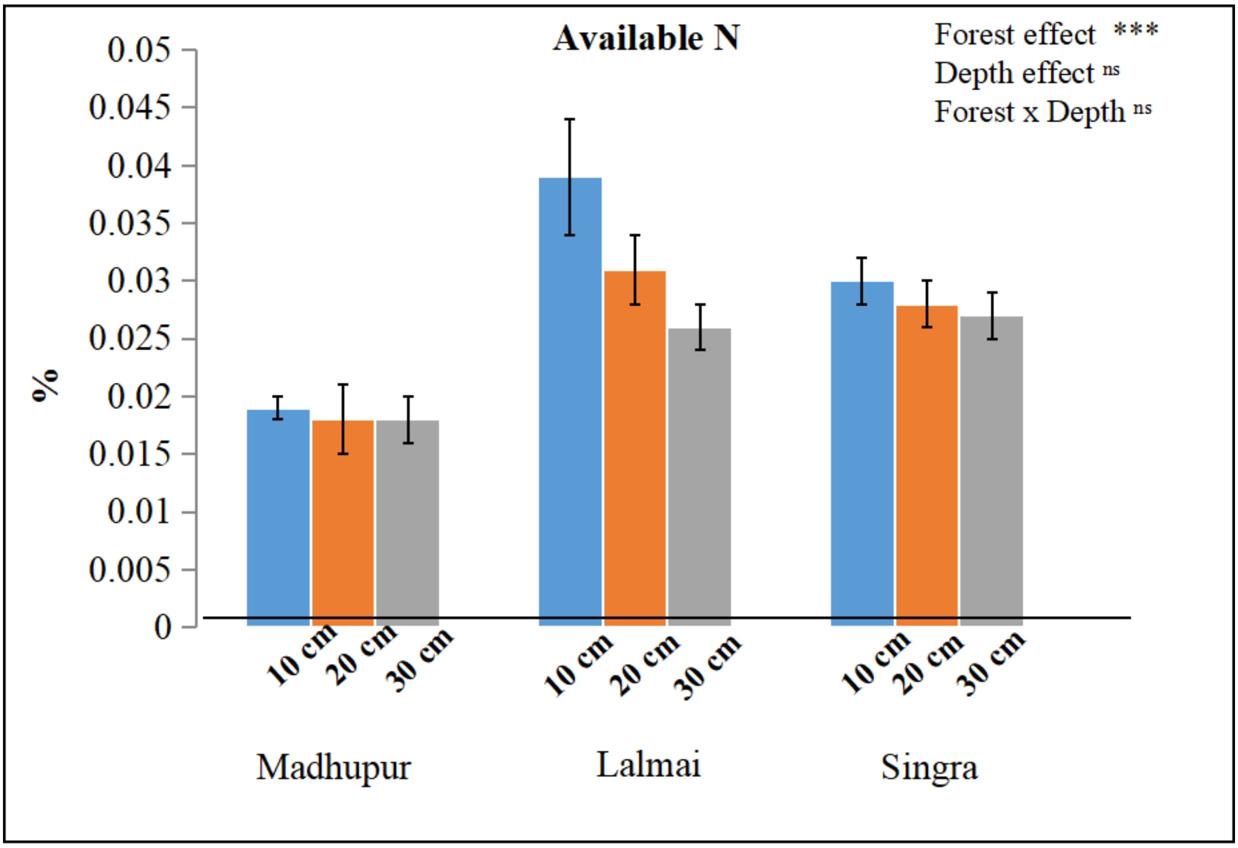


Figure 3.33: Mean values of soil available N (%) of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

3.2.8.5 Total soil P

Forest and soil depth showed significant effects on soil total P ($p < 0.0005$). But there was no significant effect of forest and soil depth interaction among them. The average value of the effect of forest, soil depth and the interaction of forest and soil depth on soil total P of Madhupur Sal forest, Lalmai Sal forest and Singra National Park was shown in Figure 3.34. Among the three forests, soil of Madhupur Sal Forest had the highest total P at 10 cm depth (0.052±0.006 %) and Lalmai Sal Forest had the lowest value at 10 cm depth (0.029±0.003 %). On the other hand, Madhupur Sal forest showed the lowest value at 30 cm depth (0.016±0.001 %).

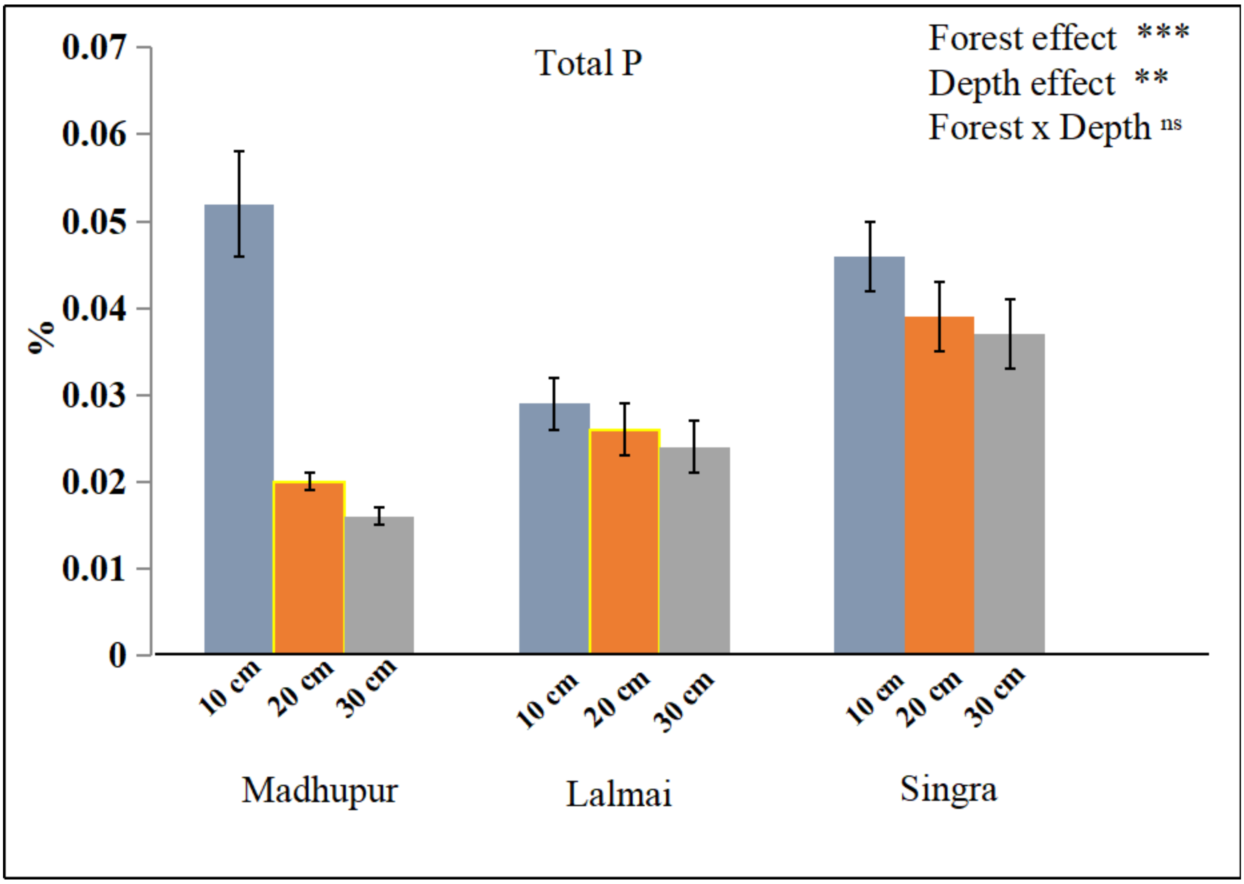


Figure 3.34: Mean soil total P (%) of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

3.3 Seasonal variation in C pools among the selected Sal forests

3.3.1 Seasonal variation in C pools

3.3.1.1 Seasonal variation in litter C

The litter biomass, litter organic C and litter total C on the floor of the three selected forests were significantly affected by season ($p = 0.014$). The effect of interaction between forest and season on soil litter C was not significant. Madhupur Sal forest showed the highest litter biomass (4.53 t/ha) in May. The value was lowest in December (2.74 t/ha). In Lalmai Sal forest, the highest value was found in May (4.87 t/ha) and the lowest value was found in December (2.6 t/ha). In Singra National Park, the highest value was found in May (3.75

t/ha) and the lowest value was found in December (2.88 t/ha). Among the three Sal forests, the highest litter biomass value was found in May in Lalmai Sal forest (Figure 3.35).

Madhupur Sal forest showed the highest litter organic C conent in May (263.15 t/ha). The value was lowest in December (158.99 t/ha). In Lalmai Sal forest, the highest value was found in May (282.63 t/ha) and the lowest value was found in December (151.04 t/ha). In Singra National Park, the highest value was found in May (217.41 t/ha) and the lowest value was found in December (167.01 t/ha). Among the three Sal forests, the highest value of litter organic C was found in Lalmai Sal forest in May (Figure 3.36).

In case of litter total C, Madhupur Sal forest showed the highest amount in May (1243.93 t/ha) and the lowest was in December (456.57 t/ha). In Lalmai Sal forest, the highest value was found in May (1399.79 t/ha) and the lowest value was found in December (466.43 t/ha). In Singra National Park, the highest value was found in May (828.04 t/ha) and the lowest value was found in December (514.81 t/ha). Among the three Sal forests, the highest value of litter total C was found in Lalmai Sal forest in May (Figure 3.37).

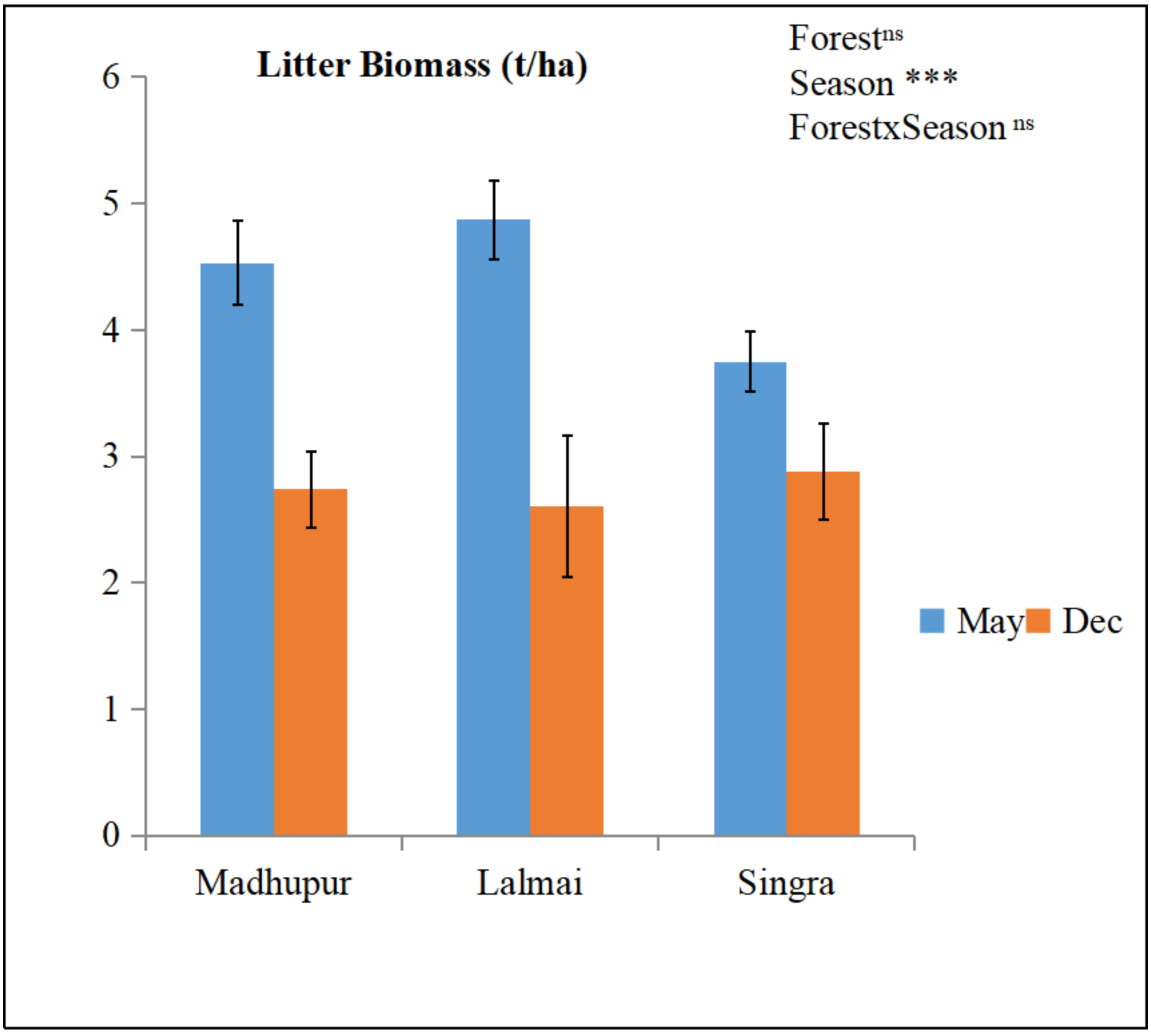


Figure 3.35: Mean values of litter biomass (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

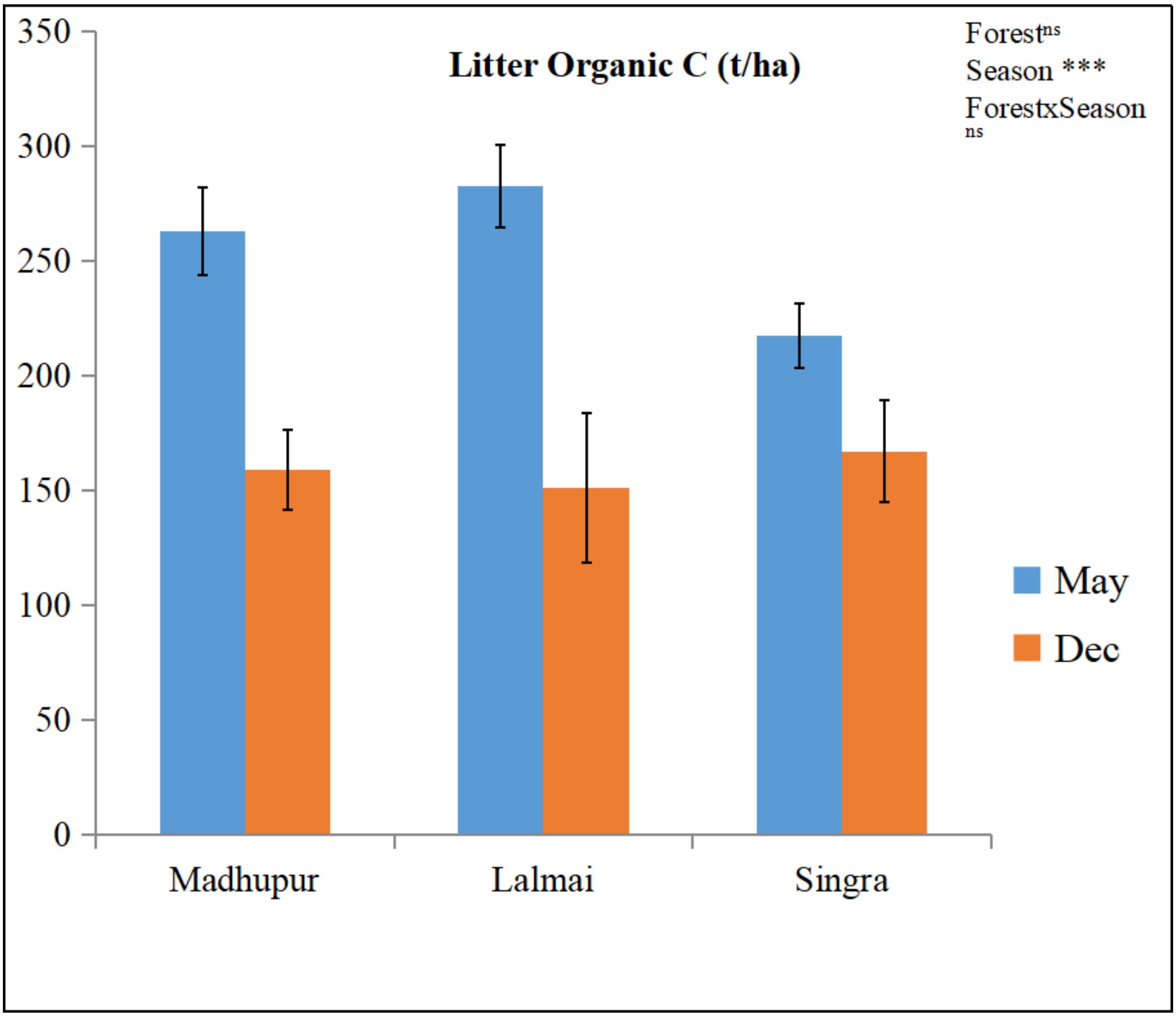


Figure 3.36: Mean values of litter organic C (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

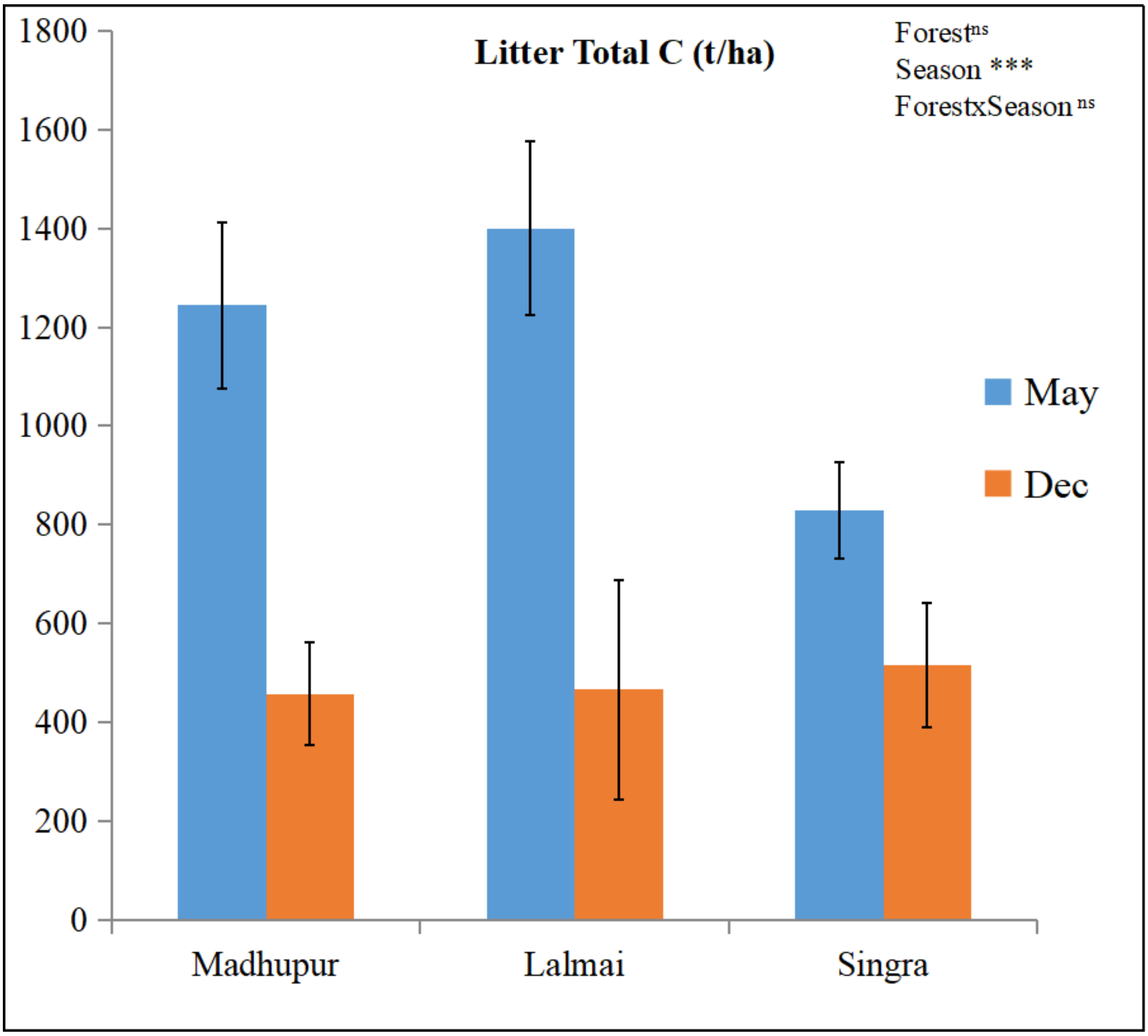


Figure 3.37: Mean values of litter total C (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.3.1.2 Seasonal variation in fine root C

Fine root biomass, fine root organic C and fine root total C in the three selected forests were significantly affected by forest ($p = 0.001$), soil depth ($p = 0.006$), and the interaction of forest, soil depth and season ($p < 0.01$). But it was not significantly affected by season and other interactions. In Madhupur Sal forest, fine root biomass showed the highest value (1.844 t/ha) at 10 cm. depth in May. Fine root biomass value was the lowest (0.738 t/ha) at 30 cm. depth in December. In Lalmai Sal forest, the highest value was found at 10 cm depth in May (1.116 t/ha) and the lowest value was found at 30 cm. depth in December (0.158 t/ha). In Singra National Park, the lowest value (0.495 t/ha) was found at 30 cm. depth in December and the highest value (2.394 t/ha) was found at 10 cm. depth in December. Among the three Sal forests, the highest value of fine root biomass was found in Singra National Park in December at 10 cm depth (Figure 3.38).

In case of fine root organic C, Madhupur Sal forest showed the highest value at 10 cm depth in May (0.318 t/ha). The lowest value of fine root organic carbon was found in December at 30 cm depth (0.127 t/ha). In Lalmai Sal forest, the highest value was found in May at 10 cm depth (0.193 t/ha) and the lowest value was found in December at 30 cm depth (0.027 t/ha). In Singra National Park, the lowest value was found in December at 30 cm depth (0.085 t/ha) and the highest value was found in December at 10 cm depth (0.413 t/ha). Among the three Sal forests, the highest value of fine root organic C was found in December at 10 cm depth in Singra National Park (Figure 3.39).

In case of fine root total C, Madhupur Sal forest showed the highest value (0.618 t/ha) at 10 cm depth in May. The lowest value (0.133 t/ha) of fine root total C was found at 30 cm depth in December. In Lalmai Sal forest, the highest value was found at 10 cm depth (0.267

t/ha) in May and the lowest value was found at 30 cm depth in December (0.006 t/ha). In Singra National Park, the lowest value (0.059 t/ha) was found at 30 cm depth in December and the highest value (1.085 t/ha) was found at 10 cm depth in December. Among the three Sal forests, the highest value of fine root total C was found at 10 cm depth in Singra National Park in December (Figure 3.40).

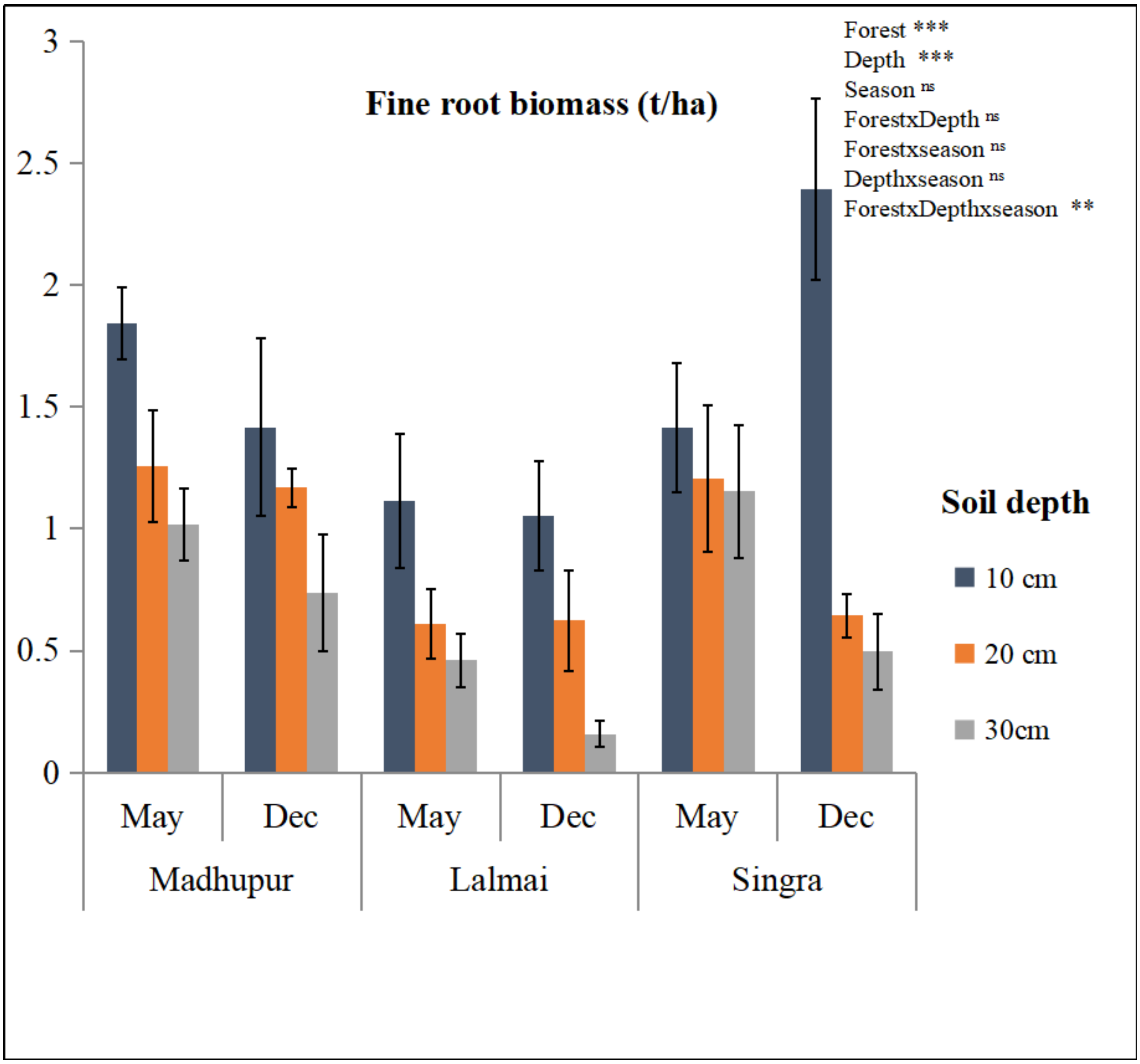


Figure 3.38: Mean values of fine root biomass (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

