REGENERATION, LEAF PHENOLOGY AND NUTRITIONAL ADAPTATION OF SAL (*Shorea robusta* Roxb. *ex* Gaertn.) IN THE DECIDUOUS FORESTS OF BANGLADESH

A THESIS
SUBMITTED IN PARTIAL FULFILLMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN BOTANY, UNIVERSITY OF DHAKA

SUBMITTED BY
MD. MOSHIDUL ISLAM
SESSION: 2019-2020
REG. NO.: 18
EXAM ROLL: 02

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August 2022

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CERTIFICATE

This is to certify that the thesis entitled **“Regeneration, leaf phenology and nutritional adaptation of Sal (*Shorea robusta* Roxb. *ex* Gaertn.) in the deciduous forests of Bangladesh”** submitted by Md. Moshidul Islam has been carried out under my supervision in the Department of Botany, University of Dhaka. This is further to certify that it is an original work and suitable for submission for the award of Doctor of Philosophy in Botany.

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DECLARATION

I, Md. Moshidul Islam, hereby declare that the thesis entitled **“Regeneration, leaf phenology and nutritional adaptation of Sal (*Shorea robusta* Roxb. *ex* Gaertn.) in the deciduous 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 own 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.

August 2022 Md. Moshidul Islam

ACKNOWLEDGEMENT

I express my heartiest gratitude to the 'Almighty Allah' whose unlimited kindness permitted me to successfully complete my research study.

I would like to express my deepest sense of gratitude to my thesis supervisor ***Mohammad Zabed Hossain*** *(Ph.D, UGAS, Iwate University, Japan; Post-Doctorate, SLU, Uppsala, Sweden), Professor, Department of Botany, University of Dhaka, for his skillful guidance, constructive criticism, masterful assistance, consonant advice, endless encouragement and moral sympathy that I availed throughout my research work.*

I feel proud to express my sense of gratitude to the Chairman, ***Professor Dr. Shamim Shamsi*** *and at the same time to the former chairman* ***Professor Dr. Rakha Hari Sarker*** *and* ***Professor Dr. M A Bashar*** *of the Department of Botany, University of Dhaka for providing me with administrative and logistic supports during my study period.*

I am thankful to ***Prof. Dr. Ashfaque Ahmed*** *and* ***Mr. Md Abul Kashem,*** *Lecturer, Department of Botany, University of Dhaka, for their inspiration.*

I am indebted to Md. Bayzid Hossain, Lecturer, Department of Soil, Water and Environment of the same University for his kind help in chemical analysis of leaf samples.

I thankfully acknowledge the financial support provided by ***University Grants Commission of Bangladesh****, Ministry of Education, Government of the People's Republic of Bangladesh for conducting this research work. I would like to extend my thanks to the Bangladesh Forest Department, for giving me permission to carry out the research in the forest areas and I am thankful to the forest officials of BFRI Charajani and BFRI Charkai for providing all kinds of support during field data collection in the study.*

I like to extend my love to my lab-mates Md. Ataur Rahman, Habib Bhai, Tropa, Pragga, Suraiya, Mitul, Faria, Tulika, Kaisar, Liza, Trisha, Zuthi and Rifa for their friendly and encouraging support and encouragement during my study. They stood beside me whenever I needed. I must extend my thanks to Md. Abdul Aziz and Md. Robiul Islam (BFRI officers) for their hard work and support during the field work in the forest.

Thanks also go to all laboratory and office staff members, Department of Botany, University of Dhaka, who occasionally extended their help for this work.

Last but not least, I owe an enormous debt to my parents, wife (Lisa), younger brother (Saiful), and sons (Akash and Avro) for their enormous sacrifice, blessings and constant inspiration throughout my life, which has led to all of my success in studies and other spheres. I express my sincere and heartfelt thanks to all those who directly and indirectly helped me in my research.

Dedication

To My Parents
And
Teachers

Abstract

The present study investigated the effects of forest management on the regeneration of the dominant tree species Sal (*Shorea robusta* Roxb. *ex* Gaertn.) of the Madhupur Sal forest by conducting a survey using the quadrat method in four different seasons namely Spring, Summer, Autumn and Winter as well as by examining the seed germination and growth of seedlings and saplings between the Core zone and Buffer zone. This study also investigated the deciduousness of Sal plants by counting leaf every month in two different Sal forest stands namely Madhupur Sal forest in Tangail and Charkai Sal forest in Dinajpur for 31 months and examined the effects of soil moisture on the leaf exchange period of Sal plants under different moisture treatment conditions in the garden for 16 months. Results showed that a maximum number of juvenile Sal plants of 0–10 cm girth class was found in the Core zone (11,833 plants per ha) and Buffer zone (15,500 plants per ha) in Autumn and a minimum number in the Core zone (533 plants per ha) and Buffer zone (766 plants per ha) in winter. The maximum IVI value of Core zone (154.18) and Buffer zone (154.33) was found in the Autumn season while those were minimum in winter with the values 84.40 and 71.90, respectively. Sal seed germination rate was higher in the Buffer zone (77.33%) than in the Core zone (51%). Seedling survival rate was also higher in Buffer zone than in the Core zone. Phenological data revealed a maximum of 22.5% of completely leafless twigs in the Madhupur Sal forest while that was 12.5% in the Charkai Sal forest during the leaf exchange period. Sal plants started to shed their leaves in dry conditions when the soil moisture content started to decrease indicating the effect of soil moisture on the deciduousness of Sal plants. Data also indicated that Sal was semi-deciduous in nature in both these two forests. The present study also investigated the nutritional adaptation of Sal plants by comparing nutrient (N, P and K) resorption in old leaves of the Sal plants grown in Madhupur Sal forest and Charkai Sal forest. Results showed that old leaves withdrew nutrients (N, P and K) significantly before leaf fall occured. The resorption of N, P and K was 25%, 23.92% and 11.96%, respectively, in the Madhupur Sal forest; whereas in the Charkai Sal forest, it was 38.07%, 45.66% and 49.82%, respectively indicating that efficient resorption of nutrients might help Sal plants with the soil environment.