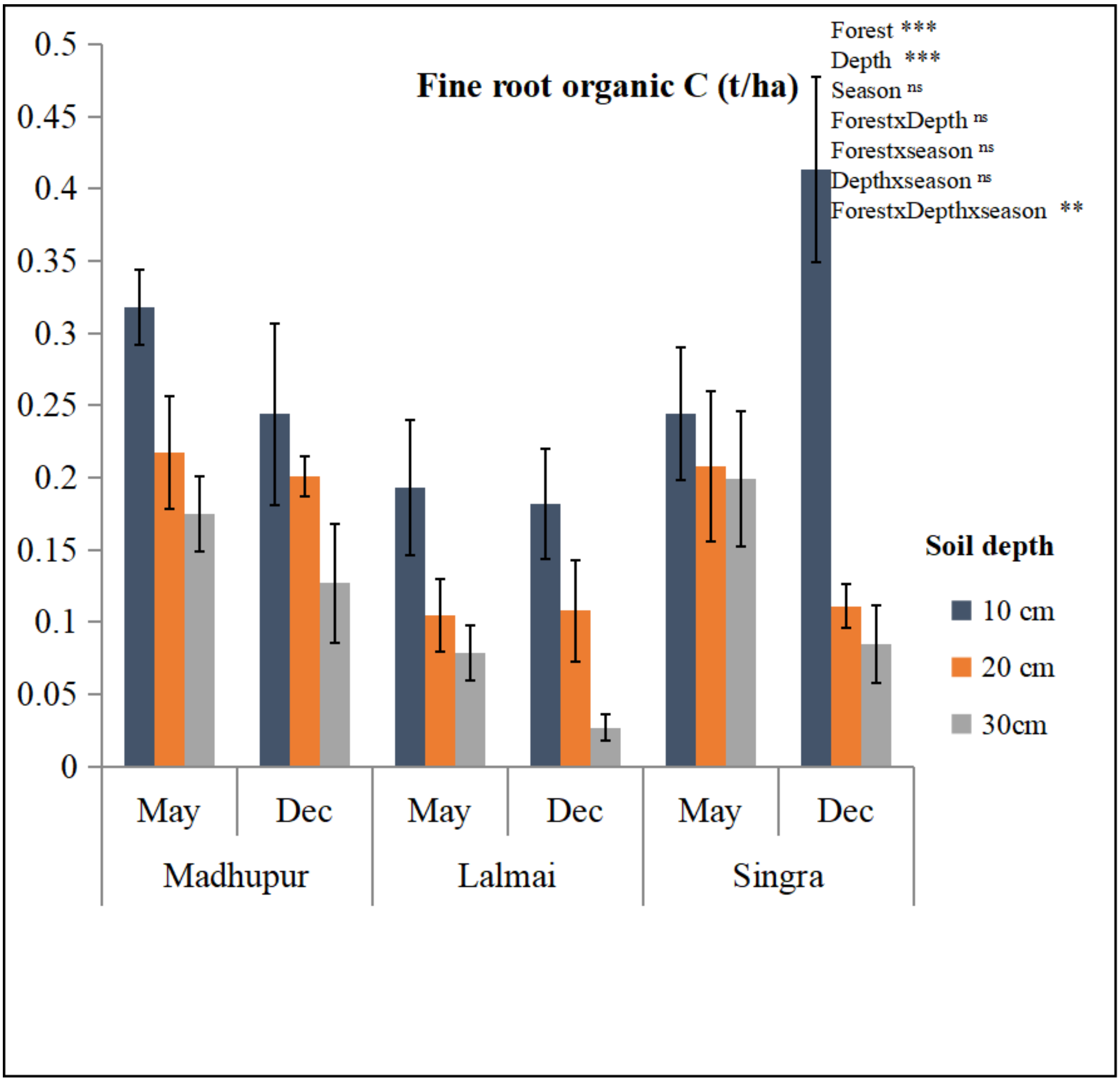


Figure 3.39: Mean values of fine root organic C (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

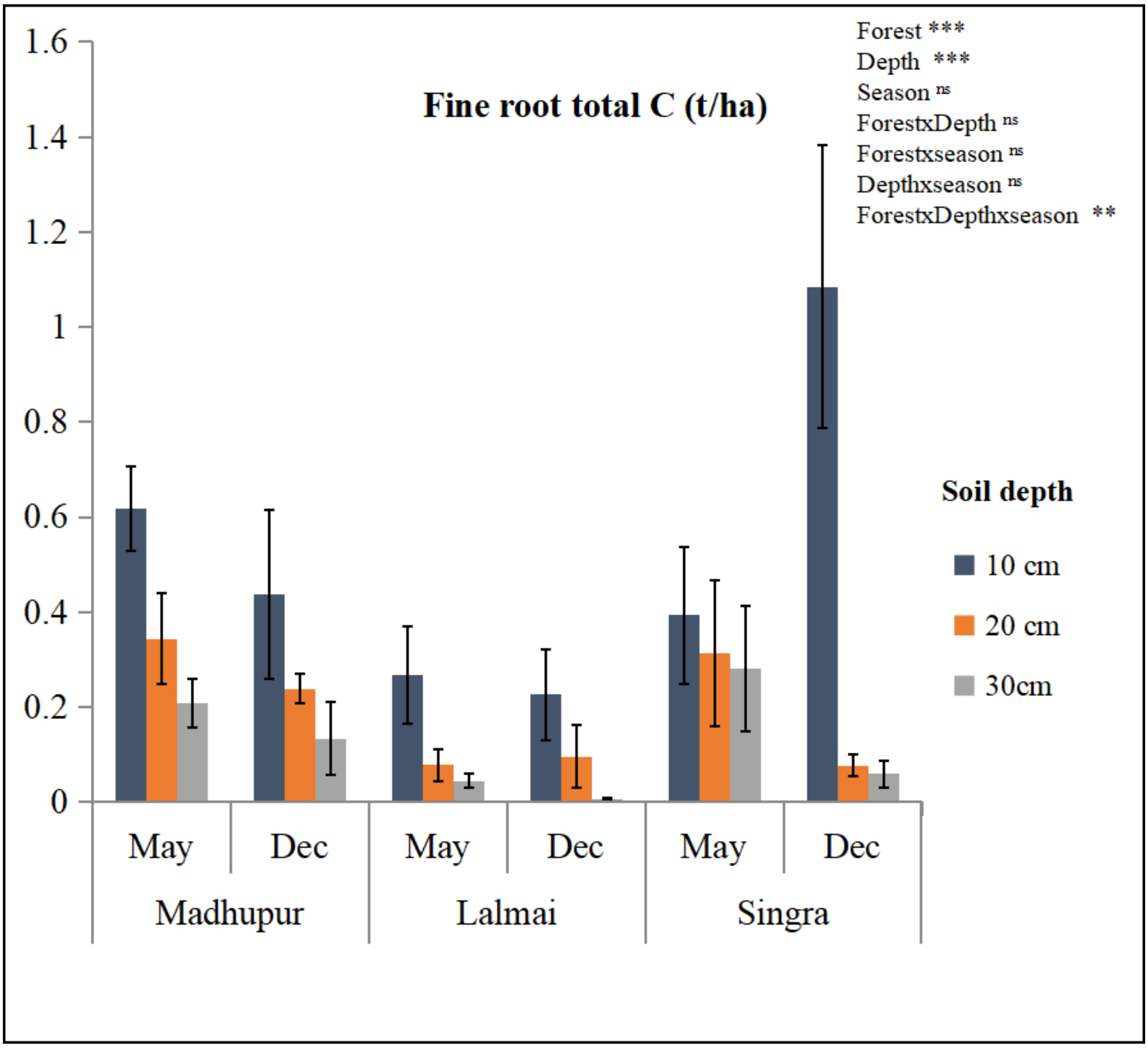


Figure 3.40: Mean values of fine root total C (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.3.1.3 Seasonal variation in soil C

The total soil C content of the three selected forests was significantly affected by forest ($p = 0.014$), soil depth ($p = 0.014$), and the interaction between forest and season ($p < 0.05$). However, effects of soil depth, season, and other interactions were not significant. In Madhupur Sal forest, the total soil C content in May showed the highest value (843.22 t/ha) at 10 cm depth. The total soil carbon value was the lowest (648.51 t/ha) at 20 cm depth in December. In Lalmai Sal forest, the highest value was found at 10 cm depth (771.06 t/ha) in December, and the lowest value was found at 30 cm depth in May (492.33 t/ha). In Singra National Park, the highest value (1069.5 t/ha) was found at 10 cm depth in December, and the lowest value (845.68 t/ha) was found at 30 cm depth in May. Among the three Sal forests, the highest soil total C was found in Singra National Park in December at 10 cm depth (Figure 3.41).

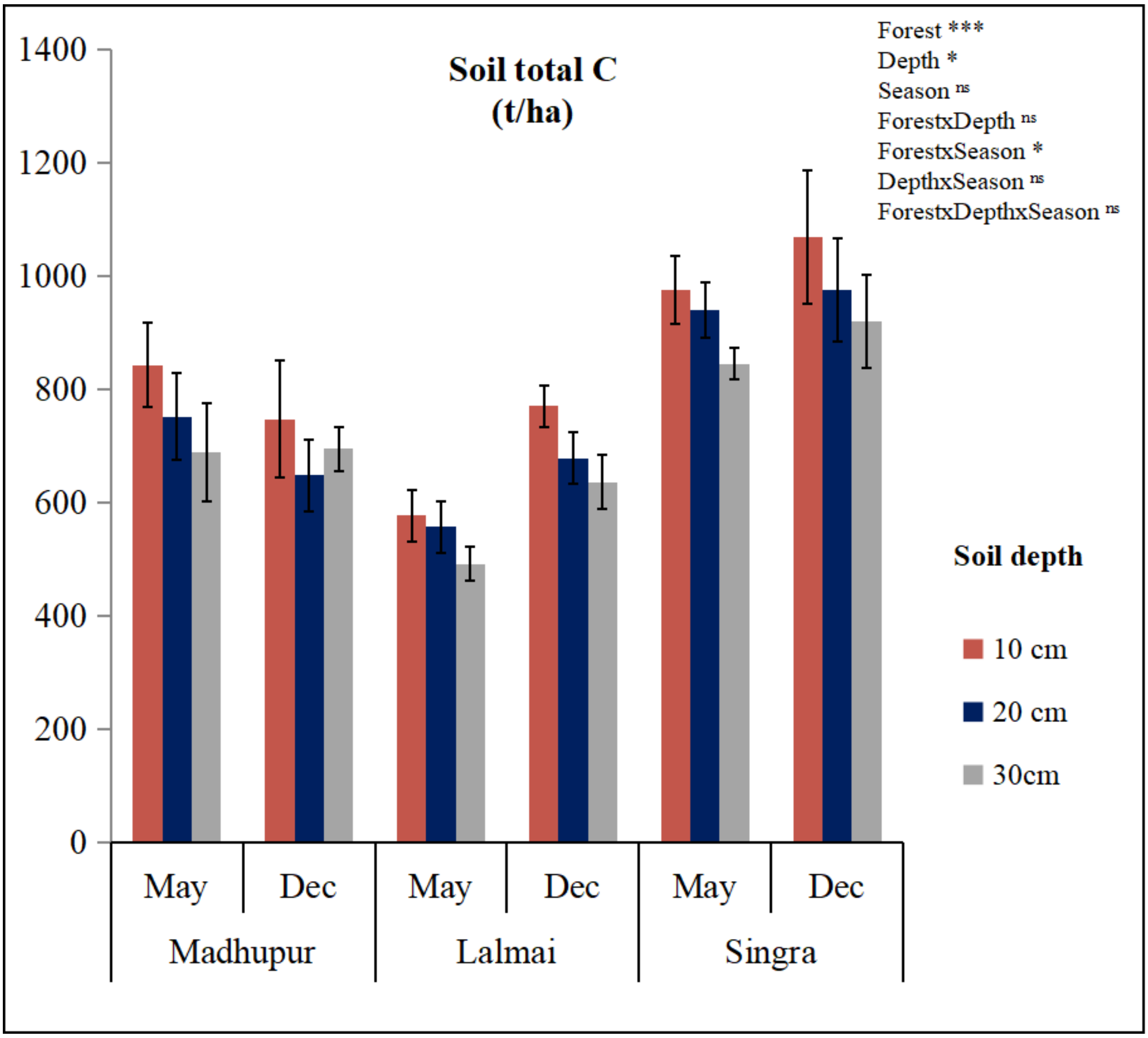


Figure 3.41: Mean values of soil total C (t/ha) of Madhupur Sal forest, Lalmai Sal forest and Singra Sal forest of Bangladesh.

3.3.2 Seasonal variation in soil properties

Two-way ANOVA statistics on soil pH, moisture (%), conductivity (μs), organic carbon (%), bulk density (%), total carbon, available nitrogen (μg/g soil), total phosphorus of Madhupur Sal forest, Lalmai Sal forest and Singra National Park were shown in Table 3.5. A two-way ANOVA was applied to test the relative effects of forest and season and their interaction on soil parameters.

3.3.2.1 Soil pH

Soil pH was significantly affected by forest ($p < 0.0001$), soil depth ($p < 0.0002$). But it was not affected by their interactions. There was variation in pH value as per soil depth. Madhupur forest showed the highest value in December (5.094) than in May (4.978), In Lalmai forest, the higher value was in May (4.748) than in December (4.77). In Singra forest, the value was higher in May (5.418) and lower in December (5.404). Soil pH value at the depth of 10-20 cm also varied from forest to forest and season to season. Madhupur forest showed the higher value in December (5.26) than in May (5.091) Lalmai forest showed the higher value in May (4.72) than in December (4.762) and Singra forest showed the higher value in May (5.756) and lower in December (5.542). At the depth of 20-30 cm, in Madhupur forest during December it was higher (5.276) than in May (5.254), in Lalmai forest it was lower (4.95) than in December (5.084) and in Singra forest it was higher in December (5.824) and lower in May (5.7). Thus, seasonal changes in pH values were not high (Figure 3.42).

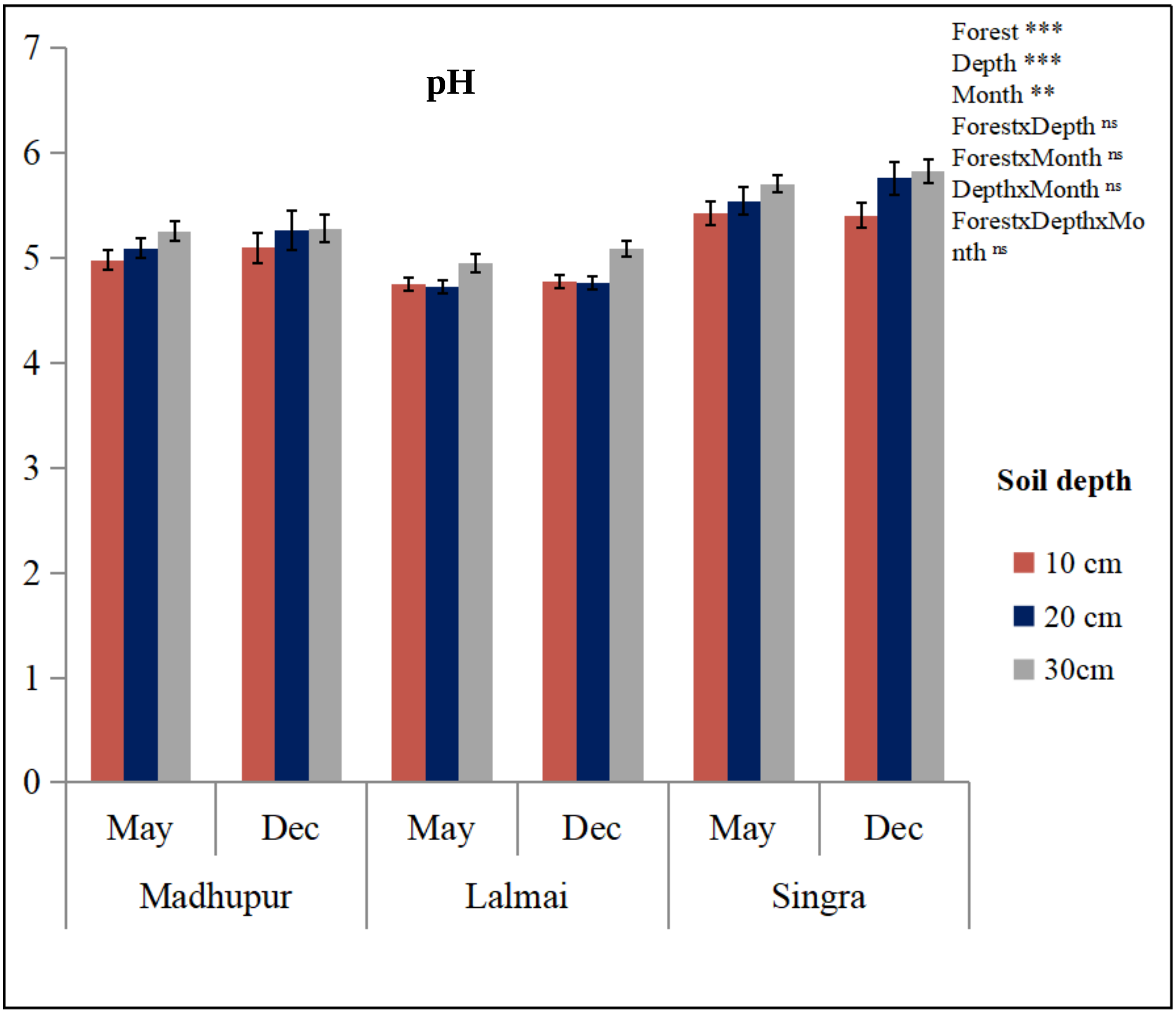


Figure 3.42: Mean pH value of the soil of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh during May and December.

3.3.2.2 Soil Moisture Content

The soil moisture content (%) of the three selected forests was significantly affected by forest ($p < 0.0001$) and season ($p < 0.0001$). However, there was no significant effect of soil depth. Moreover, there was significant effect of interaction between forest and season ($p < 0.01$). In 0-10 cm soil depth, the mean soil moisture content in May was higher in Madhupur (15.89%), Lalmai (21.30%) and Singra (14.76%), which was higher than the mean soil moisture content in December in Madhupur (11.52%), Lalmai (13.43%) and Singra (9.43%) forests. At 10-20 cm soil depth, the average soil moisture content in May was higher at Madhupur (15.81%), Lalmai (23.57%) and Singra (14.6%), compared to the average soil moisture values in December at Madhupur (14.35%), Lalmai (13.98%) and Singra (10.74%). At 20-30 cm soil depth, the average soil moisture content in May was higher at Madhupur (14.96%), Lalmai (21.379%) and Singra (15.04%), compared to the average soil moisture contents in December at Madhupur (15.23%), Lalmai (15.84%) and Singra (13.06%) forests, respectively (Figure 3.43).

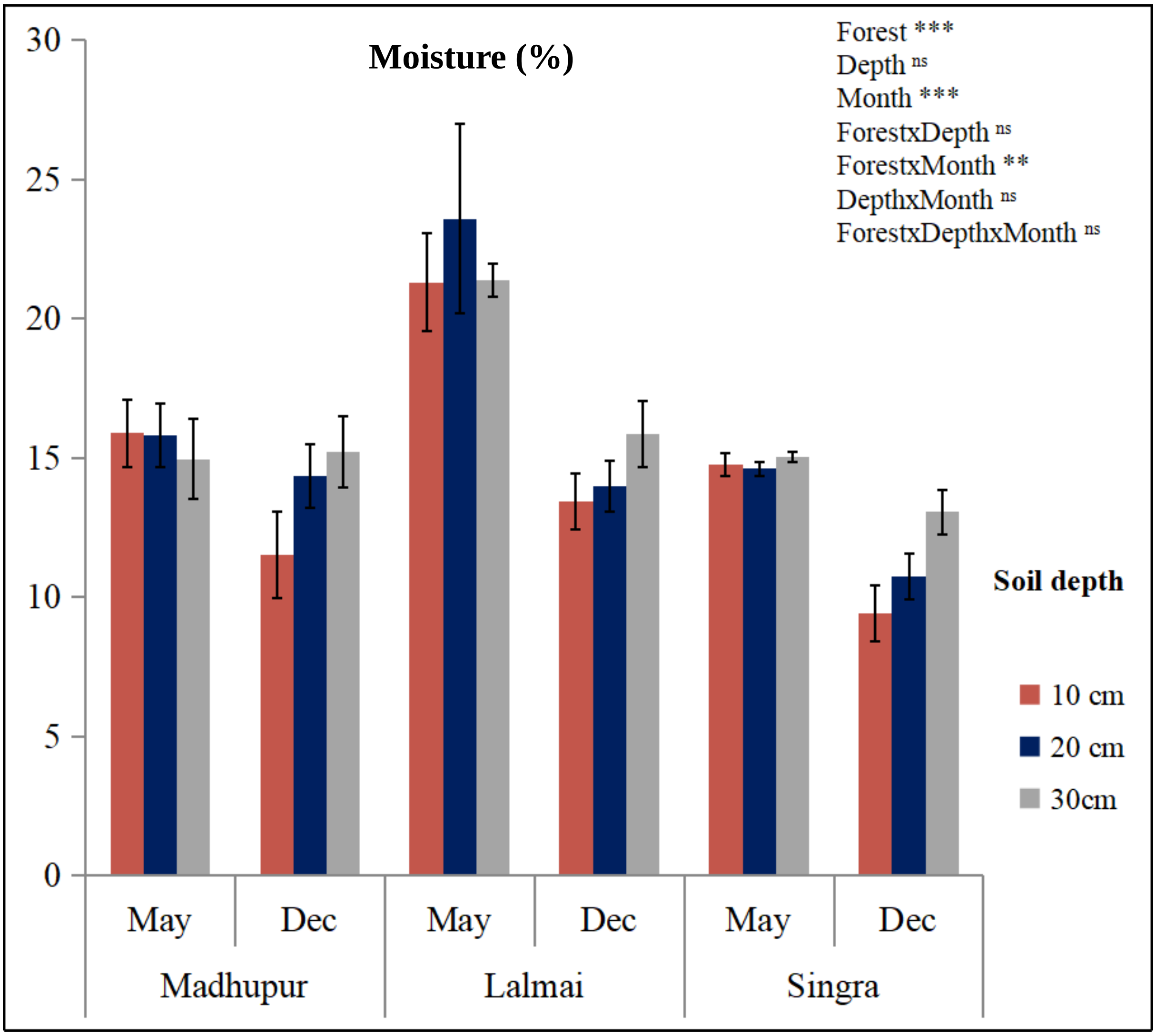


Figure 3.43: Mean soil moisture content (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh during May and December.

3.3.2.3 Soil electrical conductivity

Soil electrical conductivity was significantly affected by forest ($p < 0.0001$), soil depth ($p < 0.0001$), season ($p = 0.0142$) and the interaction between forest and season ($p = 0.0111$). No significant effects were observed in other interactions between the main factors. The highest mean soil electrical conductivity value was found in Madhupur Sal forest in May (29.467 µS/cm) at 10 cm depth, and the lowest (6.78 µS/cm) was found in December. In Lalmai Sal forest, the highest value (34.18 µS/cm) was found in December at 10 cm depth and the lowest value (18.42 µS/cm) was found in May at 30 cm. depth. In Singra National Park the highest value (34.28 µS/cm) was found in May at 10 cm depth and the lowest value (15.224 µS/cm) was found in December at 30 cm depth (Figure 3.44).

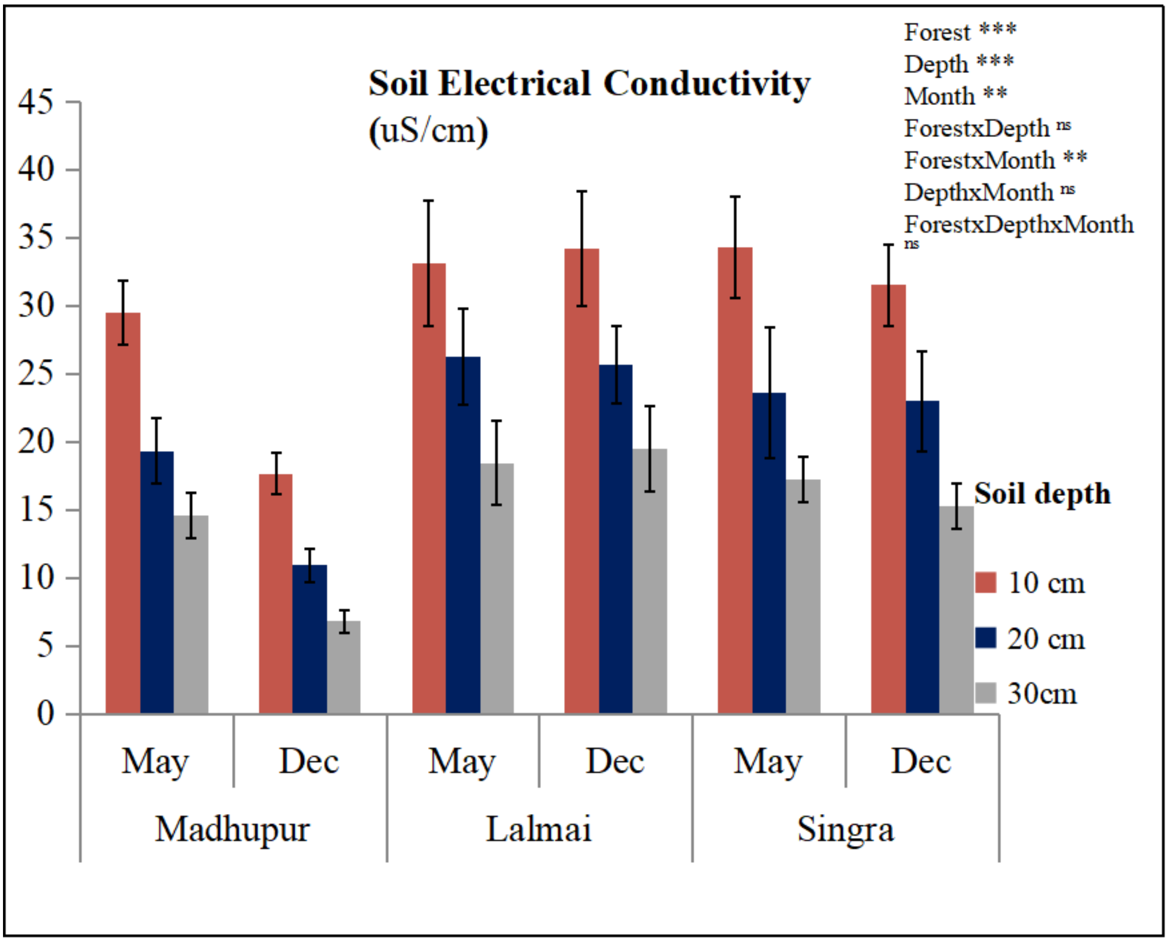


Figure 3.44: Mean value of soil electrical conductivity (µS/cm) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh during May and December.

3.3.2.4 Bulk density

Soil bulk density of Madhupur Sal forest, Lalmai Sal forest and Singra National Park did not show any significant effect of soil depth. However, it was significantly affected by forest ($p = 0.0005$), and season ($p = 0.0001$). In addition, soil bulk density was not significantly affected by the interaction between forest, depth and season. The highest average soil bulk density value was found in Madhupur Sal forest in December (1.166 g/cm^3) at a depth of 10 cm and the lowest (1.093 g/cm^3) was found in May at a depth of 10 cm. In Lalmai Sal forest, the highest value was found in December (1.146 g/cm^3) at a depth of 10 cm and the lowest value was found in May (1.054 g/cm^3) at a depth of 20 cm. In Singra National Park, the highest value was found in December (1.188 g/cm^3) at a depth of 10 cm and the lowest value was found in May at a depth of 30 cm (Figure 3.45).

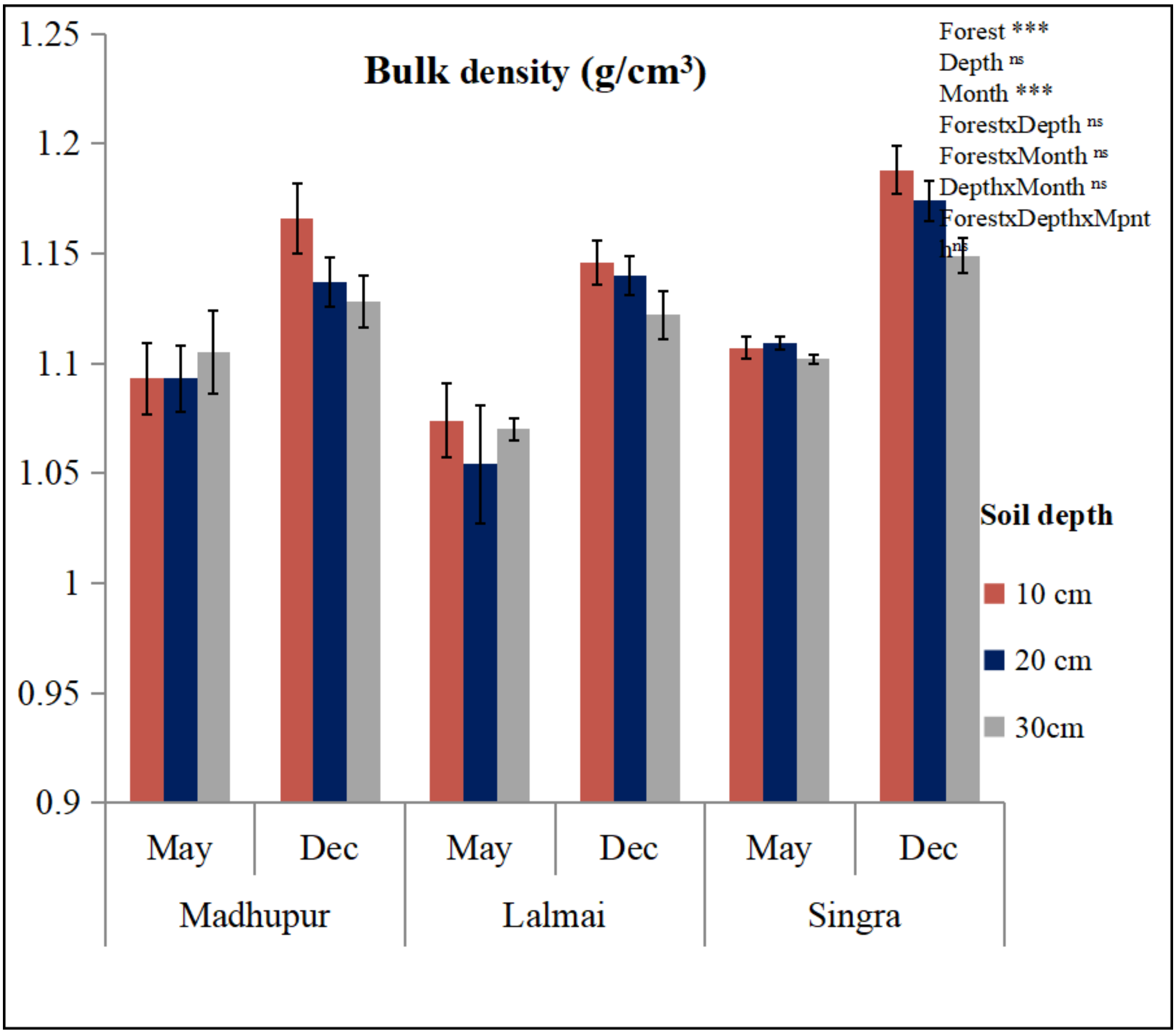


Figure 3.45: Mean values of bulk density (g/cm^3) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh during May and December.

3.3.2.5 Soil available N

Soil available nitrogen in the three selected forests was significantly affected by forest ($p = 0.014$), depth ($p = 0.0001$), and season ($p = 0.0076$). Soil available nitrogen was also significantly affected by the interaction between forest and season ($p = 0.0001$). However, there was no significant effect of the interactions between and among forest, depth and season. In Madhupur Sal forest, the highest mean soil available N value was found at 10 cm depth in December (0.037%) and the lowest value was found at 20 cm depth in May (0.013%). In Lalmai Sal forest, the lowest value was found at 10 cm depth in December (0.052%) and the lowest value was found at 30 cm depth in May (0.027%). In Singra National Park, the highest value (0.033%) was found in December at 10 and 20 cm depth and the lowest value (0.028%) was found in May at 20 cm depth. Among the three Sal forests, the highest value of available nitrogen was found in Lalmai Sal forest at 10 cm depth in December (Figure 3.46).

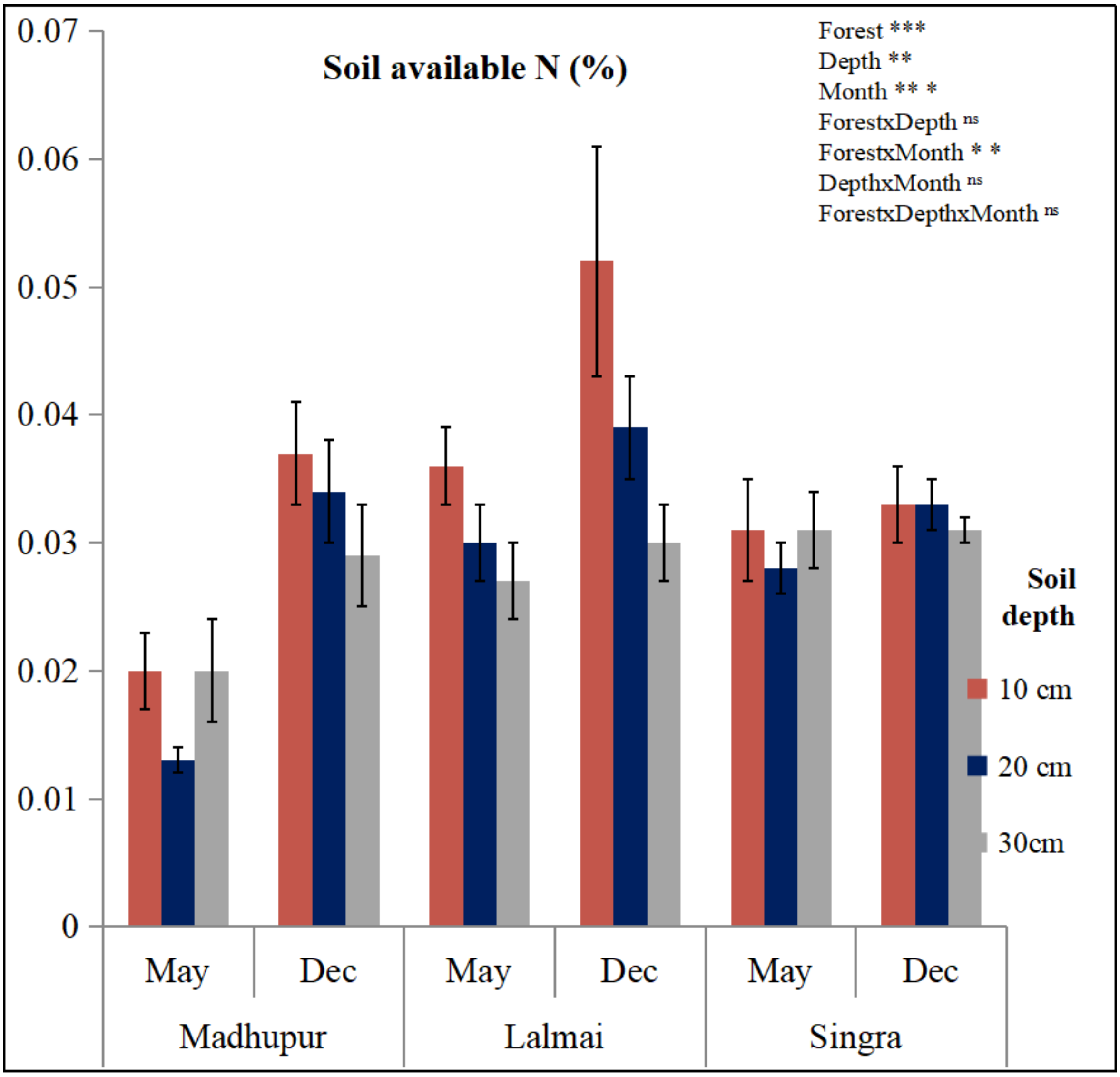


Figure 3.46: Mean value of soil available N (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh during May and December.

3.3.2.6 Soil total P

The total phosphorus content (%) of the soil in the three selected forests was significantly affected by forest ($p = 0.0001$), depth ($p = 0.014$), and season ($p = 0.0013$). In addition, the interaction between forest and season also significantly ($p = 0.0035$) affected total phosphorus content of the soil. However, there was no significant effect of interactions between and among forest, depth and season. In Madhupur Sal forest, the highest total phosphorus value was found at 10 cm depth in May (0.043%) and the lowest value was found at 30 cm depth in December (0.027%). In Lalmai Sal forest, the highest value was found in May (0.034%) at a depth of 20 cm and the lowest value was found in December (0.026%) at a depth of 30 cm. In Singra National Park, the highest value was found in May (0.056%) at a depth of 10 cm and the lowest value was found in May (0.04%) at a depth of 20 and 30 cm. Among the three Sal forests, the highest value of total phosphorus was found in Singra National Park at a depth of 10 cm in May.

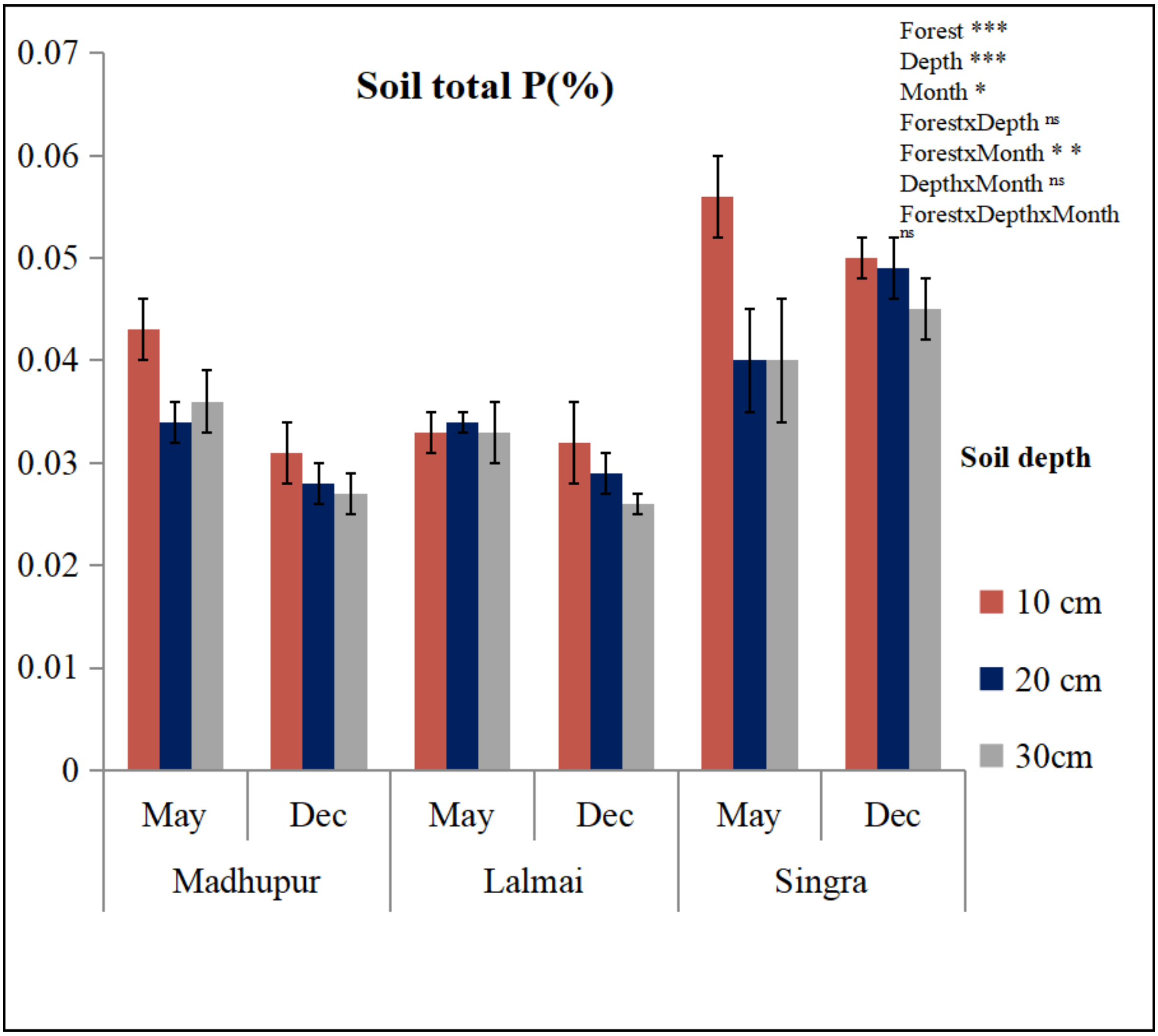


Figure 3.47: Mean values of soil total P (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.4 Litter decomposition rates

3.4.1 Mass loss rates

The results of three-way ANOVA on the effects of soil, litter species, time and their interactions on mass loss rate (%) of Sal leaf litter were shown in Table 3.6. Mass loss rate was significantly affected by time ($p < 0.0001$) and the interaction of soil and time ($p < 0.05$).

Table 3.7 shows the mean values of mass loss rate of Sal leaf litter of three forests measured at time of 6 month interval. Results showed that mass of leaf litter was lost gradually from the initial time through 6 months to 12 months. After 6 months of incubation, Sal leaf of Lalmai Sal forest (5.33±0.29%) and Singra National Park (5.03±0.67%) showed the highest mass loss rate with their own soil but the mass loss rate of Madhupur Sal forest leaf with Madhupur Sal forest soil showed the opposite pattern. Though, Sal leaf of Madhupur Sal forest with that of soil showed highest mass loss rate (11.63±2.41%) it decreased when Lalmai Sal forest leaf with Lalmai Sal Forest soil and Singra National Park leaf with Singra National Park soil were mixed after 12 months of incubation.

Table 3.6 Three-way ANOVA statistics on the effects of forest soil, litter species, incubation time and their interaction on the mass loss rate of Sal litter.

Source of variation	Mass loss rate		
	df	F ratio	P value
Soil	2	1.488	0.239
Litter	2	0.971	0.388
Time	1	102.833	< 0.0001
Soil×litter	4	0.579	0.679
Litter×time	2	0.659	0.523
Soil×time	2	4.599	0.017
Soil×litter× time	4	0.526	0.717

Table 3. 7 Mean values with standard error mean of the mass loss rate of Sal leaf litter incubated with soil collected from Madhupur Sal forest, Lalmai Sal forest and Singra National Park measured at 6 months and 12 months after starting of incubation.

Properties	Soil id	Sal leaf of Madhupur		Sal leaf of Cumilla		Sal leaf of Dinajpur	
		6 monthss	12 months	6 months	12 months	6 months	12 months
Mass loss rate	Madhupur	2.63±0.44	11.63±2.41	4.60±0.35	11.40±0.50	3.95±1.04	12.90±3.15
	Cumilla	3.90±0.15	10.60±2.26	5.33±0.29	8.57±0.35	4.63±0.66	8.97±0.98
	Dinajpur	3.63±0.17	7.37±0.61	4.80±0.10	9.50±0.60	5.03±0.67	9.80±1.06

3.4.2 Mineralized N

In the three selected forest soils, the amount of mineralized N was measured after incubation with Sal leaf litter collected from the three Sal forests. There were significant effects of soil ($p = 0.018$) and the interaction between soil and litter ($p = 0.002$). But soil mineralized nitrogen was not significantly affected by forest litter. In the Madhupur Sal forest soil, Singra National Park litter showed the highest amount of nitrogen mineralized (0.115±0.012%), and Lalmai Sal forest litter showed the lowest amount (0.074±0.003%). In the Lalmai Sal forest soil, Lalmai Sal forest litter showed the highest (0.089±0.005%) amount of mineralized nitrogen. In the Singra National Park soil, Madhupur Sal forest litter (0.085±0.008%) showed the highest amount of mineralized nitrogen, and Lalmai Sal forest litter (0.07±0.009%) showed the lowest value. Among the three forest soils, the highest mineralized nitrogen value was shown in the soil of Madhupur Sal forest in Singra National Park, and the lowest value was shown in the soil of Lalmai Sal forest in Singra National Park (Figure 3.48).

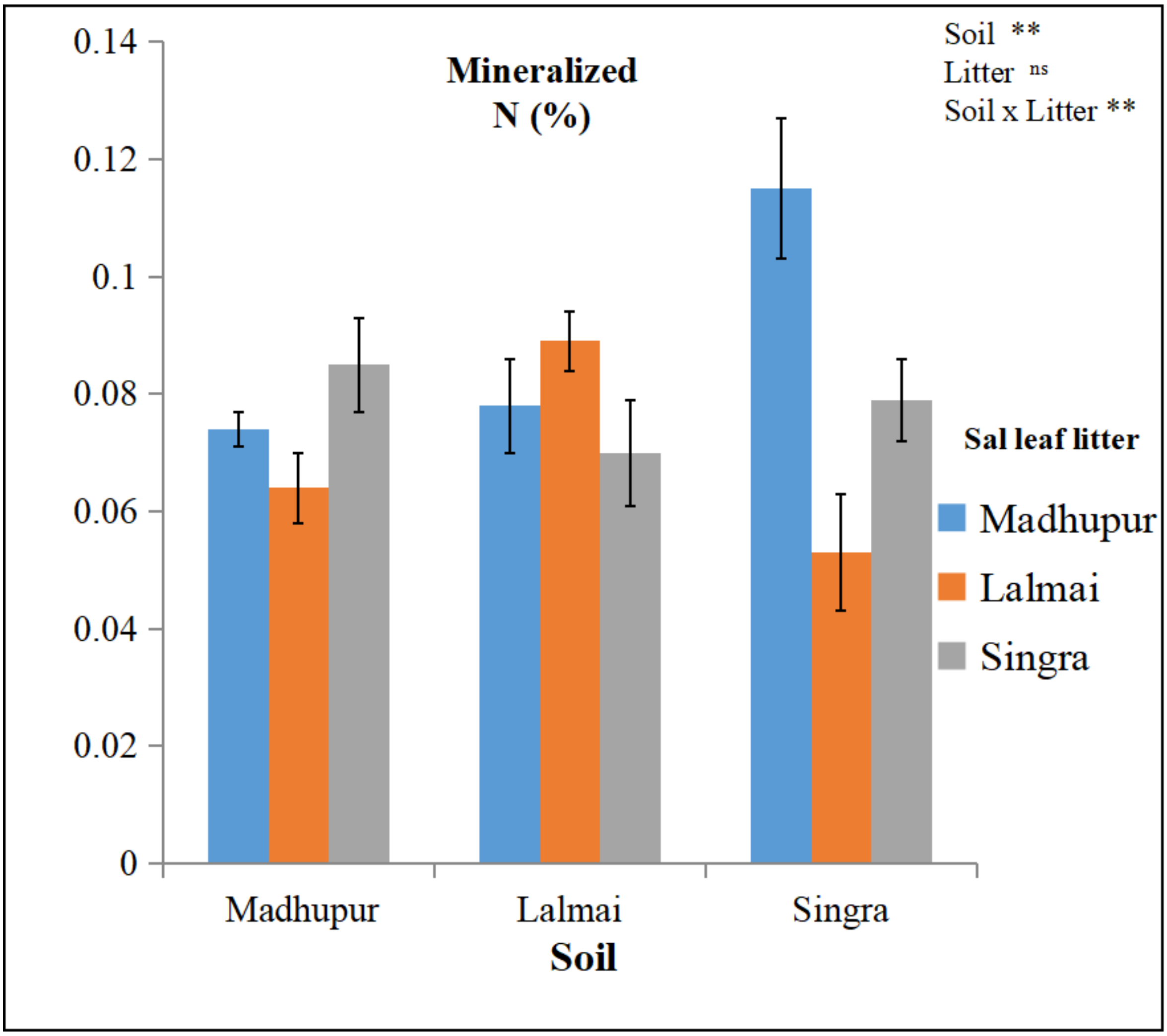


Figure 3.48: Mean values of soil mineralized N (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.4.3 Properties of Sal forest soil used in decomposition study

The soil moisture, pH, electrical conductivity, organic C, available N, available P, and N/P data of the three selected forests namely Madhupur Sal forest, Lalmai Sal forest, and Singra National Park were shown in (Figure 3.49-3.55). The three forests showed a significant ($p = 0.008$) difference in pH value. The highest pH value (5.40) was found in the soil of Singra National Park and the lowest was in Lalmai Sal forest (4.77). There was a significant ($p = 0.006$) difference in electrical conductivity value among the three forests. The highest electrical conductivity value (34.18 µS/cm) was found in Lalmai Sal forest and the lowest value (17.62 µS/cm) was found in Madhupur Sal forest. There was no significant ($p = 0.108$) difference in moisture content among the three forests. The highest moisture value (13.43%) was recorded in the soil of Lalmai Sal forest, and the lowest value of that was recorded in Singra National Park (9.43%). In case of organic C, there was no significant ($p = 0.06$) difference between the three selected forests. The highest value (0.90%) was found in Singra National Park, and the lowest value (0.63%) was found in Madhupur Sal forest. Similarly, in case of soil phosphorus content, there was a significant ($p = 0.0001$) difference among Madhupur Sal forest, Lalmai Sal forest, and Singra National Park. The highest soil P value (0.127%) was found in Lalmai Sal forest, and the lowest value (0.04%) was found in Madhupur Sal forest. The highest available N (0.02%) was recorded in Madhupur Sal forest, and the lowest value (0.004%) was recorded in Lalmai Sal forest. Soil available N showed significant difference among the three Sal forest ($p = 0.011$). The highest available N content was recorded in Madhupur Sal forest followed by Singra National Park and Lalmai Sal forest. In case of N/P, significant ($p = 0.0001$) differences were observed among the three Sal forests. The highest value was found in Madhupur Sal forest (3.020%), and the lowest value was found in Lalmai Sal forest (0.38%).

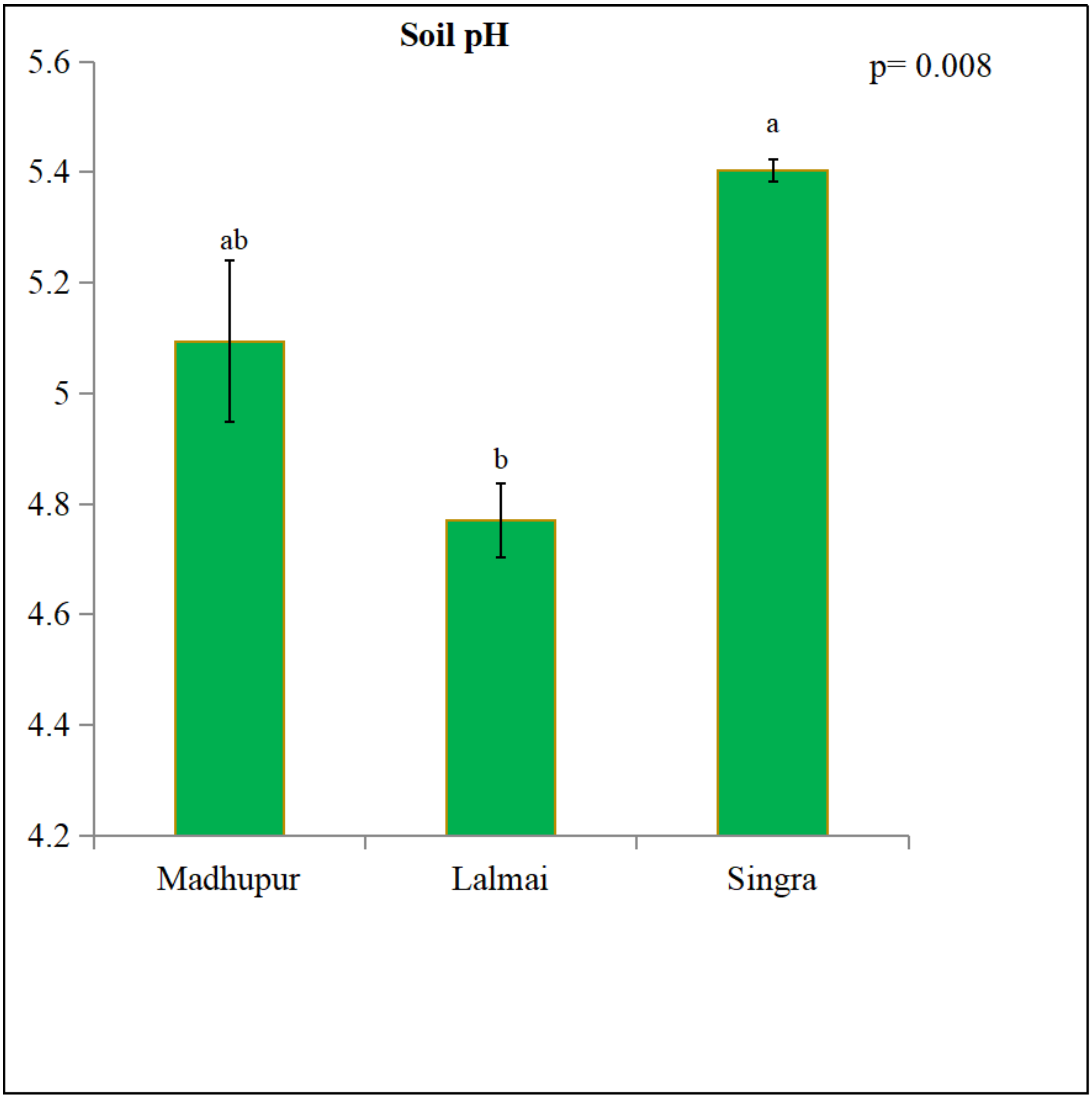


Figure 3.49: Mean values of soil pH of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