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CHAPTER 1

INTRODUCTION

1.1 Importance of Sal forests

Forests contribute an important share to the national GDP (Gross Domestic Products) in Bangladesh by providing not only the provisioning services but also the regulatory and cultural services. Forestry is an important sector in the economy of Bangladesh, which contributes about 1.28% of the country's gross domestic production (BBS 2012). The regulatory and cultural services that forests provide to people are intangible. Among the forests, deciduous Sal forests supply important products including timber, pillars, beams, railway slippers and so on. These forests are important not only for their economic importance but also significant for ecological roles by supporting biodiversity and maintaining ecosystem balance.

1.2 Disturbances on forest vegetation

The forest is being degraded at an alarming rate due to anthropogenic activities. Sal is also facing some constraints such as borer attack, short duration of seed viability, less tolerance to drought conditions and less regeneration ability (Tewari 1995). Over the last few decades, both biotic and abiotic disturbances have had a negative impact on the natural forest structure in Bangladesh, affecting regeneration and population dynamics (Shafroth *et al.* 2002, Kwit and Platt 2003). Many forces, both collectively and individually, are to blame for forest degradation. These trends of forces are extremely complex. Agriculture expansion, overextraction of wood and non-wood resources, infrastructure development, population growth, deforestation, settlement, urbanization and inappropriate management practices are the major causes of forest degradation in Bangladesh (Salam *et al.* 1999, Hasan and Alam 2008, Hossain *et al.* 2008). The rapid forest loss and degradation has resulted in an alarming rate of forest biodiversity depletion in Bangladesh (Hossain 2001, Salam *et al.* 1999).

1.3 Disturbances in Sal forests

In the Madhupur Sal forest area of the Tangail district, most of the forests have recently been seriously disrupted by human activities such as illegal felling and encroachment by local and Garo tribal people (Begum 2011). The Sal Forest patches have been depleted to such an extent that they no longer represent the traditional Sal forest in most places. Due to shifting farming and the introduction of invasive species, natural Sal forests have become endangered (Gain 1998). The majority of the Sal forest has been degraded and encroached upon, or taken over for the plantation of rubber, acacia, eucalyptus, pineapple, or exotic fuel wood species. Encroachers today own more than 66 percent of the entire area of these woods, relying mainly on the provision of wood and non-wood products (Hasan 2004). Despite the fact that the Madhupur Sal forests are protected, logging is widespread (Alam *et al.* 2008). In 1989, the Bangladesh government began agroforestry programs and the introduction of foreign species in response to competing land-use interests (Alam *et al*. 2008).

1.4 Management intervention in Madhupur Sal forest

Madhupur National Park originated as the Madhupur Sal forest but was officially designated as a national park on February 24, 1982, despite the fact that the case for national park status had been made since 1962 (BFD 2015). Madhupur Sal forest is located in the Madhupur sub-district under Tangail district. This one-of-a-kind natural forest is part of the tropical moist deciduous forest, which is rich in biodiversity. In order to ensure biodiversity protection and conservation in the Protected Areas, the

Forest Department has taken three types of activities: (i) Buffer zone plantations, (ii) Core zone protection and (iii) expanding protected areas and declaring new areas when possible (Mia *et al.* 2012). The innermost part of a park is known as the Core zone or restricted area. It is the zone where wildlife, including plants, is protected. This land might be used as a wildlife breeding ground. Human interference and control are severely limited here. Nature should be allowed to grow up naturally in this area. This area (about 3000 acres) is protected by erecting a durable wall within which no one, even forest service employees, is not permitted to access (Mia *et al.* 2012). Buffer area usually surrounds and adjoins the management zones that allow for the long-term exploitation of natural resources. Tourist hotels and restaurants, small garden zones and traditional methods of collecting fallen timber, harvesting fruits, seasonal grazing of domestic stock and bamboo or grass cutting are all common activities in Buffer zones. Burning vegetation, chopping living trees, constructing buildings and planting trees are all prohibited in Buffer zones (Mia *et al.* 2012). Such management interventions may cause changes in vegetation structure and abiotic environmental conditions which may influence seed germination and hence regeneration of the Sal plants in the Madhupur Sal forest, nevertheless, such information is not substantially available.