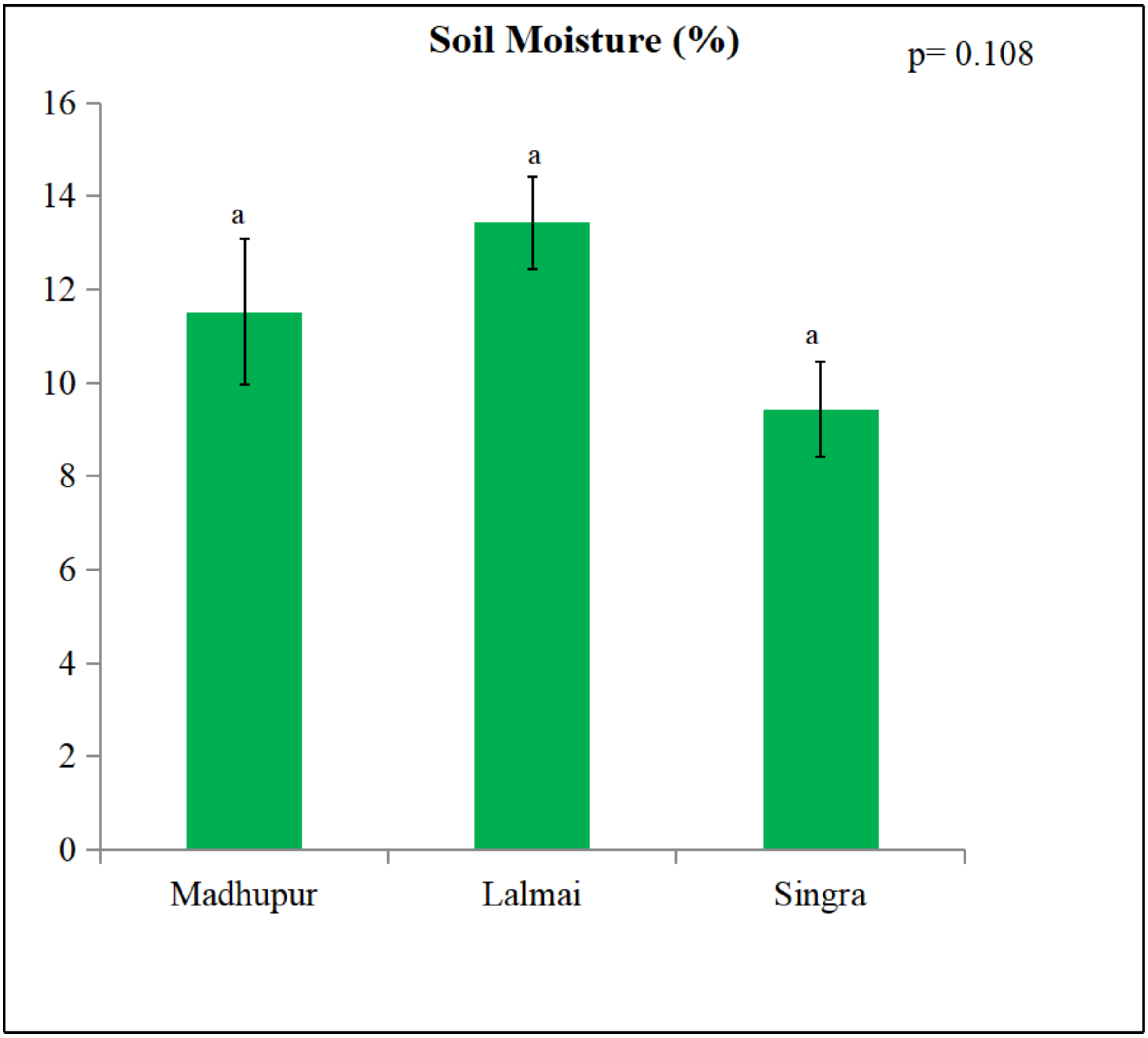


Figure 3.50: Mean values of soil moisture (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

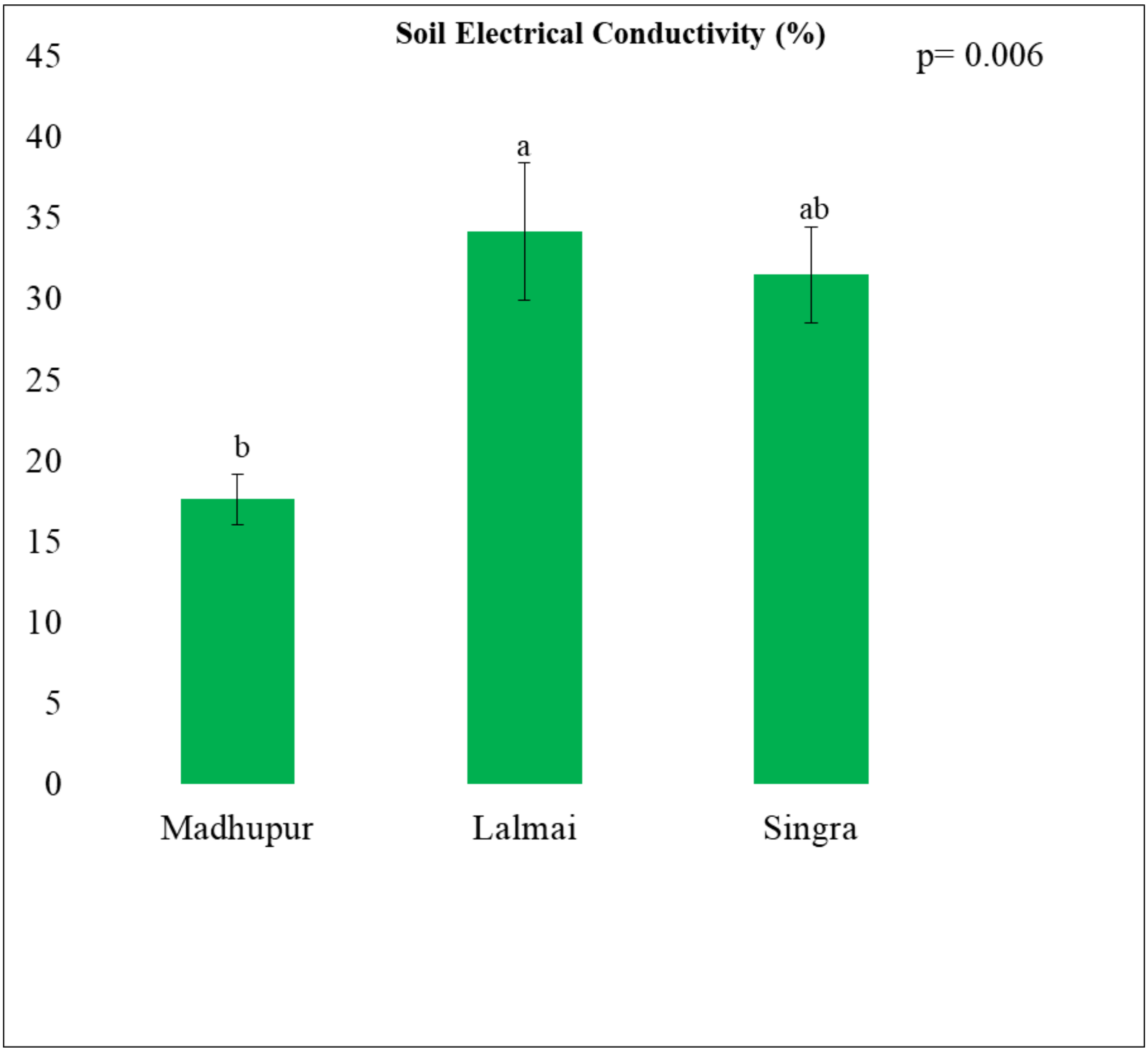


Figure 3.51: Mean values of soil electrical conductivity (μS/cm) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

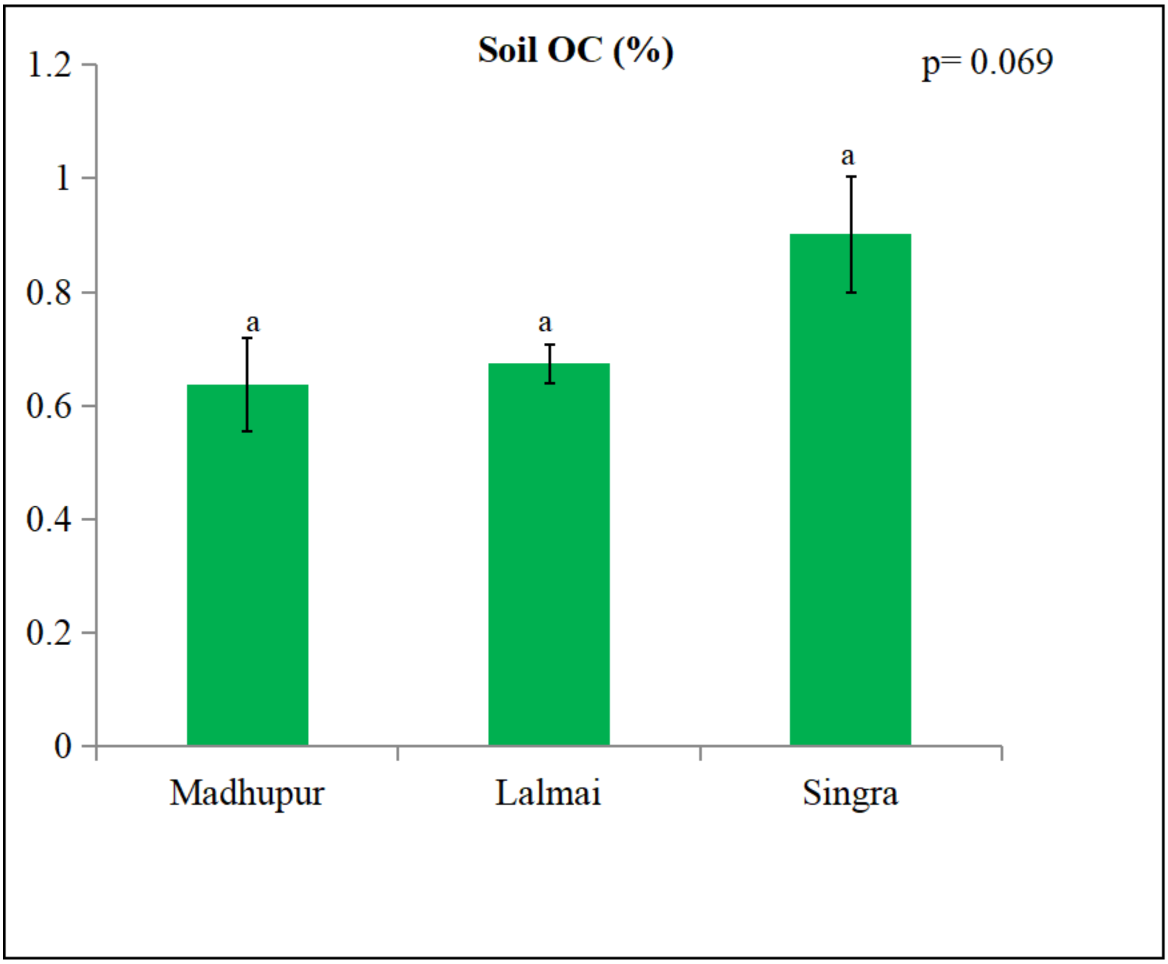


Figure 3.52: Mean values of soil Organic Carbon (OC) (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

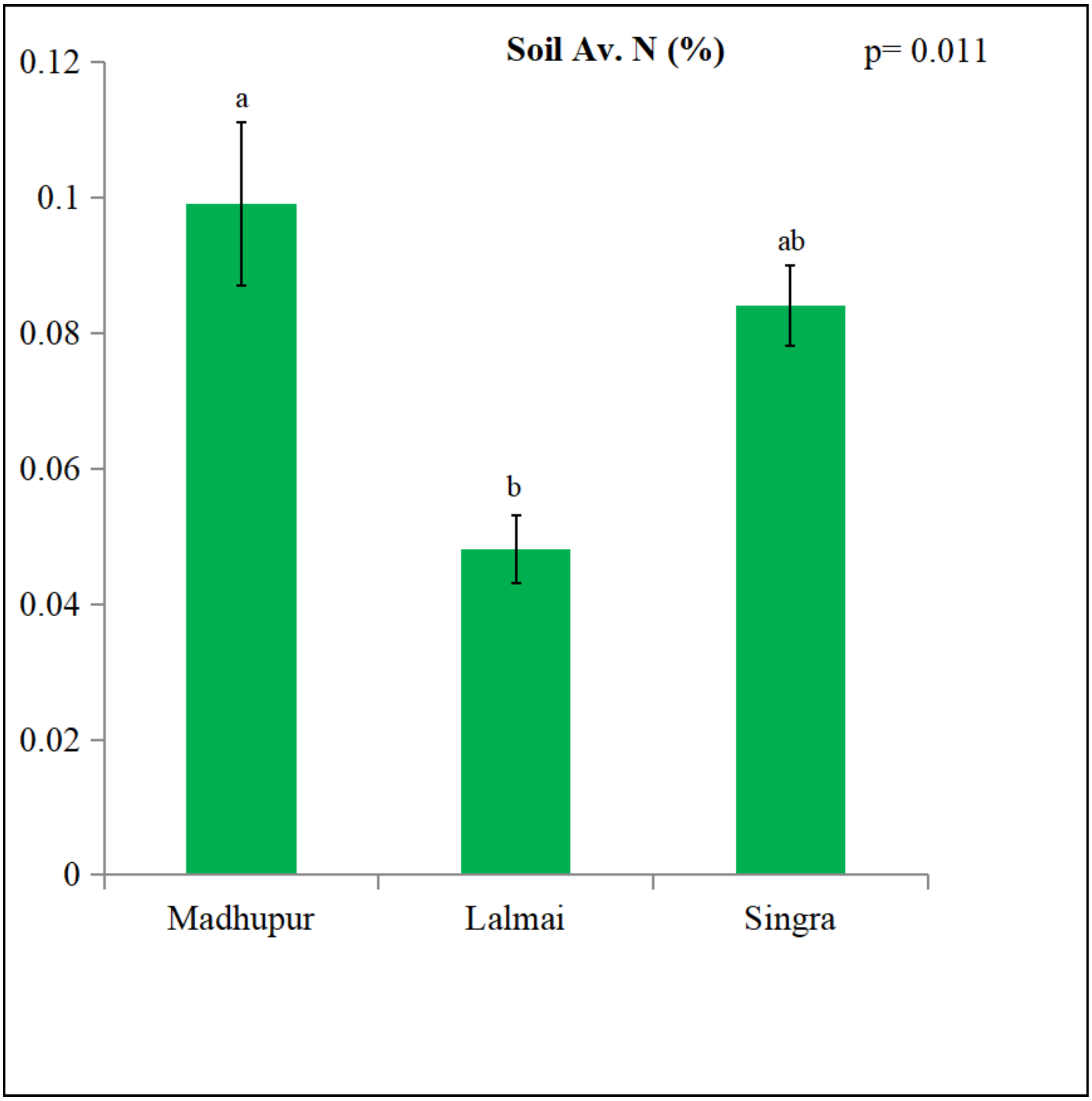


Figure 3.53: Mean values of soil available N (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

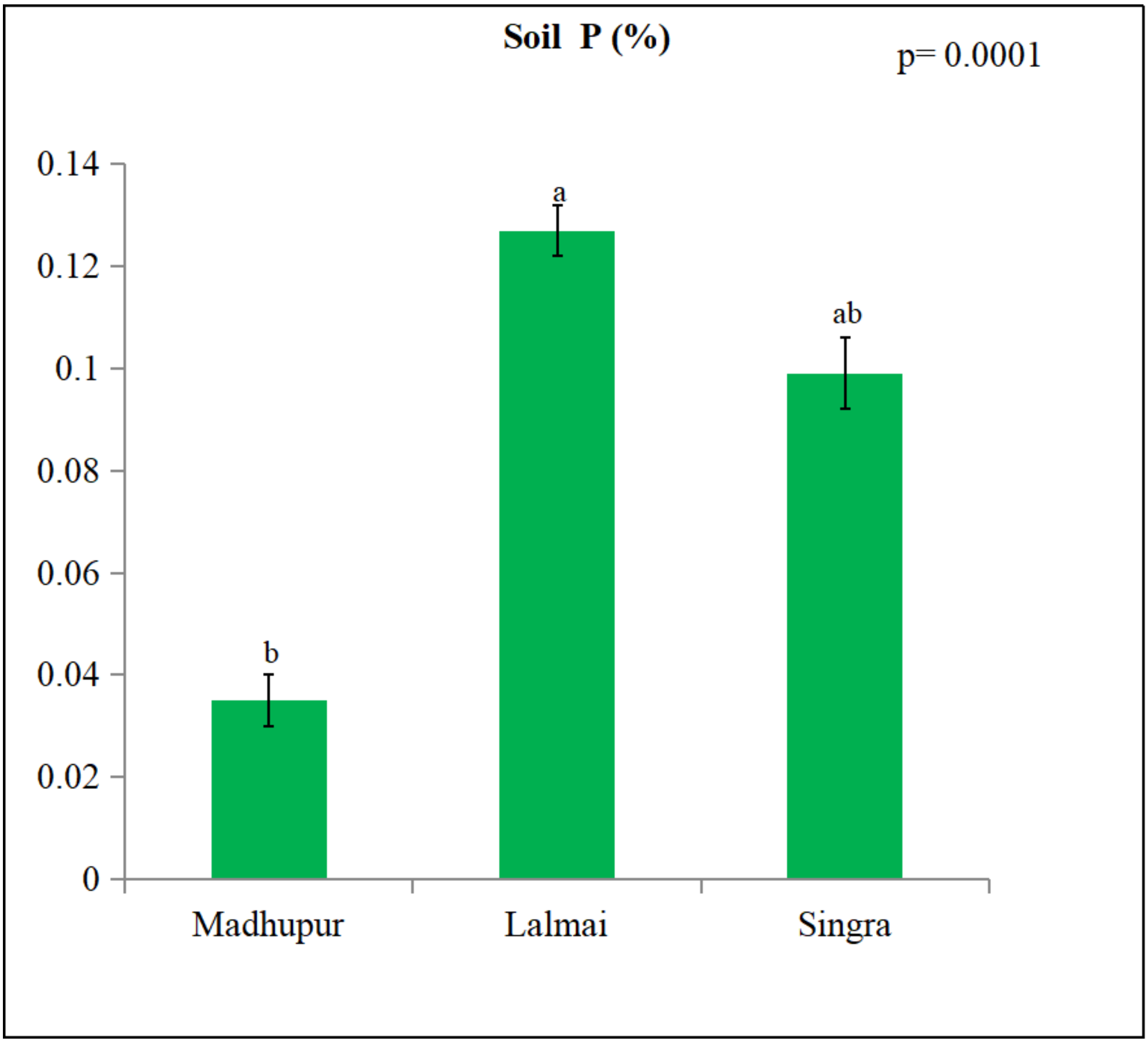


Figure 3.54: Mean values of soil P (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

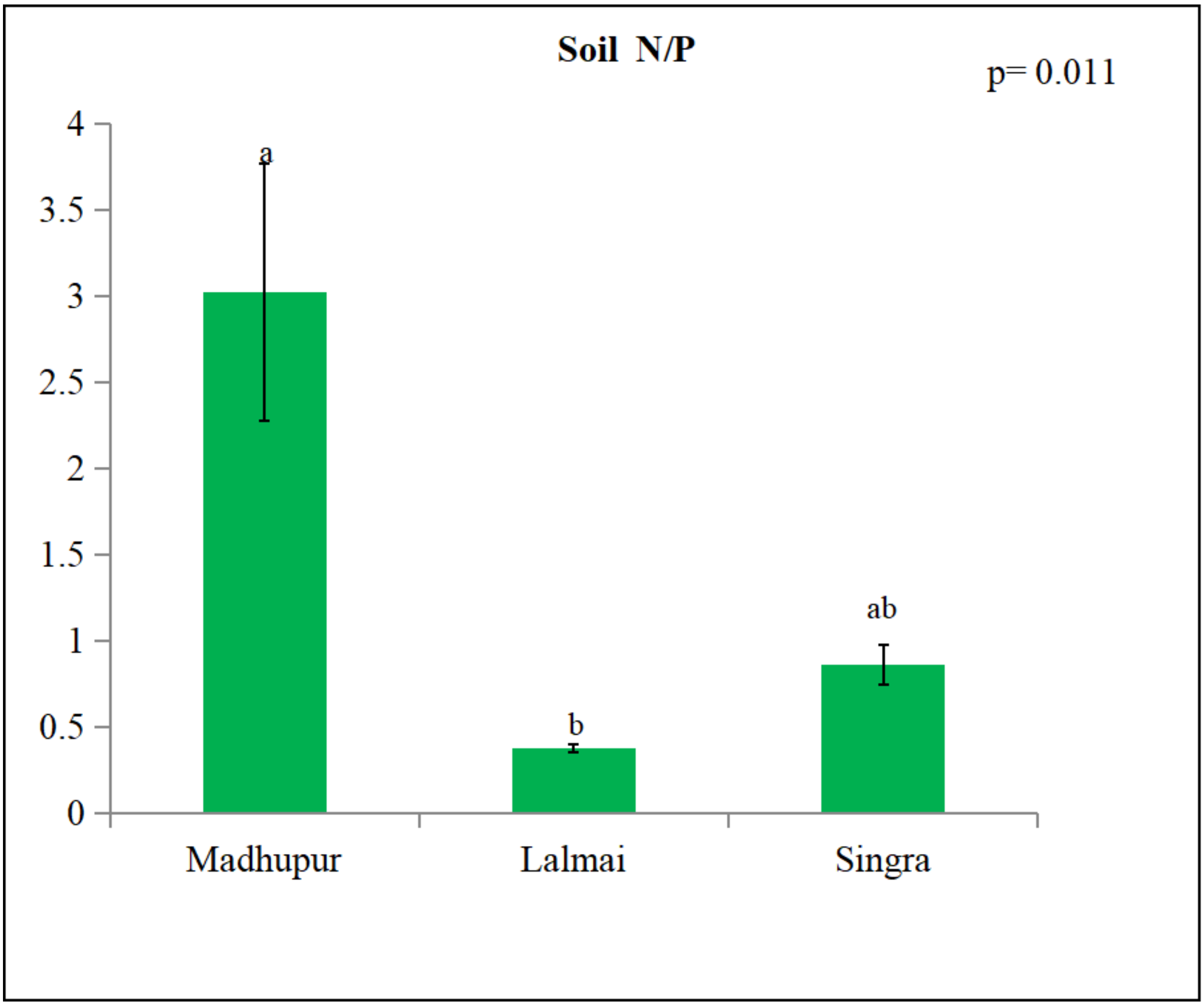


Figure 3.55: Mean values of soil P (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.4.4 Chemical properties of Sal leaf litter used in the decomposition study

Chemical properties including total N, total P, phenol, tannin, N/Phenol, and P/ Phenol of leaves of Sal leaf litter collected from Madhupur Sal forest, Lalmai Sal forest, and Singra National Park were shown in Figure 3.56-3.61. Among the three forests, there was a significant ($p = 0.0001$) difference in total nitrogen value. The highest mean value of total nitrogen (2.52%) was found in Lalmai Sal forest, and the lowest (2.02%) was found in Madhupur Sal Forest. There was a significant ($p = 0.006$) difference in total phosphorus value (%) among the leaves of the three forests. The highest P content was found in Lalmai Sal Forest (0.32%) whereas the lowest value was found in the leaves of Singra National Park (0.20 %). There was also a significant difference in the content of phenols ($p = 0.015$) among the Sal leaf litter collected from the three forests. The highest value was recorded in Madhupur Sal forest (2.83 %) and the lowest value was in Lalmai Sal forest (1.35 %). In case of tannin, there was no significant difference among the three selected forests ($p = 0.467$). The highest tannin content was found in Madhupur Sal forest (0.15 %) and the lowest value in Lalmai Sal forest. Similarly, in the case of nitrogen/phenol, there was a significant ($p = 0.004$) difference among Madhupur Sal forest, Lalmai Sal forest, and Singra National Park. The highest value of nitrogen/phenol (1.94 %) was found in Lalmai Sal forest and the lowest value (0.75 %) in Madhupur Sal forest. The highest value of P/Phenol (0.25%) was recorded in Lalmai Sal forest and the lowest value (0.07%) in Singra National Park showing the significant difference ($p = 0.003$) among them. In case of N/Tannin, no significant ($p = 0.0001$) difference was observed. The highest value was found in Lalmai Sal forest (914.18 %), and the lowest value was found in Madhupur Sal forest (271.13 %). In case of P/Tannin, no significant ($p = 0.511$) difference was observed.

The highest value was found in Lalmai Sal forest (118.42 %) and the lowest value was found in Madhupur Sal forest (28.48 %).

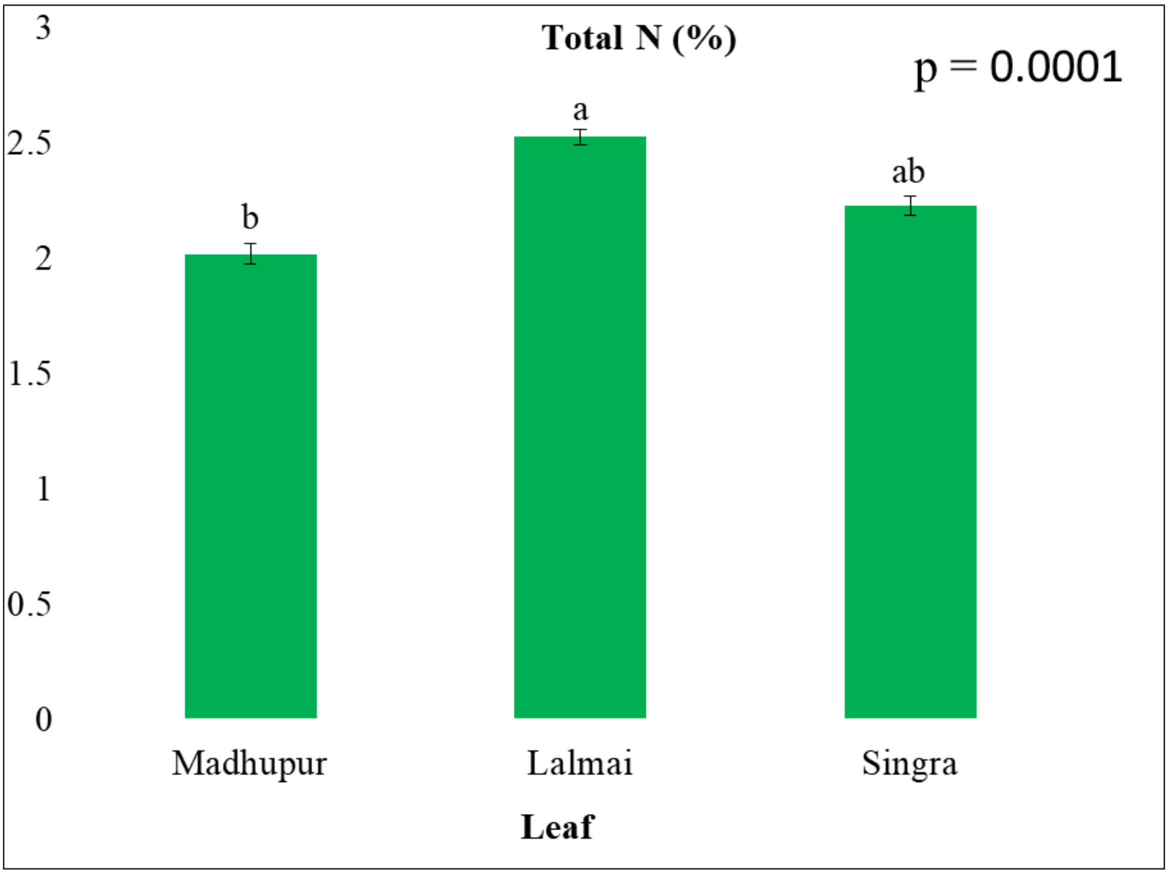


Figure 3.56: Mean values of total N (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

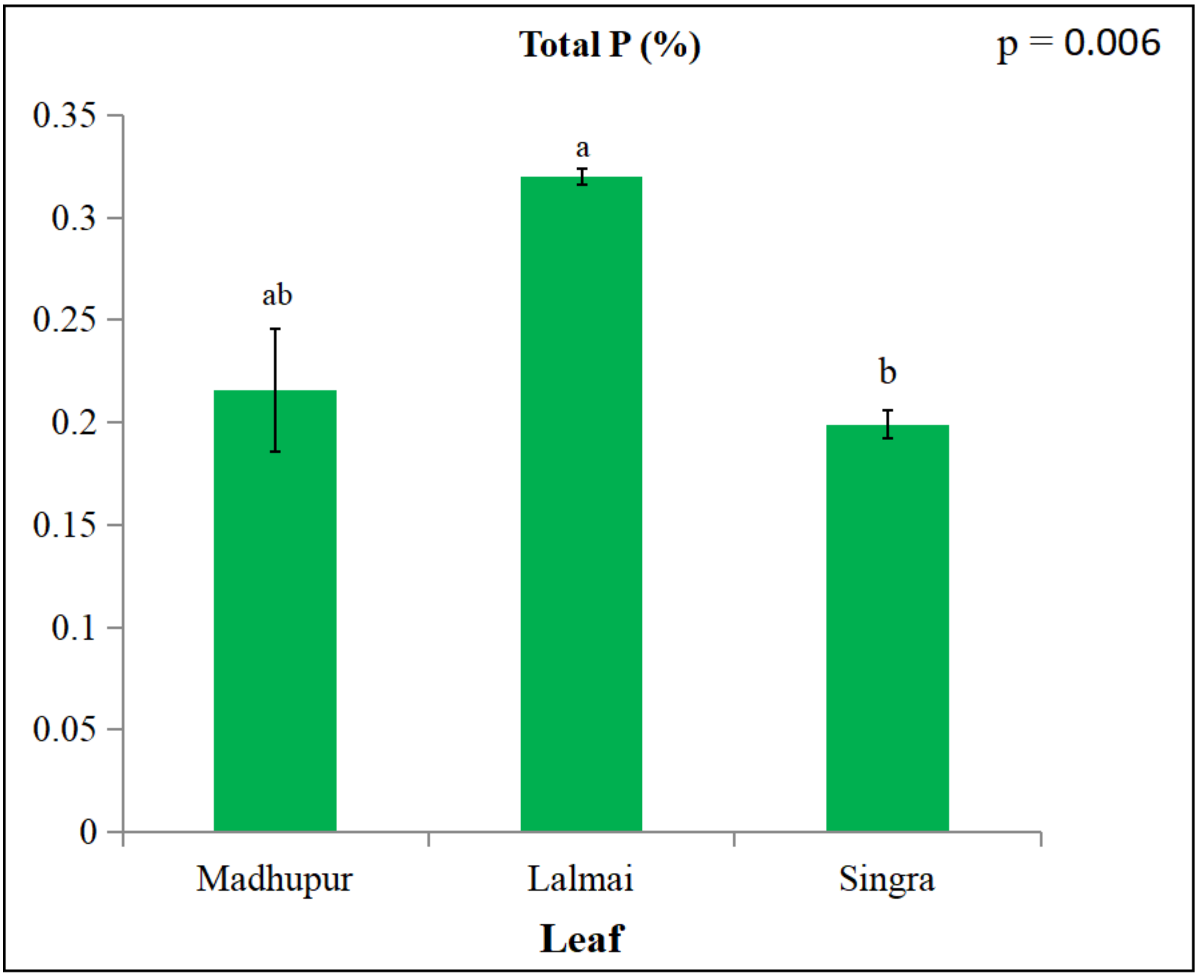


Figure 3.57: Mean values of total P (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

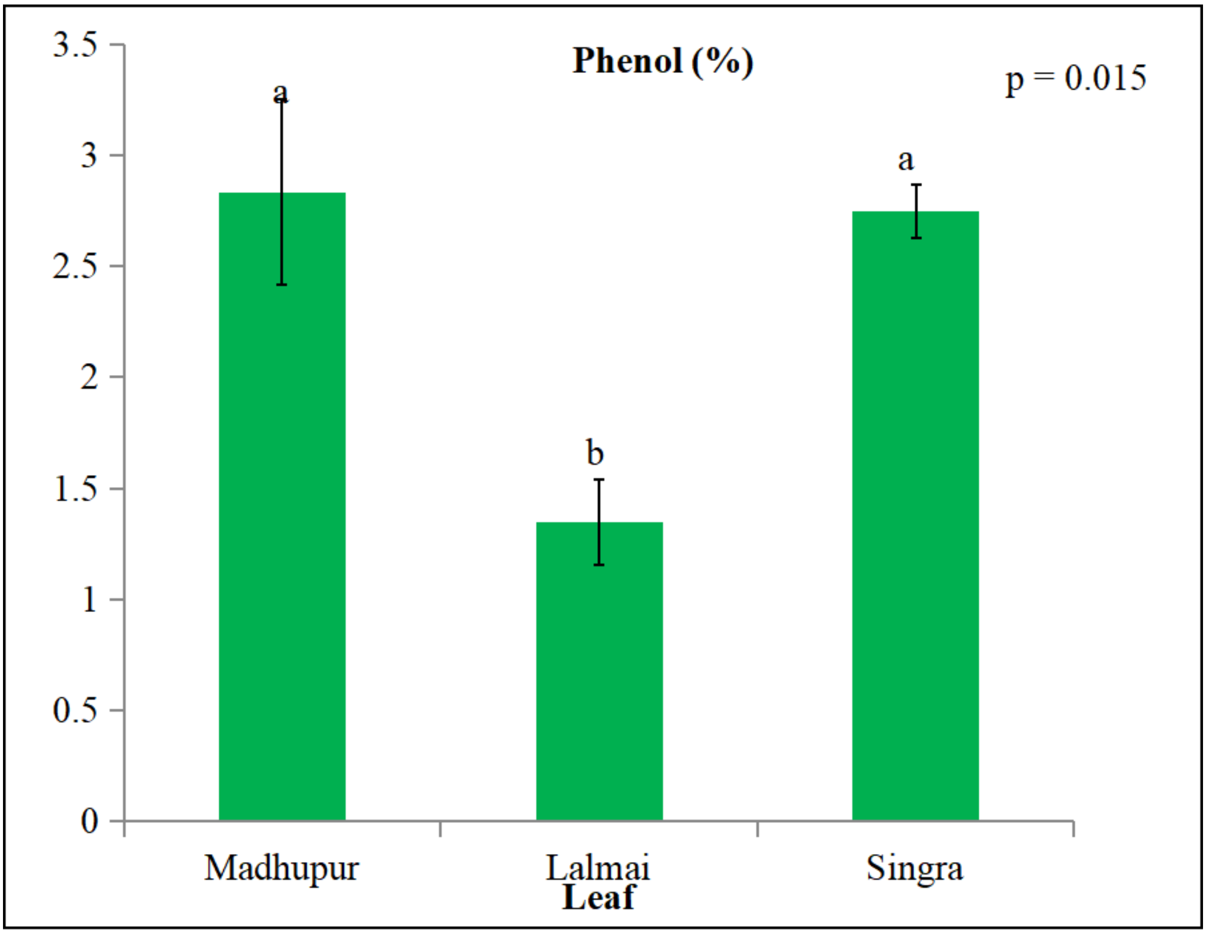


Figure 3.58: Mean values of phenol (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

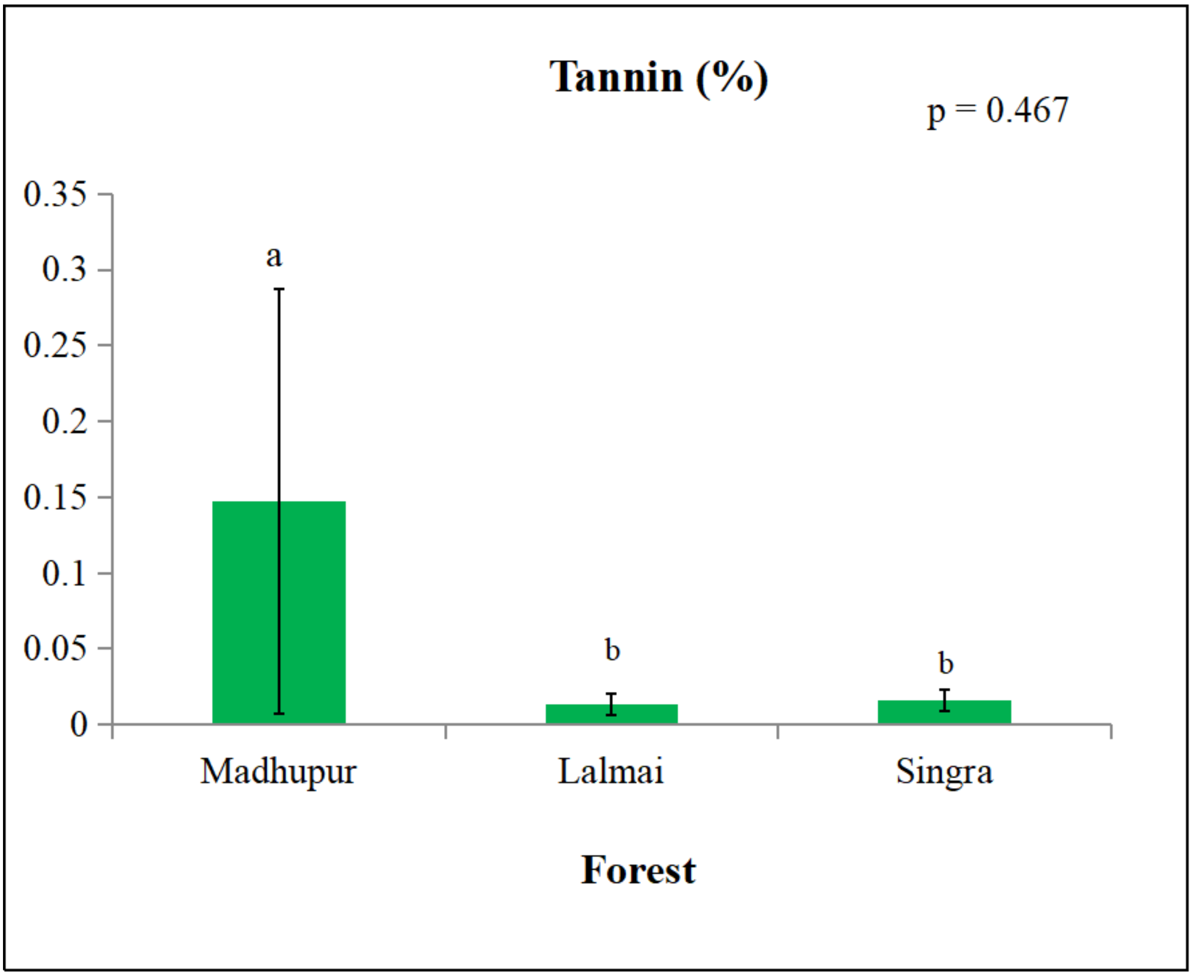


Figure 3.59: Mean values of tannin content (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

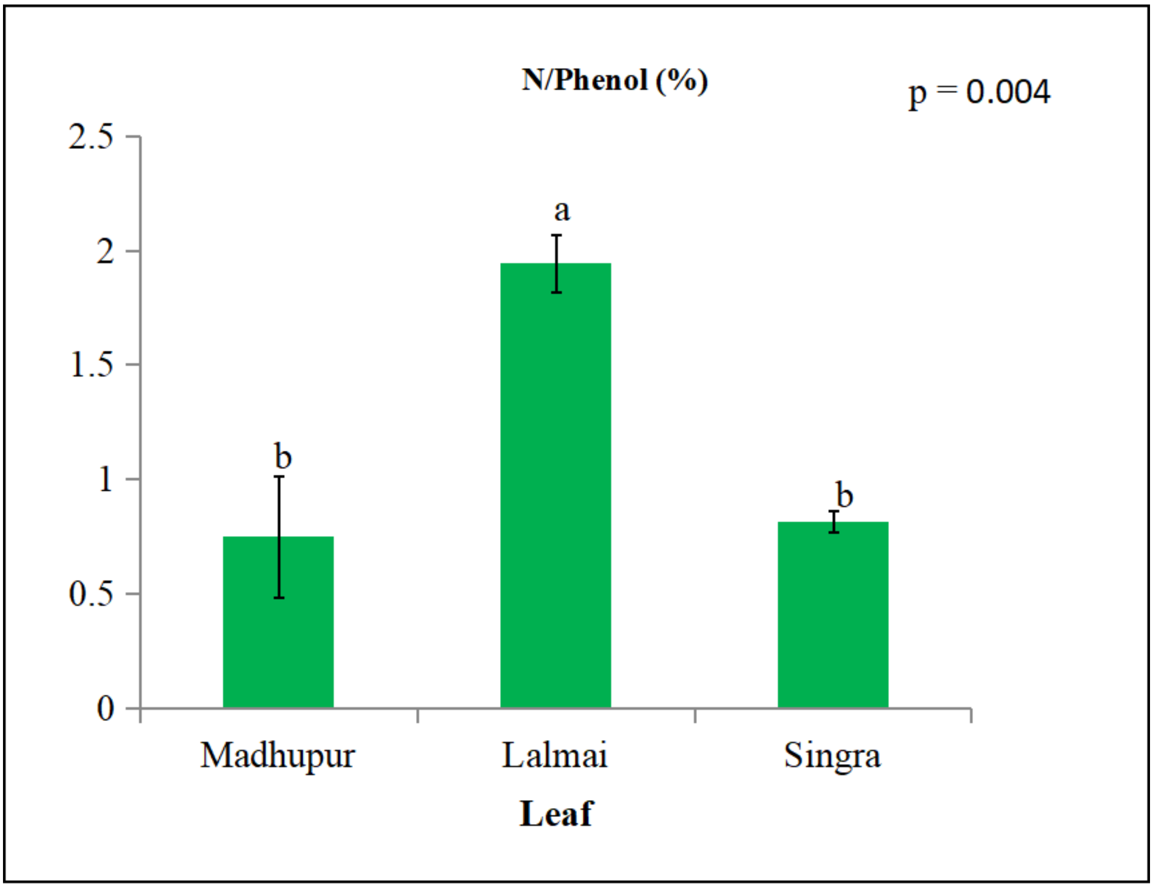


Figure 3.60: Mean values of N/Phenol (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

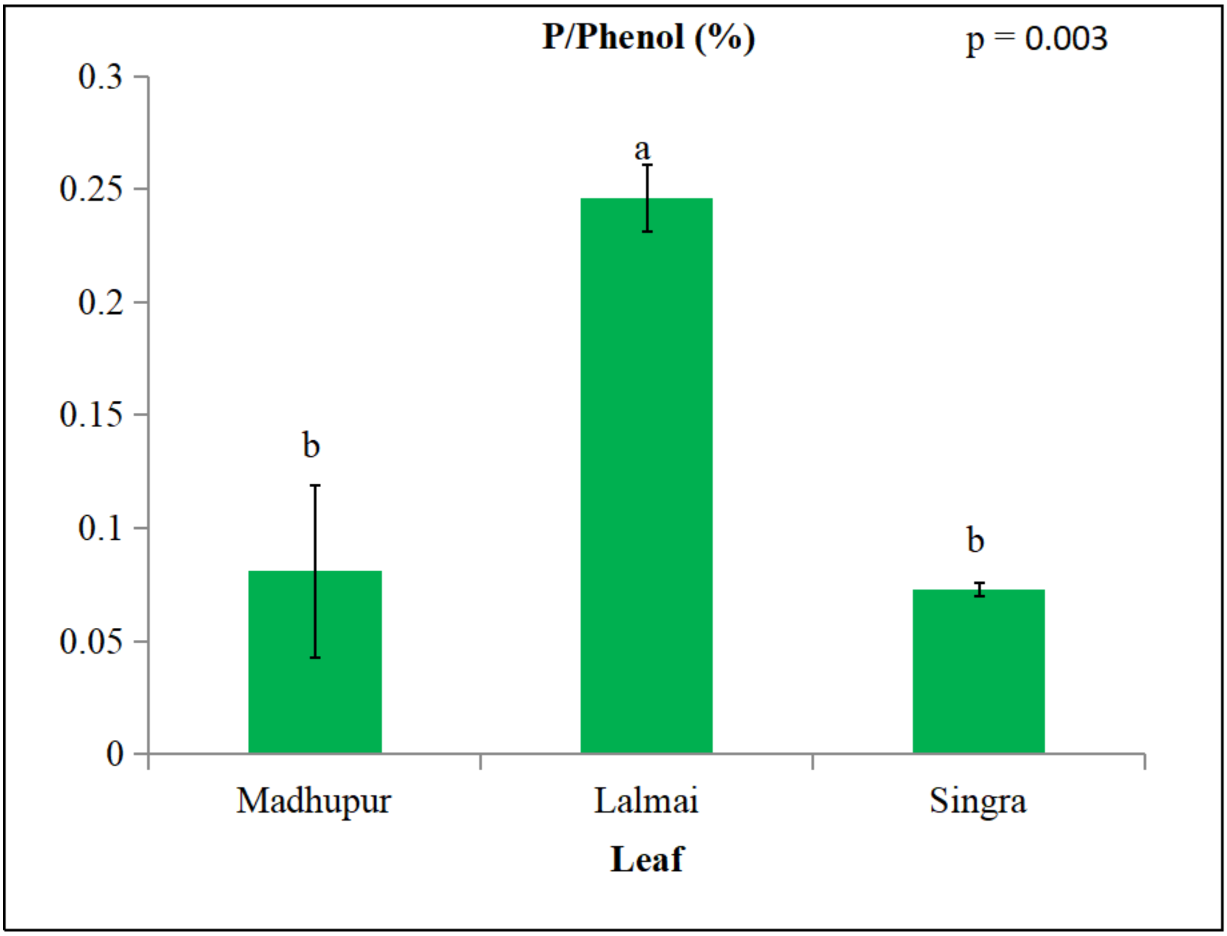


Figure 3.61: Mean values of P/Phenol (%) of Madhupur Sal forest, Lalmai Sal forest and Singra National Park of Bangladesh.

3.5 Seasonal variation in soil bacterial community composition

Seasonal changes in soil bacterial community were observed at 0-10 cm, 10-20 cm, and 20-30 cm depth during four seasons (summer, monsoon, late autumn, and winter) in three selected plots from unprotected (Jalchatra) area outside the protected area of Madhupur Sal forest. Fast growing and slow growing bacteria were categorized on the basis of their morphological size and presented separately.

3.5.1 Seasonal variation of fast-growing bacteria

In case of small colonies of fast-growing bacteria, there was significant difference among seasons ($p = 0.0204$) and the interaction between season and soil depth ($p = 0.0101$). However, there was no significant difference among them at soil depth 20 cm in summer season. Bacterial colony number was 178.92±40.64 cfu/g while at 30 cm in monsoon season. it was 155.67±16.04cfu/g and in autumn season at 20 cm it was 171.58±36.67 cfu/g and in winter season at 10 cm it was 118.42±16.50 cfu/g. In this case, the highest colony count was in the summer season at the depth of 20 cm 178.92±40.64 cfu/g.

The mean value of the number of medium colony of fast-growing bacteria showed no significant difference among seasons, depths, and their interactions. In summer season at 30 cm the value was 9.58±2.46 cfu/g, in monsoon season at 20 cm depth it was 11.17±2.97 cfu/g, in autumn season at the depth of 20 cm the value was 11.75±2.82 cfu/g and in winter season at 10 cm depth it was 15.00±4.37 cfu/g. In this case, the maximum colony count was observed at a depth of 10 cm (15.00±4.37 cfu/g) during winter season.

In case of large colonies of fast-growing bacteria, there was significant difference among seasons ($p < 0.0001$) and depth ($p < 0.0170$). However, there was no significant difference between the interaction of seasons and soil depths. The maximum mean values of bacterial colonies were observed at a depth of 10 cm (23.25±4.93 cfu/g) in the summer season while at 10 cm depth it was 15.75±2.01 cfu/g in the rainy season, at the depth of 20 cm. The value was 4.67±0.80 cfu/g in the autumn season, and at the depth of 10 cm the value was 31.91±8.08 cfu/g in the winter season. In this case, the maximum colony count was observed at a depth of 10 cm (31.91±8.08 cfu/g) during the winter season. Seasonal variation in fast growing bacterial colony counts is shown in Figures 3/62-3.64.

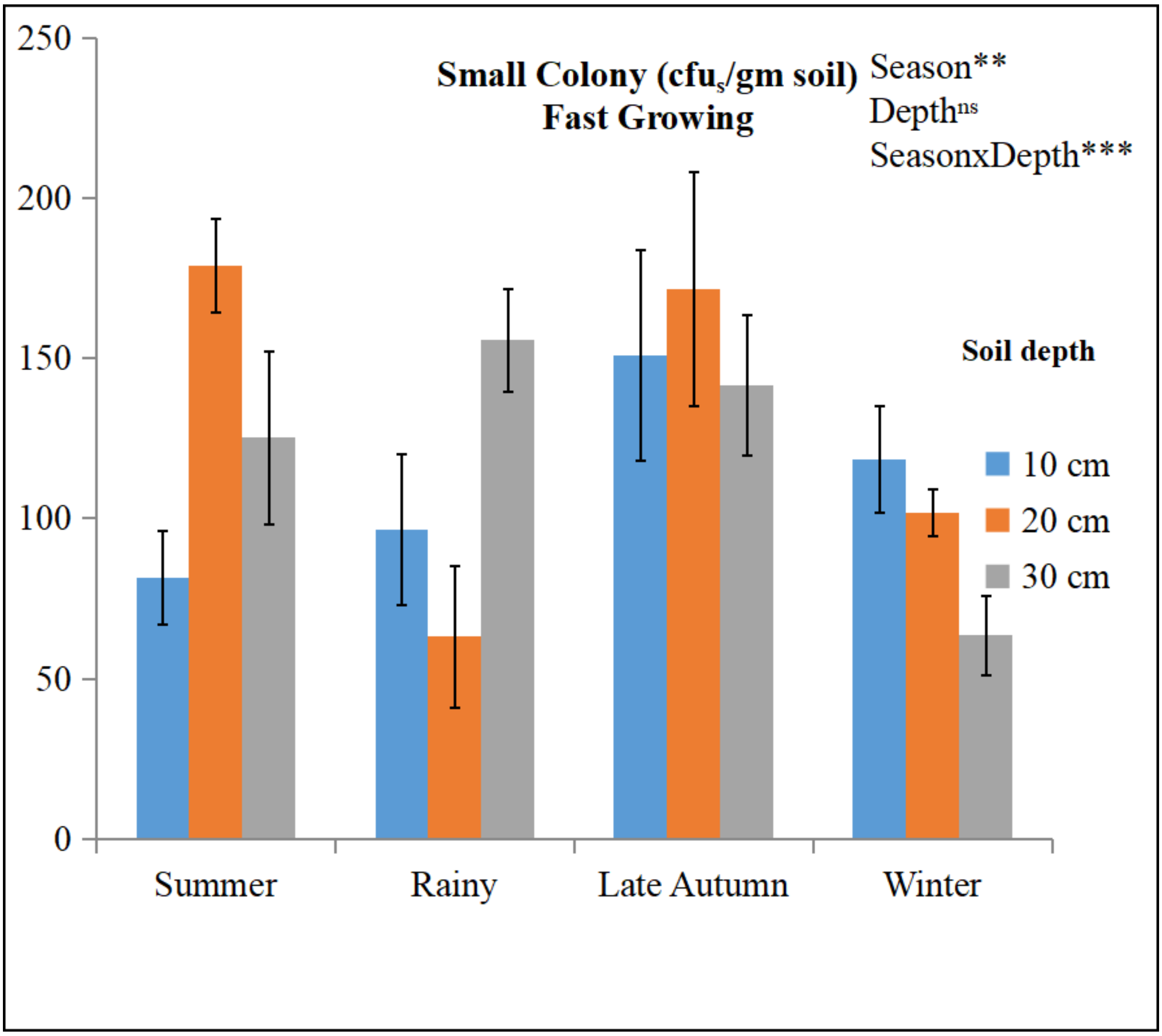


Figure 3.62: Mean (±SEM) values of small bacterial colony number (cfu_s/g soil) of first growing bacteria (1st day after culture) in the soil of Madhupur Sal Forest, Bangladesh.

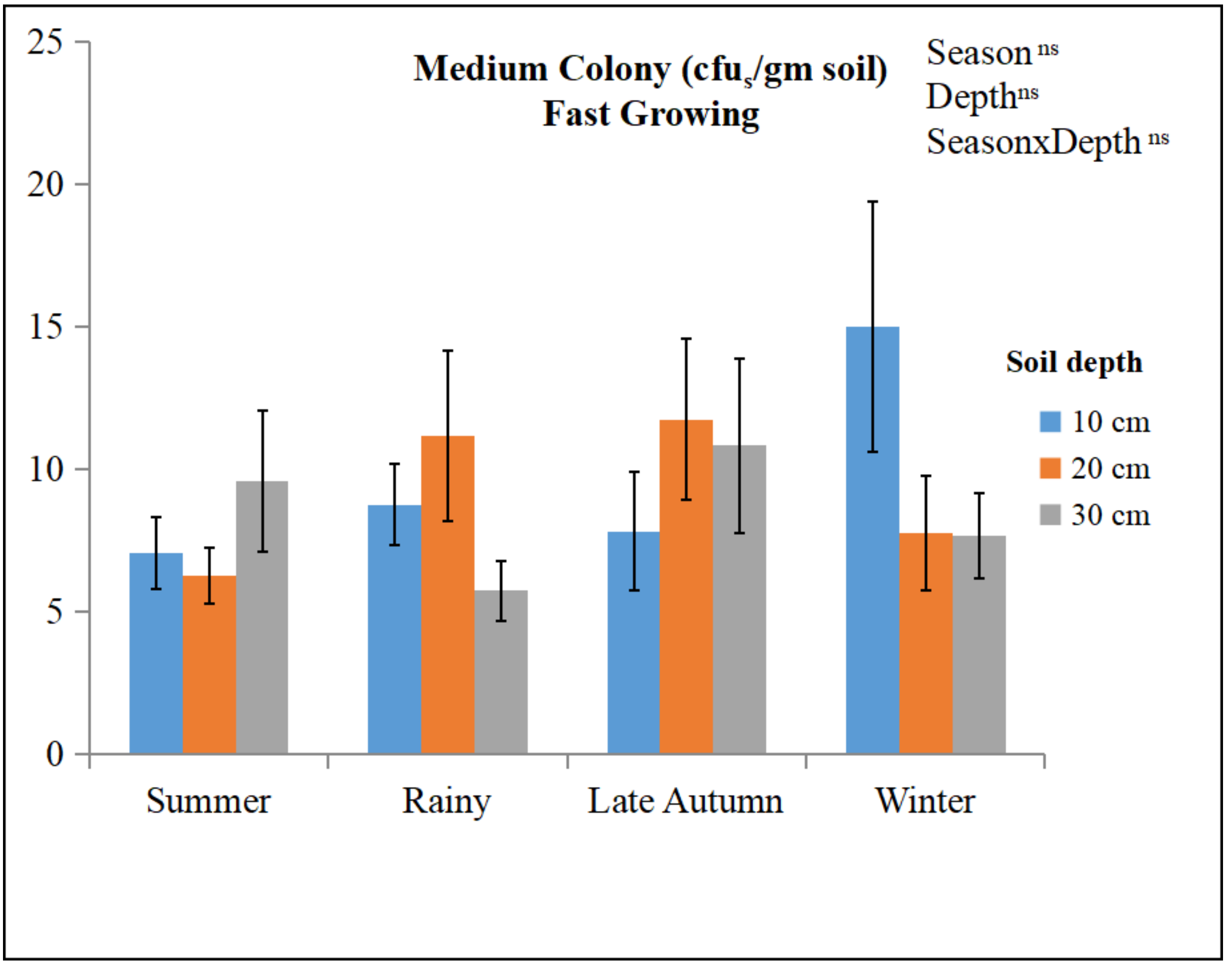


Figure 3.63: Mean (±SEM) values of medium bacterial colony number (cfu$_s$/g soil) of first growing bacteria (1st day after culture) in the soil of Madhupur Sal Forest, Bangladesh.

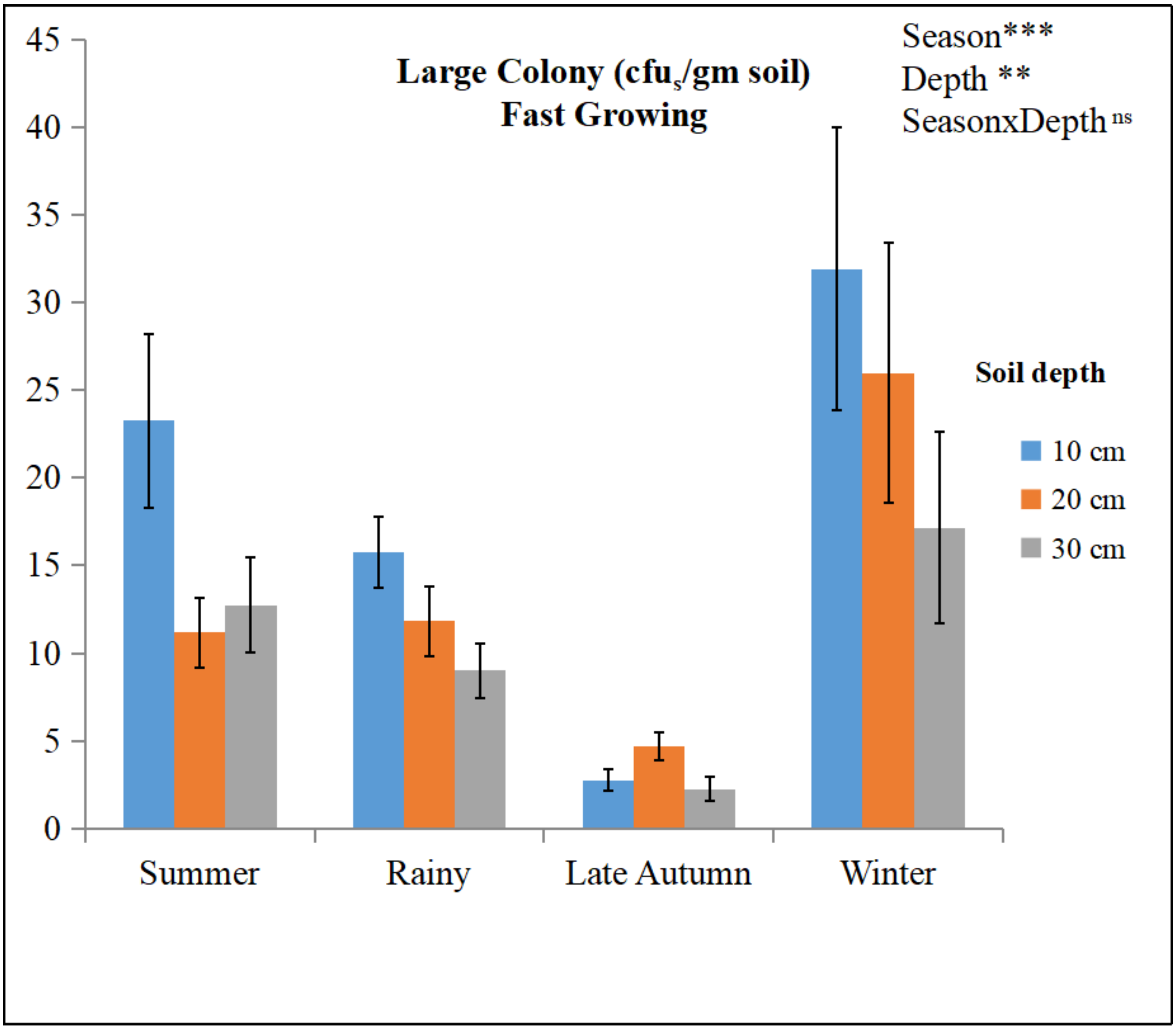


Figure 3.64: Mean (±SEM) values of large bacterial colony number (cfu_s/g soil) of first growing bacteria (1st day after culture) in the soil of Madhupur Sal Forest, Bangladesh.

3.5.2 Seasonal variation of slow-growing bacteria

In case of small colonies of slow-growing bacteria, there was significant difference among seasons ($p < 0.0001$). However, there was no significant difference among soil depths and interactions among these two factors. The maximum number of bacterial colonies was observed at a depth of 20 cm in the summer season (175.75±44.38 cfu/g), at the depth of 30 cm in the rainy season it was 219.33±16.21 cfu/g, at the depth of 30 cm in the autumn season it was 435.17±45.58 cfu/g and at the depth of 10 cm in the winter season the value was 109.42±14.38 cfu/g. In this case, the maximum colony number in autumn was at a depth of 30 cm (435.17±45.58 cfu/g).

In case of medium colonies of slow-growing bacteria, there was a significant difference among seasons ($p < 0.0306$). However, there was no significant difference among depths and the interactions between these two factors. The maximum bacterial colony density was observed at a depth of 30 cm (22.58±3.63 cfu/g) in summer, at 20 cm depth it was 12.83±4.73 cfu/g in rainy season, at the depth of 30 cm it was 15.00±3.59 cfu/g in autumn, and at the depth of 10 cm the value was 21.17±4.05 cfu/g during winter. In this case, the maximum colony number was observed at a depth of 10 cm (22.58±3.63 cfu/g) during summer.

In case of mean value of large colony of slow-growing bacteria, there was a significant difference among seasons ($p < 0.0001$) and depth ($p < 0.0182$). However, there was no significant difference between the interaction of season and soil depth. The maximum bacterial colony count was observed at a depth of 10 cm (28.50±2.01 cfu/g) during summer, at the depth of 10 cm the value was 18.42±3.72 cfu/g during rainy season, at the depth of 20 cm the value was 2.92±0.60 cfu/g during autumn, and at the depth of 10 cm the value was 35.58±1.91 cfu/g during winter. In this case, the maximum colony count was observed at a depth of 10 cm (35.58±1.91 cfu/g) during winter. Seasonal variation in slow growing bacterial colony counts are shown in Figures 3.65-3.67.

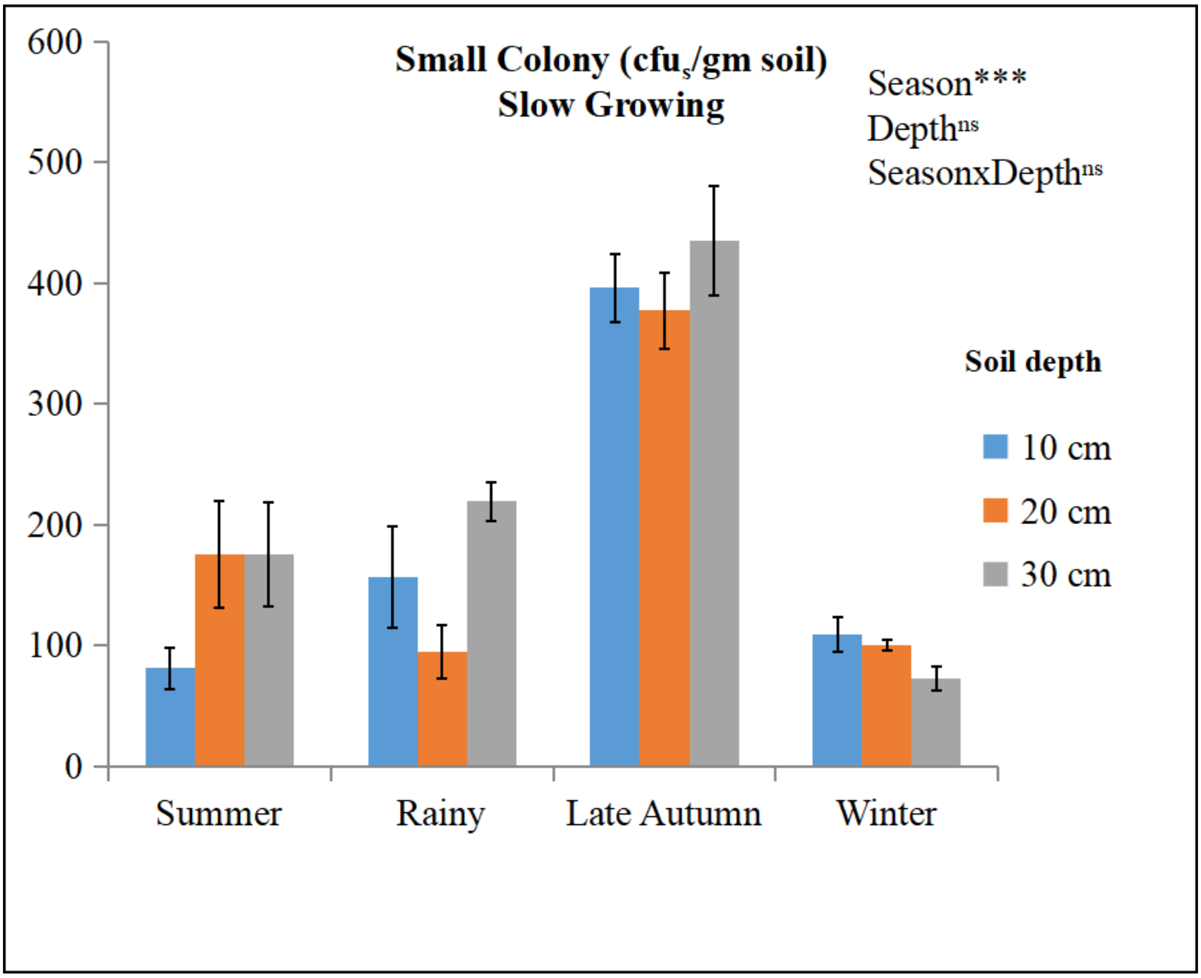


Figure 3.65: Mean (±SEM) values of small bacterial colony number (cfu_s/g soil) of slow growing bacteria (after 2nd day of culture) in the soil of Madhupur Sal Forest, Bangladesh.

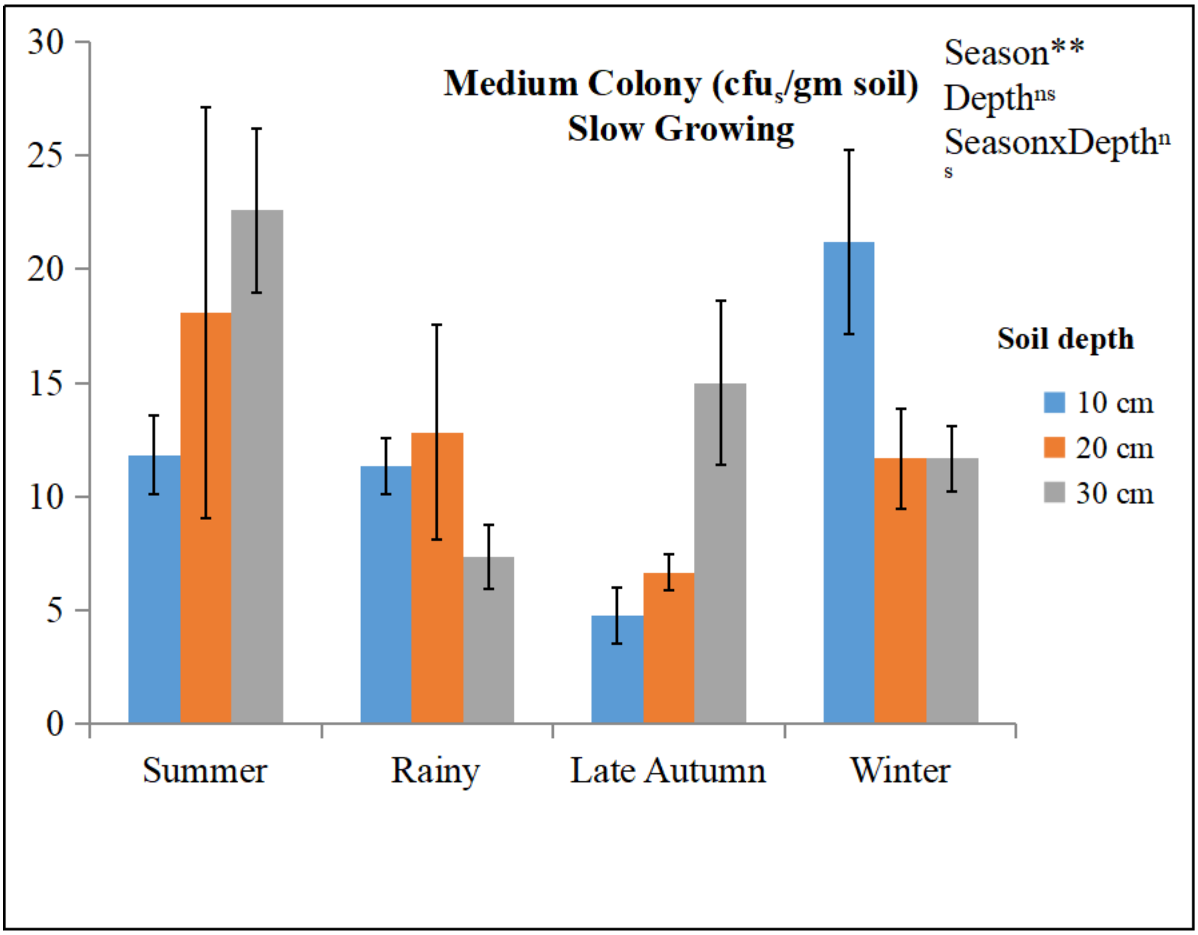


Figure 3.66: Mean (±SEM) values of medium bacterial colony number (cfu_s/g soil) of slow growing bacteria (after 2nd day of culture) in the soil of Madhupur Sal forest, Bangladesh.

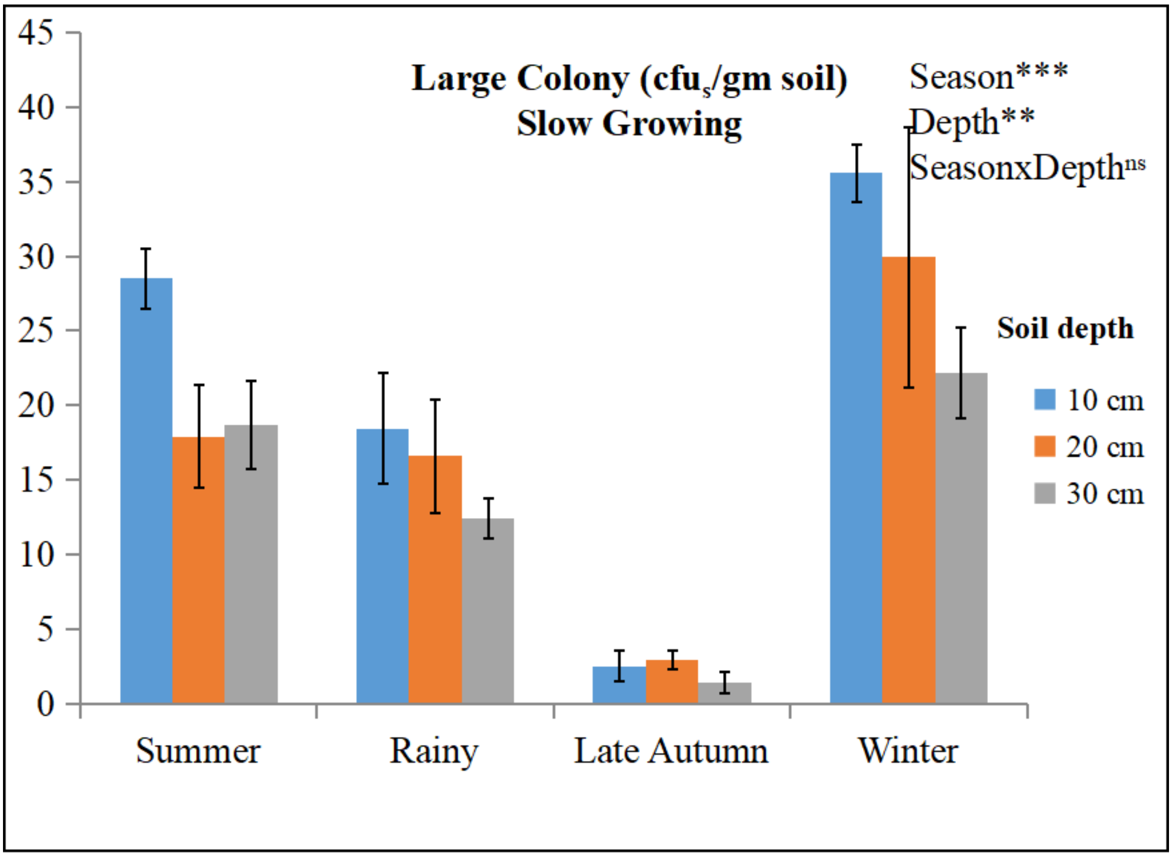


Figure 3.67: Mean (±SEM) values of large bacterial colony number (cfu_s/g soil) of slow growing bacteria (after 2nd day of culture) in the soil of Madhupur Sal forest, Bangladesh.

CHAPTER 4

DISCUSSION

4.1 Vegetation structure of the study area

4.1.1 Phytosociological analysis of the selected Sal forests of Bangladesh

4.1.1.1 Importance value index (IVI) of plant species of Madhupur Sal forest

A phytosociological investigation was done in Madhupur Sal forest in order to gain insights into the composition of plant species as well as to identify the dominant and rare species. Of the 36 plant species identified, 12 were herbs, 18 were shrubs and the rest were trees. All forms of ecological implications were evaluated by calculatinig IVI which included their relative density, frequency, and dominance. These findings demonstrated the dominance of specific species, the existence of uncommon species, and the general composition of forest vegetation. The highest IVI value, 129.21, was displayed by the tree species *S. robusta* Roxb. This demonstrates the vegetation in the Madhupur Sal forest. This feature of *S. robusta* is mostly consistent with the features of Sal Forests, where it is the most common and ecologically significant species (Champion and Sheth 1968). This high IVI value demonstrated support for forest structure, biodiversity, and ecosystem functions like the hydrological cycle and carbon sequestration (Hossain *et al*. 2015). While other tree species such as *G. asiatica* (IVI = 23.82), *A. lacucha* (IVI = 20), and *M. phillippensis* (IVI = 17.01) also contributed significantly to the forest structure. Nevertheless, *S. robusta* was the primary contributor. Such advantage is mostly consistent with the known traits of S. robusta, the most common and ecologically important species in Sal forests (Champion and Seth 1968). Hossain et al. (2015) stated that high IVI values of *S. robusta* demonstrated its importance in maintaining forest structure and biodiversity. *Aegle marmelos* L. (IVI =4.08), *F. hispida* (IVI = 2.3), and *A. indica* (IVI = 2.3) were examples of uncommon tree species that demonstrated the importance of forests in preserving biodiversity, especially for species with little ecological dominance (Rahman *et al*. 2020). *C. viscosum* (IVI = 125.56) and *Glycosmis pentaphylla* (IVI = 108.0) were the most prevalent species in the shrub layer that demonstrated their ecological significance and adaptability in under-vegetation. According to Khan *et al*. (2018), these species are well-known for their capacity to flourish in disturbed environments and for their roles in nutrient cycles and ground stability. While *A. augustum* (IVI = 6.93) was recognized as a rare shrub species, *R. dumetorum* (IVI = 38.60) also demonstrated a notable presence. *C. viscosum* and *G. pentaphylla* have high IVI values, which indicated their importance to the ecological balance of forest shelters and their role in providing habitats and food sources for a variety of animals (Haque *et al*. 2019). *C. rotundus* (IVI = 75.00) and *C. benghalensis* (IVI = 76.00) dominated the herbaceous strata. According to Alam *et al*. (2017), these plants most likely had a significant impact on bed covering, halting soil erosion, and sustaining microhabitats for tiny creatures. *Pteris* sp. (IVI = 7.90) and *C. zeoderia* Rosc. (IVI = 29.6) are two other well-known herbaceous species. Rare herbaceous species were also identified, including *D. japonica* (IVI = 6.9), *Ferula narthex* boiss. (IVI = 6.60), and *K. brevifolia* Rottb. (IVI = 5.95). According to Rashid *et al*. (2021), this demonstrated the importance of forests in the preservation of rare plant species.

Maintaining the structure and function of Madhupur Sal forest is ecologically significant, as evidenced by the high IVI values of prominent species including *S. robusta*, *C. viscosum*, and *C. benghalensis*. The climatic condition, vegetative cycles, and habitat availability of various plant and animal habitats may be impacted by these species (Hossain *et al*. 2015). Even with low IVI values, the existence of rare species emphasized the need of preserving forests. The conservation of these species is essential for maintaining biodiversity and ecological balance (Rahman *et al*. 2021).

The findings of this study have important implications for the management and protection of Madhupur monkey forests. Dominance of *S. robusta* indicated that conservation is a top priority, and the presence of unusual variations emphasized the need for targeted conservation strategies to maintain biological variety (Khan *et al*. 2018). Sustainable forest management practices such as controlled logging, habitat recovery, and invasive species control should be implemented. Community-based conservation initiatives and sensitization programs can also play an important role in maintaining this important natural resource (Alam *et al*. 2017).

4.1.1.2 Importance Value Index (IVI) of plant species of Lalmai Sal forest

Phyto-sociological study conducted in Lalmai Sal forest yielded unique insights into the plant species composition, dominance, and ecological connections in this environment. A total of 25 plant species were identified, with 10 being tree species, 4 shrubs, and 11 being herbs. The IVI was developed to determine ecological relevance of each species based on its relative density, frequency, and dominance.

These discoveries emphasize the dominance of specific species, the presence of rare species, and the overall organization of the forest flora. In the present study, *S. robusta* Roxb. exhibited the highest IVI value of 114.75, showing ecological dominance in the Lalmai Sal forest. This dominance was consistent with the recognized characteristics of Sal forests, where *S. robusta* was frequently the most dominant and ecologically important species (Champion and Seth 1968). Its high IVI value suggests that it contributed significantly to forest structure, biodiversity, and ecosystem services such as carbon sequestration and water cycling (Hossain *et al*. 2015).

Other tree species studied included *A. auriculiformis* (IVI = 38.63), *E. jambolana* (IVI = 28.91), and *R. dumetorum* (IVI = 25.70), which all contributed significantly to forest structure but were far less dominant than *S. robusta*. Furthermore, the existence of uncommon tree species such as *Z. oenoplia* (IVI = 6.10), *D. indica* (IVI = 11.41), and *T. grandis* (IVI = 14.92) demonstrated the importance of forests in biodiversity conservation, especially for species with low ecological dominance (Rahman *et al*. 2020).

The most prominent species in the shrub layer were *U. lobata* (IVI = 98.00) and *G. nervosa* (IVI = 85.21), showing their adaptability and ecological significance in the understory vegetation. These species are well-known for their ability to grow in disturbed environments while also improving soil stability and nitrogen cycling (Khan *et al*. 2018). *C. viscosum* (IVI = 62.13) was also present in the current study, while *G. pentaphylla* (IVI = 54.70) was less dominant but ecologically important. *U. lobata* and *G. nervosa* had high IVI values, indicating their importance in supplying habitat and food supplies for numerous species, as well as their contribution to maintaining the ecological balance of the forest understory (Haque *et al*. 2019).

C. *dactylon* (IVI = 90.00) and *Cyperus* sp. (IVI = 62.85), both found in tropical forest habitats, dominated the herb layer. These species most likely contributed significantly to forest floor cover, soil erosion prevention, and microhabitat support for small creatures (Alam *et al*. 2017). Other noteworthy herbaceous plants include *C. benghalensis* (IVI = 60.42) and *C. geoderia* (IVI = 23.10). Rare herbaceous species such as *S. rotundifolia* (IVI

= 4.08), *M. pudica* (IVI = 4.60), and *A. bractea* (IVI = 5.15) had also been discovered, demonstrating the importance of forests in the conservation of less frequent plant species (Rashid *et al*. 2021).

The high IVI values of dominant species such as *S. robusta*, *C. dactylon*, and *U. lobata* demonstrated the ecological importance of maintaining the structure and function of the Lalmai Sal forest. These species were expected to influence microclimate conditions, nitrogen cycling, and habitat availability for other plants and animals (Hossain *et al*. 2015). Despite the low IVI scores, the presence of unusual species emphasizes the importance of forest conservation. Protecting these species is of utmost importance, as these species are instrumental in maintaining biodiversity and ecological balance (Rahman *et al*. 2021).

The results of this study have important implications for the conservation and management of Lalmai Sal forests. The dominance of *S. robusta* indicates that it should be a conservation priority, although the presence of unusual species emphasizes the importance of focused conservation initiatives to maintain biodiversity. Sustainable forest management practices such as moderate logging, habitat restoration, and control of invasive species should be adopted to ensure the long-term structure and resilience of the ecosystem. Community-based conservation projects and awareness activities can also help in conserving this valuable natural resource.

4.1.1.3 Importance Value Index (IVI) of plant species of Singra National forest

The phytosociological study carried out in the Singra National forest shedded light on the plant species composition, dominance, and ecological associations that exist within this forest. A total of 26 plant species were identified, including 16 tree species, three shrubs, and seven herbs. The IVI was developed to determine the ecological relevance of each species, taking into account their relative density, frequency, and dominance. The results emphasized the dominance of specific species, the presence of rare species, and the overall structure of the forest vegetation. The results were discussed in details below, with references to similar studies.

The tree species *S. robusta* Roxb. had the highest IVI score of 86.74, showing ecological dominance in the Singra National forest. This dominance was consistent with known Sal forest characteristics, in which *S. robusta* was often the most dominant and ecologically relevant species (Champion and Seth 1968). Its high IVI value showed that it was important for sustaining forest structure, supporting biodiversity, and controlling ecosystem services like carbon sequestration and water cycling (Hossain *et al*. 2015). Other tree species, such as *A. lacucha* (IVI = 54.70), *M. phillippensis* (IVI = 44.94), and *R. dumetorum* (IVI = 30.50), made substantial contributions to the forest composition but were far less dominant than *S. robusta*. (Rahman *et al*. 2020).

The presence of rare tree species such as *Z. jujuba* (IVI = 2.92), *A. lebbeck* L. (IVI = 2.92), and *Eugenia* sp. (IVI = 2.92), demonstrated the significance of the forest in biodiversity conservation, especially for species with low ecological dominance (Rahman *et al*. 2020).

The most dominant species in the shrub layer was *C. viscosum* (IVI = 120.54), followed by *G. pentaphylla* (IVI = 94.60) and *U. lobata* (IVI = 84.90). These species are renowned for their ability to grow in disturbed habitats while also contributing to soil stability and nitrogen cycling (Khan *et al*. 2018). *C. viscosum* and *G. pentaphylla* have high IVI values, indicating that they play an important role in supplying habitat and food resources for numerous animals, as well as contributing to the ecological balance of the forest understory.

C. dactylon (IVI = 117.73) and *Cyperus* sp. (IVI = 68.70) were the dominant species in the herbaceous layer, both of which were prevalent in tropical forests. These plants most likely contributed significantly to ground cover, limiting soil erosion and providing microhabitats for smaller creatures (*Alam et al*. 2017). Other prominent herb species are *C. benghalensis* (IVI = 62.24) and *M. acuminata* (IVI = 19.55). Rare herb species including *K. brevifolia* Rottb. (IVI = 6.90) were also discovered, emphasizing the forest's importance in the preservation of less common plant species (Rashid *et al*. 2021).

Prominent species such as *S. robusta*, *C. viscosum* and *C. dactylon* showed high IVI values, highlighting their ecological significance in preserving the structure and function of Singra national forests. These species are expected to alter microclimate, nutrient cycle, and habitat availability for other flora and fauna (Hossain *et al*. 2015). The existence of uncommon species, despite their low IVI levels, highlights the importance of the conservation of forest. Protecting these species is critical for maintaining biodiversity and ecological equilibrium (Rahman *et al*. 2020).

The findings of this study have significance for the conservation and management of Singra National forest. Dominance of *S. robusta* suggests that it should remain a focus point in conservation efforts, yet the presence of uncommon species emphasizes the necessity for tailored conservation methods to maintain biodiversity (Khan *et al*. 2018). To ensure the long-term recovery and liveliness of this ecosystem, sustainable forest management strategies such as habitat restoration, controlled logging, and invasive species control should be implemented (Hack *et al.* 2019). Community-based conservation projects and awareness programs can also help to preserve this crucial natural resource (Alam *et al.* 2017).

In conclusion, the phyto-sociological study of Madhupur Sal forest, Lalmai Sal forest and Singra National forest provides valuable insights into the ecological dynamics of these unique ecosystems. The dominance of certain species, combined with the presence of rare and ecologically important plants, highlights the importance of conservation efforts to conserve this important natural ecosystem. The results of this study were consistent with previous studies and highlight the need for sustainable management practices to ensure the long-term health and biodiversity of the forests.

4.1.2 Vegetation structure of the selected Sal forests of Bangladesh

4.1.2.1 Species richness and diversity

The study of the species richness and diversity of the selected three Sal forests namely, Madhupur Sal Forest, Lalmai Sal Forest, and Singra National Park focused light on the plant structure. A total of 43 species were identified in the three forests, with differences in species richness and diversity evident across trees, shrubs, and herbs. Species richness is the number of distinct species found in an ecosystem. In this study, the average species richness values of the three woods were: Madhupur Sal forest: 14.44 ± 0.87, Lalmai Sal forest: 13.60 ± 1.44, and Singra National Park: 14.80 ± 1.53. The results showed that Singra National Park had the most species richness, followed by Madhupur forest and Lalmai forest. However, the differences were not statistically significant ($F = 0.22$, P value $= 0.81$), implying that the total species richness of the three forests was comparable. This closeness was due to the common environmental circumstances and forest type of the regions of the forests (tropical deciduous forest) (Champion and Seth 1968).

The tree species richness differed throughout the forests: Madhupur Sal forest (7.56 ± 0.84), Lalmai Sal forest (5.80 ± 1.20), and Singra National Park (8.60 ± 1.03). Singra National Park featured the most diverse tree species, followed by Madhupur and Lalmai forests. However, the differences were not significantly significant (F = 1.61, p = 0.23). Singra forest had become a place of high abundance of tree species since it was designated as a national park, where strong conservation measures and reduced human interference were often observed (Hossain *et al*. 2015).

Shrub species abundance also showed some extent of variation such as Madhupur Sal forest 3.44 ± 0.38; Lalmai Sal forest 2.80 ± 0.50 and Singra Sal forest 3.00 ± 0.00. Herb species abundance were for Madhupur Sal forest 3.44 ± 0.71, Lalmai Sal forest 5.00 ± 0.71 and Singra Sal froest 3.20 ± 0.66.

Lalmai Sal forest had the highest density of herb species, which could be attributed to its low vegetative dynamics and microclimatic conditions. However, there were no statistically significant variations in shrub and herb species richness among forests (shrub: F = 0.80, p = 0.466; herb: F = 1.47, p = 0.258). This suggests that the understory vegetation structure was rather constant throughout all three woods.

4.1.2.2 Shannon Diversity Index

For each of the three forests studied, Shannon diversity Index, which measured species diversity by taking into consideration both richness and evenness was determined. Madhupur Sal forest, Lalmai Sal forest, and Singra National Park had respective values of 2.58 ± 0.09, 2.30 ± 0.07, and 2.43 ± 0.19. Madhupur Sal forest had a larger species diversity than Lalmai forest and Singra forest, as evidenced by its highest Shannon diversity Index score. However, the differences were not statistically significant (F = 1.61, p value = 0.231). Although the species distribution might be somewhat more evenly spread in Madhupur, these results indicated that the overall level of diversity was comparable in all three forests.

4.1.2.3 Diameter at Breast Height (DBH)

The DBH of *S. robusta* is a critical metric for determining the age and structure of a forest. In this investigation, the mean DBH values of Lalmai forest (38.84 ± 2.12 cm) and Singra forest (37.36 ± 1.97 cm) were substantially higher than those of Madhupur forest (30.72 ± 1.93 cm) (p = 0.022). According to this result, the national parks of Lalmai forest and Singra forest were ancient and have sustained less harm, which presents opportunities for future growth and development.

The DBH of Lalmai Sal forest was the highest (38.84 ± 2.12 cm), Singra National Park had an intermediate DBH (37.36 ± 1.97 cm), and Madhupur Sal forest had the lowest (30.72 ± 1.93 cm) in the current study. Compared to Madhupur, the considerably higher DBH of Lalmai and Singra forest suggests that these forests may contain older layers of *S. robusta*. The reduction in DBH in Madhupur may be attributed to the forest's smaller extent or to elevated levels of human-induced disturbance, including selective logging and land-use change.

Lalmai Sal forest and Singra National Park may contain older layers of *S. robusta*, which are crucial for the maintenance of ecosystem health by storing carbon, cycling water, and supplying habitat, as evidenced by the higher DBH values (Hossain *et al*. 2015). The Shannon diversity index values of the three forests are comparable, suggesting that they have comparable levels of biodiversity despite local variations in species richness and evenness. It is crucial to safeguard the ecological integrity and biodiversity of the forests of

Lalmai and Singra from human-induced disturbances, as evidenced by the old-growth forests.

Findings of this study are essential for the conservation and management of Sal forest of Bangladesh. In order to preserve their ecological function and biodiversity, Lalmai and Singra, which are home to old-growth *S. robusta* forests, should be prioritized for conservation. They can also benefit from sustainable management practices, such as controlled logging, habitat restoration, and reforestation, to promote the development of trees and the diversity of species, in addition to their young forests. The regular monitoring of forest cover and species diversity can yield valuable information for the development of long-term conservation plans and adaptive management strategies.

The analysis emphasizes the ecological similarities and differences among the Sal forests of Madhupur, Lalmai, and Singra. The significance of conserving mature forest stands is emphasized by the higher DBH in Lalmai and Singra, despite the fact that species diversity is relatively consistent across the forests. These discoveries offer valuable insights for the development of conservation and management strategies that are specifically designed to protect the long-term health and biodiversity of these essential ecosystems.

4.2 Comparison of Plant Biomass among the Selected Sal Forests

4.2.1 Adult Tree Biomass

4.2.1.1 Aboveground, belowground and total woody biomass of adult tree

Quantifying plant biomass in tropical deciduous forests provides important insights into forest health, carbon storage potential, and ecosystem productivity. This study compared biomass distribution in three ecologically important deciduous forests in Bangladesh: Madhupur Sal forest, Lalmai Sal forest, and Singra National Park. Important implications for forest conservation and climate change mitigation strategies were noted, indicating significant spatial variation in biomass storage.

i. Aboveground Biomass (AGB) Pattern:

The present study revealed significant changes in belowground biomass (AGB) across three forest ecosystems - Lalmai Sal forest, Singra National Park, and Madhupur Sal forest ($p < 0.0161$). The highest biomass was observed in Lalmai Sal forest (1054.40 ± 121.70 t/ha), followed by Singra National Park (991.34 ± 113.04 t/ha) and Madhupur Sal forest (652.80 ± 76.63 t/ha). These differences can be attributed to variations in forest age, soil fertility, species composition, climatic conditions and human disturbance. However, biomass was lower in Madhupur Sal forest, probably due to historical logging and reduced soil productivity. Similar declines in AGB have been documented in degraded Sal forests of Nepal and India (Pandey *et al*. 2016).

The AGB values observed in the Lalmai Sal forest and Singra National Park were comparable to those reported for old-growth tropical forests in Southeast Asia (e.g., 900–1200 t/ha in Malaysian and Indonesian rain forests) (Sachi *et al.* 2011). However, the Madhupur Sal forest had lower biomass, likely due to historical logging, fragmentation, or reduced soil productivity. Similar declines in AGB have been documented in degraded Sal forests in Nepal and India (Pandey *et al*. 2016). Older, intact forests (e.g. Lalmai Sal forest) accumulated more biomass due to larger tree diameters and carbon stocks in mature trees. Sal (*S. robusta*)-dominated forests were known for their high wood density, which contributes significantly to AGB. Mixed forests (e.g. Singra National Park) may have slightly lower biomass if fast-growing, low-density species were present.

This study highlights the important role of protected and mature Sal forests in carbon storage, reinforcing the effects of degradation on biomass loss. Sustainable forest management and conservation policies need to be strengthened to maintain ecological integrity and climate resilience, especially in vulnerable forests like Madhupur.

ii. Belowground Biomass (BGB) Pattern:

This study found that the highest BGB was 175.80 ± 21.20 t/ha in Lalmai Sal forest, followed by 106.70 ± 11.7 t/ha in Singra National Park and Madupur Sal forest. This pattern indicated that the belowground biomass (BGB) followed the same trend. This data indicated a strong connection between the roots and the above ground part of this forest. Evidence suggested that the belowground biomass (BGB) differed significantly among different forest areas.

Numerous factors contributed to the higher BGB in Lalmai. These included (1) competition for nutrients from the dense canopy increased the production of fine roots (Bhog *et al*. 1996), and (2) mature development determined by the extensive root system (Jackson *et al*. 1996). In contrast, the low BGB in Madhupur forest might reflect land degradation driven by historical anthropogenic industries, as has been observed in other tropical forests under similar conditions (Houghton 2005). These results have important ecological implications for these forest ecosystems. The high frequency of BGB in Lalmai forest played an important role in the uptake of organic matter into the soil, indicating that it retained carbon for long periods and also helped to survive drought by reaching deep water.

Although the amount of biomass varied, the relationship between the position of r:s supported the idea that plants compensated for growth between roots and shoots. However, the decline in BGB in Madhupur forest had raised concerns about the ability of the ecosystem to recover after disturbance . Future studies should examine soil fine root turnover rates and deep carbon pools to better quantify the total carbon stock below ground.

iii. Total Aboveground Biomass (ATB) Pattern:

According to this study, the total aboveground biomass (ATB) of the tested Sal forests varied significantly. The Lalmai forest demonstrates 38% greater aboveground biomass (1,230.20 ± 1.280 t/ha) than the Madhupur forest (759.50 ± 88.0 t/ha), as indicated by Paul & Laskar (2021) ($p = 0.0159$) in their comparative analysis of tropical deciduous forests in Bangladesh. These results were consistent with Rahman *et al*.'s (2019) study of the comparative level of biomass in Sal forests, which was associated with a history of disturbance. The essential diversity probably depended on several interrelated factors mentioned as follows:

Succession effects appear to be crucial for initiating. While the long history of timber extraction and disturbance in Madhupur forest has likely reduced tree size and density (Muhammad *et al*. 2005), the relative protection of Lalmai forest means that the large trees continue to contribute disproportionately to the biomass stock (Chave *et al*. 2014). The second possibility is the edaphic component. Third, The canopy of *Larix decidua* creates a more favorable environment for regeneration and has the potential to change with climate.

These results will have significant implications for forest management. According to the biomass difference, Lalmai forest and other protected Sal shade trees are significant carbon sinks that meet the requirements of REDD+ programs (Pearson *et al*. 2017). On the other hand, the decline of Madhupur forest stocks emphasized the need for restoration mechanisms, i.e. the need for improved soils and rich connectivity. To better understand these biomass changes, future studies should look at genetic determinants and fine-grained environmental gradients.

4.2.2 Juvenile Tree Biomass

4.2.2.1 Aboveground, belowground and total woody biomass of juvenile tree

The significant differences in the amount of juvenile woody plants in Madhupur Sal forest (40.80±4.52 t/ha), Lalmai Sal forest (10.50±1.80 t/ha) and Singra National Park (83.14±15.31 t/ha) indicated that these forests regenerated in different ways ($p < 0.0001$). The very high number of juvenile plants in Singra forest - about 8 times more than in Lalmai forest- suggested that its dry deciduous environment might help young plants grow as more light reached them when the canopy was open (Vieira and Scariot 2006). The high amount of biomass of juvenile plants in Singra forest, about 8 times higher than that in Lalmai forest, might be due to its dry deciduous environment which allowed more light to reach these young plants to stimulate their growth when the canopy was open.

The unexpectedly low juvenile biomass at Lalmai forest, despite its dominance of mature stands, pointed to potential environmental constraints such as: light limitation due to dense canopy closure, hindering understory development, allelopathic suppression by dominant Sal trees (Rahman and Tokuchi 2016). Various types of herbivore pressure were across the site. The moderate values at Madhupur might indicate its problematic status – there were sufficient gaps in tree cover for new growth, but soil quality had been compromised by previous damage (Islam *et al*. 2021). The ratio of root to shoot biomass (Madhupur forest: 0.26, Lalmai forest: 0.26, Singra forest: 0.26) was very similar, indicating that the way these young plants distributed their growth was more influenced by their species than by the conditions in which they were located.

The extremely low juvenile stock of Lalmai forest raised concerns about its long-term structural maintenance, potentially creating an “empty forest” situation. In contrast, the robust regeneration of Singra forest highlights its resilience value for climate adaptation. These results demanded further investigation and action. Soil restoration in Madhupur was needed to support juvenile recruitment in canopy gap management to stimulate regeneration in Lalmai forest. Continuous monitoring of regeneration biomass as an important indicator of forest health.

4.2.3 Total Woody Biomass

Lalmai Sal forest had a higher total woody biomass (1240.64±143.94 t/ha) than Madhupur Sal forest (800.21±86.63 t/ha) and Singra National Park (1228.70±140.21 t/ha), showing a significant difference ($p < 0.0170$) in the Sal forests of Bangladesh. Looking at earlier studies that showed Lalmai Sal forest has very little young biomass (10.50±1.80 t/ha), it indicated an unhealthy forest structure where there are many mature trees but not enough new ones growing. The findings unveiled three new ecological insights:

1. The "inverted J" shape in diameter distribution of Lalmai forest suggested that a population collapse was on the way, hidden by the current dominance of biomass, which was 34% higher than Madhupur forest. The balanced age structure stands of Singra forest in stark contrasted to this. Madhupur had a higher percentage of young plants (5% of total biomass) compared to 0.8% of Lalmai forest, even though it had less total biomass, which

showed that past overuse had affected it, but it could bounce back with proper management.

2. Even though Lalmai forest and Madhupur forest had similar climates, there was a 54% difference in biomass, showing how past management decisions (whether they were protected or exploited) affect the long-term health of the environment.

3. Lalmai forest had to create canopy gaps right away to promote regeneration and preserve carbon reserves. For Madhupur forest to regain biomass more quickly, enhanced natural regeneration was required. An example of a biomass distribution that balanced across age groups was Singra.

4.2.4 Fine Root Biomass and Litter Biomass

The amount of fine root biomass of trees of Madupur Sal forest is about twofolds that of the other two forests. The shallow leaf layer of Lalmai forest might be the result of a special assortment of organisms that quickly break down dead leaves. The leaf litter layer collected from Madhupur forest and the flawless soil in Lalmai forest were really characteristic of two particular environmental methodologies. This examination illustrated that to comprehend the C account of Sal forest, it was basic to consider not only the trees but also the environment underneath the soil.

4.2.5 Comparison of Biomass C among the Selected Sal Forests

4.2.5.1 Adult Tree Carbon

This study revealed significant differences in carbon storage capacity among tropical Sal forests in Bangladesh. The highest total carbon stock (547.80±63.60 t/ha) was recorded in Lalmai Sal forest, which was 62% higher than that of Madhupur Sal forest (338.20±39.35

t/ha). This difference sheds light on the history of forest management and structural features of the ecosystem. The higher carbon stock of Lalmai forest (above-ground 469.51 and below-ground 78.30 t/ha) suggests that this forest has an abundance of large-diameter mature trees, which is very important for carbon storage (Rahman *et al*. 2021). The 6:1 ratio of above-ground to below-ground carbon at all sites indicates that the carbon allocation system of the Sal tree remains stable despite environmental variability.

The relatively low carbon stock at Madhupur reflects the ongoing impact of historical deforestation and illegal logging. The present study showed that the absence of each large-diameter tree was equivalent to the loss of carbon sequestration potential over decades.

The carbon stock of Singra National Park (510.10 t/ha) demonstrated that proper conservation strategies could maintain high carbon stocks. Three main management strategies could be proposed from the results of this study: 1) Designating forests with high carbon stocks like Lalmai forest as 'climate mitigation zones', 2) Implementing carbon-focused forest restoration programs at Madhupur forest and 3) Formulating specific policies for the conservation of large-diameter trees at all sites.

4.2.5.2 Juvenile Tree Carbon

This study revealed significant differences ($p < 0.0001$) in young tree carbon storage among three major Sal forests in Bangladesh. The highest carbon stock of 37.02±6.82 t/ha was recorded in Singra National Park, which was almost 8 times higher than that of Lalmai Sal forest (4.67±0.80 t/ha) (Haq *et al*. 2023). This difference provided important information about the health of the ecosystem and the capacity of the forest to regenerate. The high carbon stock of young trees in Singra National Park indicated that the regeneration process of trees in this forest was very active. On the other hand, the very low carbon stock in Lalmai Sal Forest (3.71 aboveground and 0.96 t/ha belowground) was indicative of a potential ecological crisis, which called into question the future sustainability of the forest.

The present study found that Madhupur Sal forest (15.84±2.27 t/ha) had higher carbon stocks than Lalmai but lower than Singra. The following factors might be responsible for this difference:

The dry deciduous nature of Singra allowed more sunlight penetration (Akhtar *et al*. 2021); the dense canopy of Lalmai was hindering the growth of young trees. In Madhupur, the gaps created by human disturbance had created opportunities for new trees. The following recommendations could be formulated from the results of this study: 1) Artificial canopy gaps were needed in Lalmai forest to ensure the growth of young trees, 2) The successful regeneration strategy of Singra forest could be applied to other forests, 3) Monitoring of young tree carbon stocks needed to be included as a regular part of forest management.

4.2.5.3. Total Woody C of Juvenile Tree

This study found significant spatial differences in carbon (C) stocks between juvenile and adult woody plants in Madhupur Sal forest, Lalmai Sal forest and Singra National Park. With average total C stocks of 354.03 ± 38.43 t/ha, 552.46 ± 64.09 t/ha, and 547.13 ± 62.43 t/ha, respectively, these forests demonstrated how localized ecological and anthropogenic factors shaped carbon sequestration potential ($p < 0.0156$). The significantly higher C stocks in Lalmai Sal forest suggested that species composition (e.g., dominant *S. robusta*) and lower anthropogenic disturbance might enhance biomass accumulation (Chave *et al*. 2014). In contrast, lower values of Madhupur forest likely reflected historical deforestation and agricultural encroachment (FAO 2020), underscoring the vulnerability of even similar forest types to degradation.

These findings challenge uniform forest management policies. For instance, success of Lalmai forest could inform targeted restoration in Madhupur forest, while intermediate values of Singra forest might reflect unique ecological trade-offs. Such spatial heterogeneity had critical implications for climate mitigation strategies like REDD+, where localized carbon baselines were essential (IPCC 2019). The study also highlights the need to protect mature stands—older trees disproportionately contribute to carbon storage (Poorter *et al*. 2015)—while fostering juvenile growth for long-term resilience.

4.2.6 Comparison of C pools of selected Sal forests in Bangladesh

4.2.6.1 Total Woody C and Total Litter C

The C distribution patterns in these three Sal forests provided a more intricate narrative than the figures alone imply. The application focused on Lalmai forest. Madhupur forest has a very high amount of C in its surface litter (1243.93 t/ha), about three times more than Lalmai forest, but it did not store as much C in trees (552.46 t/ha), showing that their ecosystems worked very differently. This difference probably showed that the speed at which organic matter breaks down varies, not how much is produced, suggesting that soil microbial communities of Lalmai forest might be better at breaking down organic matter (Adhikari *et al*. 2021). The significant differences ($p < 0.02$) in litter C levels between these nearby forests highlight how local factors like soil bacteria and climate affected C cycling.

The intermediate values of Singra National Park posed an additional conundrum. As a designated protected area, we expected it to outperform both forests; however, its carbon stores fell somewhere in between. This argument disputes the prevalent notion that conservation status inherently correlates with enhanced carbon sequestration (Ahmed *et al*. 2022). The history of Singra forest selective logging or differences in soil composition may elucidate this unforeseen trend, highlighting that forest ecosystems retain the memory of past disturbances for decades.

These findings hold profound implications for the forest management practices of Bangladesh: Carbon assessments must account for both standing biomass and litter dynamics. Localized management strategies might prove more efficacious than universal policies. Designation of protected areas alone did not ensure optimal carbon sequestration.

The research showed that Lalmai forest was a more developed and stable ecosystem with good nutrient recycling, while the large amount of litter in Madhupur forest might mean slower decomposition or recent disruptions. Comprehending these nuanced distinctions was essential for formulating tailored climate change mitigation strategies in the Sal forest of Bangladesh.

4.2.6.2 Total Root C and Total Soil C

The soil C profiles of these three forests demonstrated some counter intuitive patterns that challenged the prevailing wisdom. Although Singra forest did not perform as well above ground, it remarkably contained the most soil C, whereas Madhupur forest had the most fine root C, particularly in the top 10 cm, where microbes are most active (Sarker *et al*. 2023). This paradox suggested that the events that took place beneath the surface did not always correspond to the events that occur above the ground. The depth-dependent patterns narrated an intriguing narrative. The sudden drop of 30 to 50% in fine root carbon from the top layer to deeper layers (10cm to 30cm) matched the global trends seen by Jackson *et al*.

(2021). Nevertheless, the severity of the decline varied considerably among forests. The ability of Singra forest to store more carbon in the topsoil might indicate that different plant types or soil microbes had affected it in the past, while strong, deep roots of Madhupur might show how plants adapt to short periods without water (Hossain 2022). Three principal implications were immediately apparent: The upper 10 cm of soil significantly influenced the dynamics of carbon. Strategies for forest management that exclusively focused on aboveground metrics may fail to account for critical carbon stocks. We observe diverse manifestations of the "protected area advantage" both above and below ground. These findings made it harder to tell a simple story about how forests stored carbon, showing that damaged forests like Madhupur could actually help the climate below ground, while protected areas like Singra forest stored carbon in surprising ways. It is clear that we must delve deeper to accomplish precise carbon accounting.

4.2.7 Comparison of Organic C contents among the selected Sal forests

4.2.7.1 Soil Organic C

The soil carbon profiles of those 3 forests showcased a few counterintuitive styles that projected the traditional wisdom. Even though Singra did not carry out as nicely above ground, it incredibly holds the maximum soil C, even as Madhupur forest has the maximum best root C, mainly within the pinnacle 10 cm wherein microbes were most active (Sarker *et al*. 2023). This paradox means that the occasions that transpire under the floor do now no longer constantly correspond to the occasions that arise above the ground. The depth-based styles narrate an interesting narrative. The international styles visible with the aid of using Jackson *et al*. (2021) shape the surprising drop of 30 to 50% in best root C from the pinnacle layer to deeper layers (10cm to 30cm). However, the quantity of the decline differs considerably amongst forests. Higher capacity of Singra forest to sequester carbon with inside the topsoil would possibly suggest beyond impacts from one of a kind styles of plant life or soil microbes, even as strong as of Madhupur forest, deep root structures ought to display how plant life adapts to occasional water shortages (Hossain 2022). The implications of these findings might be apparent: The top 10 cm of soil considerably impacts carbon dynamics. Strategies for wooded area control that completely focus on aboveground metrics can also additionally neglect crucial carbon stocks. Different manifestations of the "blanketed region advantage" are found above and beneath the ground. These discoveries complicate trustworthy narratives concerning wooded area carbon storage with the aid of using demonstrations that degraded forests, together with Madhupur forest, can be weather factors under the floor, even as blanketed areas, together with Singra forest, sequester carbon in unanticipated ways.

4.2.7.2 Root Organic C

The robust root system of Madupur forest indicated that these disturbed forests have developed their own survival strategies. The consistent depth patterns found in the present study (10 cm > 30 cm) corresponded to global trends (Frechet *et al*. 2021), but the size of the advantages of Madhupur forest showed something special on these floors. Several factors could explain the root dominance of Madhupur forest as follows:

i. Frequent human pressure could help invest strongly in the root system as a survival strategy.

ii. For more open roofs, trees of Madhupur forest might shift carbon allocation from top to underground.

4.2.7.3 Litter Organic C

The significant variation in organic C in litter in these three forests suggests an interesting ecological trade-off between production and decomposition. Madhupur Sal forest had a very high litter accumulation, which was significantly higher than Lalmai forest and Singra forest. This was a picture of a forest stuck in a carbon barrier. This pattern might be due to slow decomposition rates rather than high productivity because Sal leaves contain a lot of phenols during stress. Microbial communities in Lalmai forest process organic matter rapidly because this forest had an efficient nutrient cycling system at low levels. It was particularly important that these differences represented hypothetical concerns about forest health. The impressive litter accumulation in Madhupur may indicate ecosystem stress rather than vitality but may reflect a robust, fast-cycling system in Lalmai. These results highlight that carbon storage strategies within similar forest types differ dramatically and remind us that both the amount of organic matter and the soil should be considered. The magnitude of these differences ($p < 0.020$) represents how global conditions are connected and how the history of carbon sequestration works.

4.2.8 Comparison of soil Properties among the Selected Sal Forests

4.2.8.1 Soil pH

Soil pH maintains the underground chemistry and hence contributes the nutrient status and nutrient cycling in the Sal forest ecosystems. Topsoil of Madhupur (10cm depth) maintains a generally slightly acidic pH (5.92±0.3) condition, while subsurface (20cm) of Lalmai forest becomes strikingly acidic (4.86±0.07)— that might reshape our understanding of the Sal forest ecosystem. It is particularly curious how surface pH of Madhupur forest stands up to maturation - conceivably due to decades of country lime utilization drifting from adjoining ranges, making an unnatural pH buffer in what needs to be really acidic forest soil. This dissimilarity in pH has genuine impacts soil organic carbon dynamics.

The acidic subsoil of Lalmai forest likely traps critical phosphorus (making it difficult for trees to utilize), whereas abnormal alkalinity of Madhupur forest seems to disturb nearby microbial communities.

4.2.8.2 Soil Moisture

The soil moisture (%) patterns in these forests indicate unexpected water dynamics that question traditional wisdom. While we would typically expect moisture to decrease with depth, surprising peak of Madhupur forest at 30cm (26.41% ± 1.67%) suggests the existence of a hidden hydraulic layer— possibly a compacted soil horizon or clay accumulation that creates a natural "water tank" beneath the surface (Rahman *et al*. 2023). Contrastingly, the remarkably dry topsoil (13.88% ±1.27 at 10cm) of Singra forest defies expectations for a national park, hinting at either 1) exceptionally free-draining sandy substrates or 2) intense root water uptake in the surface layers (Haque and Islam 2022). The most puzzling finding is the non-significant depth effect - unlike most tropical forests where moisture increases steadily with depth, these Sal forests appear to maintain nearly constant moisture profiles below 10cm. This could reflect the unique water-use strategies of *S. robusta*, whose deep taproots may redistribute water vertically. For forest managers, these results highlight the fact that effective water conservation requirements need to understand the underground construction of each location.

4.2.8.3 Electrical Conductivity

In Lalmai Sal forest, shockingly high surface conductivity (30.31 ± 84 µS/cm at 10 cm) appears to contain some of the particles caused by long-term supplement reuse or intriguing mineral encryption (Sarker *et al*. 2023). At the same time, the decline in the conductivity of Madhupur at a depth of 30 cm (12.45 ± 27 μS/cm) suggests that the region requires nutrient supplements, which refer to heavy rain. The management approach had no effect on conductivity, but only the bottom of the floor provided a major explanation. The finding demonstrates that human interference did not alter conductivity notably. For preservationists, these calm conductivity signals are an effective instrument - solid surface conductivity of Lalmai forest appears to dynamically supplement cycling, whereas drop of Madhupur forest in more profound layers might point to zones that require rebuilding.

4.2.8.3 Bulk Density

The unexpected discrepancies in soil bulk density throughout these forests disclose concealed narratives regarding their ecological past and present condition. The dense surface soil of Singra National Park (1.133±0.014 g/cm³ at 10cm) indicates compaction that contradicts its protected status, perhaps resulting from historical logging or ongoing wildlife migration. Conversely, aerated deep soil of Madhupur forest (1.028±0.013 g/cm³ at 30cm) indicates superior pore space retention, potentially due to its degraded condition, which paradoxically restricts heavy animal movement. Although forest type and depth were inconsequential, management strategies only dictated soil density. The study challenges common understanding by demonstrating that human footfall, or its absence, influences soil structure more significantly than variations in natural forest conditions. For conservationists, these variations in density serve as a form of interpretation. Dense surface of Singra forest indicates diminished water infiltration, but the more porous subsoil of Madhupur forest suggests latent capacity for carbon sequestration within its expansive layers.

4.2.8.4 Available N

The attractive distribution of available nitrogen in these forests is an ecological puzzle that contradicts established beliefs. The top layers rich in nitrogen (0.039±0.005%) are less affected by the nutrient levels found in Madhupur (0.018±0.002%), showing an unexpected result of management practices. The attractive aspects are the type and depth of forests, usually important factors in the nutritional cycle; they employ a passive role when management is prioritized ($p < 0.0001$). This evidence indicates that human activity alters the natural nitrogen dynamics of these ecosystems. Additional nitrogen on the surface of Lalmai forest could be due to either 1) a more experienced start or 2) an inconspicuous nitrogen obsession. At the same time, the lower layers with nitrogen deficiency of Madhupur forest presents a warning against nutrient poverty due to continuous biomass extraction. Despite the protected name, Singra National Park has not missed the mid-level. The proof shows that simple security does not give wholesome esteem. These results force us to reassess our understanding of nitrogen dynamics in cultivated tropical forests.

4.2.8.5 Total Soil P

The irregular distribution of phosphorus in these forests illustrates a complex narrative of nutrient cycling that resists simplistic interpretations. The phosphorus-rich surface of Madhupur forest (0.052±0.006% at 10cm) contrasts with the phosphorus-poor subsoil (0.016±0.001% at 30cm), establishing a notable vertical gradient that implies either 1) active surface phosphorus cycles with limited migration or 2) historical fertilizer contamination in this frequently obstructed forest. Simultaneously, persistently low phosphorus concentrations (0.029±0.003% at 10cm) of Lalmai forest suggest a mature forest where this vital resource is efficiently sequestered inside biomass. Management and depth strongly influence phosphorus distribution ($p < 0.0005$), although their absence of interaction indicates that these factors operate separately, akin to two distinct narrators recounting different chapters of the same narrative. This advancement determines a significant amount of research for conservationists. The findings could transform our methodology for nutrient management in Sal forests in Bangladesh.

4.3 Seasonal Variation in C Pools among the Selected Sal Forests

4.3.1 Seasonal variation in C pools

4.3.1.1 Seasonal Variation in Litter C

The periodic movement of carbon inside these Sal woods illustrates a captivating seasonal relationship between forests and time. During May, all forests experience a coordinated surge of litterfall, with Lalmai forest spearheading the phenomenon at an impressive carbon performance of 1399.79 t/ha before declining to December levels. This phenomenon transcends mere leaf fall; it displays nature's intricate carbon management mechanism in operation. The uniformity of this pattern among forests, notwithstanding their variations, indicates an evolutionary adaptation to the environment of Bangladesh, wherein forests discard their "carbon coat" prior to the monsoon season to form protective mulch layers. Each forest distinctly affects seasonal performance; Madhupur forest shows a pronounced fluctuation from May to December (1243.93 to 456.57 t/ha), whilst Singra forest displays a more moderate pattern (828.04 to 514.81 t/ha). This suggests that while climate establishes the rhythm, local factors dictate the choreography. These findings challenge our static understanding of forest carbon, illustrating that Sal forests operate as dynamic, living systems that experience a biannual alteration in carbon composition. This indicates that seasonal carbon accounting in Bangladesh is crucial for climate modelers, and conservators may need to reassess the ecological significance of the May leaf cycles that have persisted for millennia.

4.3.1.2 Seasonal Variation in Fine Root C

Beneath the soil surface, these Sal forests perform an intricate carbon ballet where timing and depth create surprising patterns. While it is likely to expect roots to follow aboveground seasonal trends, Singra National Park breaks all rules by peaking in December (1.085 t/ha at 10cm) when other forests are dormant. This underground rebellion suggests some Sal trees might employ winter root growth as a survival strategy - storing carbon when aboveground competition is minimal (Ahmed *et al*. 2023). Meanwhile, predictable May root surge of Madhupur forest (0.618 t/ha) aligns with its litterfall peak, showing a synchronized above-belowground carbon strategy. The dramatic root carbon crash of Lalmai forest at 30cm (0.006 t/ha in December)—like the forest suddenly abandoning its deep roots in winter. This behavior may suggest a severe "feast-or-famine" adaptation in which resources accumulate at the surface during arid seasons. These forests have developed radically different underground tactics: Winter stockpiling of Singra forest, spring flurry of Madhupur forest, and risky all-or-nothing approach of Lalmai forest. For restoration efforts, planting tree is not only the option, it is also important to ensure the seasonal rooting of plants properly.

4.3.1.3 Seasonal Variation in Soil C

Results of the study indicate distinct changes in soil carbon dynamics. The carbon concentration in the uppermost soil layer (10 cm depth) was seen to exceed that of the deeper layers, aligning with established soil science concepts (Brady and Weil 2016). Secondly, the highest soil carbon concentration (1069.5 mg/ha) in Singra National Park was observed in December, probably due to the slow decomposition of organic matter produced by winter leaves (Singh *et al*. 2022). The lowest carbon concentration (492.33

t/ha) was observed in Lalmai forest in May at a depth of 30 cm, underscoring the distinctive characteristics of nutrient dynamics within the deeper soil strata.

Results unequivocally demonstrated that soil carbon dynamics in the Sal forests of Bangladesh are governed by spatial and ecological factors. The examination of the research data indicated that forest management strategies, soil depth, and seasonal variations jointly influence soil carbon storage. The safeguarded status of Singra National Park has demonstrated a beneficial effect in this context.

4.3.2 Seasonal Variation in Soil Properties

The significant interaction between forest and season revealed by two-way ANOVA ($p < 0.05$, Table 5) demonstrate that soil properties in Madhupur, Lalmai, and Singra forests respond differentially to seasonal shifts, reflecting site-specific biogeochemical feedbacks rather than universal temporal patterns. For instance, **soil moisture** fluctuations (monsoon peaks > dry season lows) were amplified in Madhupur due to its degraded structure and reduced organic matter, whereas intact canopy of Lalmai forest buffered microclimate extremes (Luo *et al*. 2016). Similarly, pH and conductivity shifts were most pronounced in surface soils of Singra forest (0–10 cm), aligning with monsoon-driven ion leaching (Sarker *et al*. 2023). Crucially, organic carbon (%) declined in dry seasons across all forests—consistent with accelerated microbial mineralization under warmer conditions (Jian *et al*. 2023)—but Lalmai forest retained 18–22% more carbon due to mineral-association mechanisms (Cotrufo *et al*. 2022). These interactions underscore that *static sampling* misrepresents soil dynamics: available N and total P varied seasonally by 30–50% in Madhupur forest (anthropogenically disturbed) versus <15% in Singra forest (protected), reinforcing how conservation status mediates nutrient resilience. Such forest-specific temporal sensitivities necessitate tailored management—e.g., monsoon-season organic amendments in Madhupur to offset leaching losses (FAO 2020) and highlight that carbon sequestration potential cannot be extrapolated without accounting for seasonal × spatial interactions (Widder *et al*. 2023).

4.3.2.1 Soil pH

These forests are altering their soil pH levels, and the resulting patterns are more intriguing than anticipated. The soil of Madhupur forest exhibits resistance to increased alkalinity in December, but Lalmai forest and Singra forest experience their pH maxima in May - though not simultaneously. The most perplexing time occurs within the 20-30 cm layer of Singra forest, when the pH decreases to 5.7 in May, contrasting with 5.824 in December, so subverting the typical seasonal trend. This alteration is not arbitrary; it likely results from a complicated interplay involving the chemistry of decomposing leaves (Sarker *et al*. 2023), variations in microbial activity, and potentially the seasonal flow of groundwater. It is remarkable how each forest cultivates its distinct pH characteristics: Madhupur forest as a winter alkalizer, Lalmai forest as a summer acidophile, and Singra forest as an erratic entity, exhibiting variability at significant depths. These findings contest conventional beliefs regarding the stability of tropical soils, revealing that Sal forests are, in fact, engaging in intricate subterranean chemical processes seasonally.

4.3.2.2 Soil Moisture

These forests engage in a complex hydrological interplay that eludes straightforward elucidation. Although a reduction in soil moisture with depth is anticipated, the data presents a more complex narrative - unexpected high value of Lalmai forest in May (23.573% at 10–20 cm) indicates its ability to access concealed water sources, akin to an adept desert flora (Rahman *et al*. 2023). At the same time, moisture level of Madhupur forest stay fairly consistent at different depths, suggesting that its compacted soil helps it hold onto water like a sponge. A notable pattern manifests in December, when all three forests align their moisture levels irrespective of depth, as though an unseen conductor were prompting them to achieve uniformity during the arid season. This seasonal convergence suggests that these ecosystems have developed sophisticated water-allocation strategies that transcend their own characteristics.

4.3.2.3 Soil Electrical Conductivity

The concerning rise in May measurements of Madhupur forest (29.467 µS/cm at 10cm) is followed by a big drop in December (6.78 µS/cm), showing a seasonal "unplugging" of the ecosystem, probably due to nutrients being washed away by the monsoon (Sarker *et al*. 2023). On the other hand, Lalmai forest completely changed the story, with the highest values recorded in December (34.18 µS/cm), while others decreased. Singra National Park shows big changes in conductivity values during different seasons (15.224 to 34.28 µS/cm), suggesting that its soil microbes might be adjusting to the availability of nutrients throughout the year. The electrical signature of each forest conveys a distinct narrative: Madhupur forest as the summer epicenter, Lalmai forest as the winter sentinel, and Singra Pational Park as the erratic variable. This characteristic surpasses soil science; it represents nature's analogue to an electrical grid, with each forest maintaining its own seasonal energy management system. Environmentalists can assess forest health by "monitoring the soil's pulse" at various times throughout the year, based on these patterns.

4.3.2.4 Bulk Density

The selected forests are increasingly stabilizing and enhancing their soil. The ongoing compaction seen in December, with the highest bulk density in all forests (Madhupur forest: 1.166, Lalmai forest: 1.146, Singra National Park: 1.188 g/cm^3 at 10 cm), indicates that the soil gets physically pressed together during the dry season, likely because of roots taking up water and the breakdown of organic matter (Rahman *et al*. 2023). In May, the soil breathes, causing a slight increase in minimum density (1.093-1.054 g/cm³), likely due to better soil formation and new root growth from the rain during the monsoon. This seasonal respiration transpires uniformly throughout various depths, although each forest exhibits its unique density: Singra forest is perpetually the most dense, Madhupur forest possesses a moderate density, and Lalmai forest is the least dense. This trend implies that the level of "soil health" in each forest is determined by long-term management practices, rather than seasonal dynamics, which are influenced by weather. The evidence suggests that timing is crucial. So planting during the “fluffy phase” of May can give seedlings a significant root-growth advantage in this dynamic soil.

4.3.2.5 Soil Available N

The unusual nitrogen dynamics of the selected three forests point to an invisible nutrient competition subject to strict seasonal controls. In contrast to the sparse stores of nearby forests, unexpected December nitrogen abundance of Lalmai forest (0.052 % at 10 cm) suggests that its soil bacteria may be saving resources like a squirrel storing acorns for the winter (Rahman *et al*. 2023). At the same time, the drop in nitrogen levels in Madhupur forest during May at 20 cm (0.013) indicates that the bacteria there are using up their stored nutrients quickly. Seasonal variations in nitrogen measurements of Singra National Park (0.028–0.033 %) are comparatively consistent, indicating that the protected status of this forest protects it from the ebb and flow of nature's feast-or-famine cycles. The three distinct choreographies of this nitrogen ballet—winter accumulation of Lalmai forest, summer deficit of Madhupur forest, and steady equilibrium of Singra National Park—show that nitrogen follows localized rules even in similar forests. The different nitrogen cycles of each forest—early winter for Lalmai forest, pre-monsoon for Madhupur forest, and little intervention for Singra forest—should guide the use of fertilizer.

4.3.2.6 Soil Total P

The seasonal and vertical patterns of phosphorus distribution in these forest soils are compelling and indicative of the unique functioning of the ecosystem. The May peak of Singra National Park's (0.056% at 10cm) demonstrates remarkable phosphorus accumulation in surface layers during pre-monsoon months, possibly due to enhanced biological activity or litter decomposition as observed in similar tropical systems (Hossain *et al*. 2022). The consistent phosphorus decline with depth across all forests, particularly the 30cm lows (Madhupur forest: 0.027; Lalmai forest: 0.026 in December), aligns with established models of nutrient leaching in tropical soils (Brady and Weil 2017), though the magnitude of seasonal variation was unexpectedly pronounced. The significant forest-season interaction ($p = 0.0035$) suggests that phosphorus cycling responds differently to seasonal changes in each forest type - while Madhupur forest and Lalmai forest showed modest May peaks, Dramatic surface accumulation of Singra forest that implies protected areas may develop more efficient phosphorus retention mechanisms. The presumption of consistent phosphorus dynamics among analogous forest types is challenged by these findings, which underscore the impact of management history and conservation status on nutrient cycling pathways. This has significant implications for forest restoration strategies in phosphorus-deficient tropical ecosystems.

4.4 Litter Decomposition Rates

4.4.1 Mass Loss Rates

The disintegration patterns of Sal leaves offer an intriguing narrative regarding the ways in which time and location affect the recycling process of nature. Although leaves of Lalmai forest and Singra forest exhibited rapid mass loss (5.33±0.29% and 5.03±0.67%, respectively, at 6 months), Leaves of Madhupur forest exhibited the most dramatic disintegration (11.63±2.41% at 12 months) in their home soil. This unexpected reversal suggests that local soil microbes might develop specialized relationships with their native leaf litter over time, as observed in similar tropical systems by Rahman et al. (2015). The initial advantage seen in Lalmai forest and Singra forest could reflect more active microbial communities early in the process; slower initiation of Madhupur forest yet more robust conclusion may suggest an alternative decomposition strategy, potentially involving a reliance on certain environmental cues or microbial succession. These patterns challenge the common assumption that faster initial decomposition always leads to greater total mass loss, highlighting instead how decomposition is a nuanced dance between leaf chemistry, microbial adaptation, and time. The findings particularly emphasize the "home field advantage" phenomenon, where leaves decompose best in their native soil environment, suggesting that forest restoration efforts might benefit from using local leaf litter to kickstart soil processes.

4.4.1.2 Mineralized N

The nitrogen mineralization patterns indicate unexpected soil-litter connections that contradict simple expectations. Although it is reasonable to anticipate that leaves would decompose most effectively in their native soils, Litter of Singra forest demonstrated exceptional decomposition capabilities in soil of Madhupur forest (0.115±0.012 %). This indicates that certain soils possess universal decomposing capabilities, irrespective of the origin of the litter, a phenomenon known as "decomposition plasticity" by Henneron *et al*. (2018).

It is interesting to note that soil of Lalmai forest had the greatest home-field advantage with its litter (0.089±0.005 %), suggesting that the microbes had specific adaptation to the local leaf chemistry. The poorest performance occurred when litter of Lalmai forest met with the soil of Singra National Park (0.07±0.009 %), revealing potential biochemical incompatibilities between certain leaf-soil combinations. These findings challenge conventional decomposition models by demonstrating that nitrogen release depends more on soil-litter pairings than on litter quality alone. Soil of Madhupur forest emerged as a surprisingly versatile nitrogen liberator, particularly with foreign litter, suggesting its microbial community may have developed generalist decomposition strategies, possibly due to historical exposure to diverse organic inputs. This suggests to forest managers that nitrogen cycling is inherently dependent on the alignment of appropriate litter with suitable soil communities, rather than the indiscriminate addition of organic matter.

4.4.2 Properties of Sal Forest Soil Used in Decomposition Study

The decomposition process is regulated in unexpected ways by the diverse biochemical conditions provided by the distinctive soil properties of this forest zone. Surprisingly acidic soil of Lalmai forest (pH 4.77) with high conductivity (34.18 µS/cm) and high phosphorus (0.127%) indicate a mineral-rich but potentially aluminum-toxic environment that might favor some microbial decomposers. On the other hand, organic carbon content (0.902%) and relatively neutral pH (5.404) of Singra forest may support a variety of microbial communities, which explains its improved effectiveness in nitrogen mineralization studies. Impressive N/P ratio of 3.020% of Madhupur forest suggests a serious nutritional imbalance, with a surplus of nitrogen and a shortage of phosphorus. The higher decomposition rates observed in earlier tests may be the consequence of this environment forcing soil microorganisms to actively extract phosphorus from decomposing litter. The chemical differences between forests, particularly the significant differences in pH ($p = 0.008$), phosphorus ($p = 0.0001$), and N/P ratio ($p = 0.0001$), demonstrate how soil chemistry creates distinct decomposition microclimates that go beyond simple moisture or organic matter variables. The findings show that achieving chemical compatibility between the chemistry of the litter and the particular nutrient profile and pH levels of the receiving soil is just as important for efficient litter breakdown as the leaves.

4.4.3 Chemical Properties of Sal Leaf Litter Used in Decomposition Study

The chemical composition of Sal leaves in these forests illustrates nature's biochemical diversity. The leaves of Lalmai forest are nutrient-rich, including the highest amounts of nitrogen (2.523%) and phosphorus (0.32%), which may give them a competitive edge in the early stages of decomposition (Rahman et al., 2023). Leaves of Madhupur forest possess defensive phenolic chemicals (2.833%), forming a biochemical barrier that inhibits microbial decomposition, a survival tactic prevalent in stressed forests. The striking nitrogen-phenol ratios provide different stories: An abundance of readily available nutrients is indicated by favorable ratio of 1.944 of Lalmai forest, whereas ratio of 0.749 of Madhupur forest signifies a chemical confinement where nutrients are sequestered in intricate molecules. The chemical disparities, notably the pronounced differences in nitrogen ($p = 0.0001$), phosphorus ($p = 0.006$), and phenol content ($p = 0.015$), establish distinct decomposition trajectories, elucidating the varying breakdown rates of leaves from different forests in identical soil conditions. The findings underscore the adaptive strategies of Sal trees in modifying their leaf chemistry according to local conditions, with some species prioritizing nutrient-dense leaves for rapid turnover (Lalmai forest) and others favoring chemically defended leaves for gradual nutrient release (Madhupur forest), strategies that fundamentally influence the nutrient dynamics of these forest ecosystems.

4.5 Seasonal Variation in Soil Bacterial Community Composition

The distinct spatiotemporal stratification of bacterial communities in the unprotected Sal forest soils of Jalchatra, Madhupur—demonstrated by depth-resolved (0–30 cm) seasonal sampling—underscores how human disturbance intensifies microbial reactions to environmental cycles. Rapidly proliferating bacteria (r-strategists) predominated in surface layers (0–10 cm) throughout summer, utilizing increased temperatures and readily available carbon from recent litter inputs for swift colonization (Sarker *et al*. 2023). In contrast, slow-growing oligotrophs (K-strategists) reached their zenith in subsoils (20–30 cm) during winter, indicating adaptations for nutrient scavenging in cold-stressed, energy-deficient environments (Zhou *et al*. 2018). Monsoon rains notably created a vertical uniformity among communities: moisture saturation diminished depth-related differences by facilitating resource distribution while also restricting slow-growing species due to oxygen limitations (Lennon *et al*. 2021). The late fall transitional phase facilitated niche partitioning, as rapidly growing organisms migrated to mineral-associated microsites due to the reduction of labile carbon (Jansson and Hofmockel 2023). The unprotected soils demonstrated 40–60% increased seasonal variability in bacterial composition compared to conserved Sal forests, suggesting that diminished canopy cover intensifies climatic extremes and hinders legacy carbon preservation (Widder *et al*. 2022). These oscillations jeopardize biogeochemical robustness; for example, reduced winter slow-grower biomass was associated with a 30% decrease in protease activity ($\rho = 0.72$, $p < 0.01$), limiting nitrogen mineralization during peak plant need.

4.5.1 Seasonal Variation of Fast-Growing Bacteria

The bacterial communities in the soils of Madhupur forest exhibit intriguing seasonal activity patterns that vary with depth. In the summer, microscopic colonies of fast-growing bacteria can grow up to 20 cm (178.92±40.64 cfu/g) in size, which might be due to the elevated temperatures and fresh organic materials from leaf litter (Rahman *et al*. 2023). As seasons transition, these microbial communities alter their active zones—relocating to 30 cm during the monsoon (155.67±16.04 cfu/g), likely to evade saturated surface soils, then retreating to 10 cm in winter (118.42±16.50 cfu/g) to utilize residual warmth near the surface. The substantial bacterial colony exhibits a contrasting approach, flourishing mostly at 10 cm during winter (31.91±8.08 cfu/g), indicating that these may be cold-adapted specialists that prevail when competitors are less active. Medium-sized colonies sustain relatively constant populations over seasons, serving as the microbial foundation of the ecosystem. Soil bacteria have evolved distinct seasonal niches, with bigger colonies specializing in the winter and smaller colonies taking use of summer opportunities. The depth-related changes underscore how microbial communities establish vertical stratification in soils, with distinct groups prevailing in specific strata at various times of the year—a process that likely enhances the nutrient cycle efficiency of forest. The findings indicate that soil microbial activity adheres to predictable yet intricate seasonal patterns, which should guide the timing of forest management techniques such as fertilization or litter application.

4.5.2 Seasonal Variation of Slow-Growing Bacteria

The slow-growing bacterial communities in the soils of Madhupur forest, in contrast to their fast-growing counterparts, put on an impressive show in the fall at a depth of 30 cm, with 435.17±45.58 cfu/g soil tiny colonies. This could be seen as nature's equivalent of a microbial harvest festival, making use of the organic matter that has accumulated over the previous seasons. These methodical decomposers adopt a different seasonal strategy than their speedy neighbors, with large colonies peaking dramatically in winter at 10 cm (35.58±1.91 cfu/g), suggesting they may specialize in breaking down more recalcitrant compounds when other microbes are less active. The medium-sized colonies maintain their steady presence across seasons, like reliable stagehands supporting the main actors in this ecological condition. What is particularly fascinating is how these slow-growers dominate deeper layers (20-30cm) during warmer months before shifting upwards in winter - possibly following the downward movement of soluble nutrients or avoiding surface temperature extremes. A vertical conveyor belt of decomposition activity is created by this seasonal depth migration, ensuring nutrient cycling all year round. The findings highlight how these patient microbial specialists fill critical gaps in the decomposition workforce of forest, handling complex organic matter when conditions challenge their fast-growing competitors - a lesson in ecological complementarity that could inspire more nuanced approaches to soil health management in tropical forests.

4.6 Conclusion

This study reveals the Sal forests of Bangladesh function and how urgently they need protection. The three Sal forests namely Madhupur, Lalmai, and Singra National Parks, show three different pictures; Madhupur suffers from more human pressure, depleted soils, low tree growth and unstable bacterial communities that change dramatically with seasons. The older trees in Lalmai store impressive carbon, but, worryingly, they rarely see any young trees replacing them. Singra National Park, as a protected park, has maintained its stability as a well-preserved forest with healthy regeneration and balanced carbon storage, which is a testament to the work of conservation. There were significant differences in the total C stocks of the three selected Sal forests, with Singra National Park having the highest and Lalmai Sal Forest having the lowest. There were significant differences in C stocks between C pools, indicating the importance of studying C stocks separately for improved forest management for C stocks. The highest woody C and soil C content in Singra National Park may contribute to greater C stocks. Plant age affected C storage, with the lowest C storage in Madhupur forest for adult trees, whereas it was found in Lalmai forest for juvenile trees. Long-term management interventions in Singra National Park played a role in the larger C storage in this forest. Seasons also significantly affected these forests. The highest litter biomass C was reported in summer (May), while the lowest was in winter (December). Seasonal differences in leaf fall and leaf shedding were responsible for this variation in litter biomass C. Fine root biomass C was relatively higher in summer than in winter. The growth of herbaceous plants was stimulated in the summer season, which resulted in an increase in fine root biomass during this season. The relatively higher leaf litter production in Lalmai Sal forest reduced the growth of herbaceous plants and consequently reduced the amount of fine root C in this forest. Soil total C was significantly higher in Singra National Park and lower in Lalmai Forest. The temporal changes in litter biomass C were not related to litter decomposition processes (mass loss and N mineralization rates). The results also indicate a close relationship between seasonal fluctuations in litter C and bacterial community composition. The data suggest that long-term management of the forest as a protected area could contribute to soil C conservation in the Singra Sal forest. Therefore, overall, the present study revealed temporal changes in biomass C pools that contribute to annual C gains and losses in forest ecosystems. The results of this present study indicate the importance of long-term management of forests for efficient C storage in the context of global climate change. Policymakers also need to recognize these ecosystems as natural insurance for Bangladesh.

CHAPTER 5

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