1.5 Paradox on deciduousness of Sal plants

S. robusta has been paradoxically described as deciduous, semi-deciduous or evergreen species (Singh and Kushwaha 2005, Reich *et al.* 2004), although this contradiction has not yet been resolved. Sal plants are considered as deciduous species in Bangladesh. Leaf phenology of Sal plants is not well understood in different geographical and climatic conditions of Bangladesh although it is important because it reflects the influence of evolution and environment on plant characteristics and plant functioning (Shankar 2001). Such variation in functional properties through leaf phenology has been attributed to environmental factors including soil moisture, rainfall, drought, temperature and rooting depth (van Schaik *et al.* 1993). To assess this contradiction and to understand the plant characteristics and plant functioning, study of leaf phenology is important (Perez-Harguindeguy *et al.* 2016).

1.6 Nutrient resorption by Sal plants

Nutrients are required for organisms to grow effectively in any ecosystem (Costa *et al.* 2018). Plants use a variety of mechanisms to adapt to their surroundings. Many factors including plant nutrients influence plant adaptation, distribution and net primary productivity (Ordonez *et al.* 2009, Wright *et al.* 2001). Leaves play key roles in plant function and long-term adaptation to the environment (Royer *et al.* 2008). Tree species adjust to variable micro-habitat conditions and often show different leaf strategies. Leaf strategy primarily denotes adaptations in leaf dynamics controlling the ability of a tree species to utilize resources (e.g., water, nutrients and CO_2) in relation to its ability to conserve the same (Singh and Kushwaha 2005). Some studies described that old yellow color leaves return back their nutrients before shedding of leaves from the tree occurs (Holopainen and Peltonen 2002).

The resorption of nutrients from senescing leaves is an important component of plants' nutrient conservation strategy (Milla *et al.* 2005). Nutrient levels in senesced leaves, or nutrient resorption proficiency, differ between species, ecosystems and soil fertility levels (Killingbeck 1996, Yuan and Chen 2015). According to Killingbeck (1996), there is a minimum level of nutrient reduction that species can achieve in their senescing leaves.

1.7 Objectives

The specific objectives of the study were to

- investigate the forest management effects on regeneration status of Sal plants by comprising seedling and sapling status between Core zone and Buffer zone of the Madhupur Sal forest.
- study the nature of deciduousness (deciduous, semi-deciduous or evergreen) of Sal plants in the selected Sal forests of Bangladesh by counting leaves as well as examine the role of soil moisture on the deciduousness of Sal plants grown under different water treatments condition.
- examine whether Sal plants withdraw nutrients (N, P and K) from the older leaves before senescence occurs in order to maximize nutrient use in stress condition.

CHAPTER 2

LITERATURE REVIEW

2.1 Definition of forest

There are different types of landforms with different geographical characteristics (Hargitai and Kereszturi 2015). Forestlands are one of the most important geographical landforms on Earth (Pagdee *et al.* 2006). A forest is essentially a piece of land that is mostly covered in various types of trees, bushes and plants (Herold 2008). Forests provide essential environmental resources and habitats for a variety of wildlife species (Thomas 1979). A forest is a large area of land covered by a thick growth of trees and other plants. It is the home of many different birds, insects and other animals. Moreover, land with a tree canopy cover of more than 10% and an area of more than 0.5 ha with trees taller than 5 meters is known as forest (FAO 2020).

2.2 Types of forests

There are many factors that influence the establishment of distinct forest types. Among the factors some include temperature, topography, wind, microclimate, soil types, soil moisture, rainfall, humidity and the geography of the area (Das 1990).

Generally, there are three types of forests globally:

A. Tropical forest
B. Temperate forest
C. Boreal forest

A. Tropical Forest

A tropical forest is defined as a forest that grows with remarkable diversity around the equator which is located at 23.5° north and 23.5° south in the equatorial region (Kanwar and Youngdahl 2012). It can be found in Africa, Southeast Asia and South America all along the equator. Despite the fact that the equator area is modest in comparison to the global forest area, it boasts the highest species diversity. Tropical Rain Forest subcategories are as follows (Kanwar and Youngdahl 2012).

1. Evergreen - there is no dry season and it rains throughout the year.

2. The seasonal - relatively brief dry season, generally rainy and humid tropical region that encourages the growth of evergreen forests. However, because the forest undergoes distinct seasonal changes, the trees also develop at the same time.

3. Dry - there is a long dry season and the trees are deciduous.

4. Montane - mist and fog are the main sources of precipitation, rather than rain. The cloud forest is a common name for this type of woodland.

5. Tropical and subtropical coniferous - dry and warm climate. Conifers, which are suited to changing weather, can be found here.

6. Sub-tropical - sub-tropical woods are found to the north and south of tropical forests and are adapted to the dry Summer season.

B. Temperate Forest

The temperate forest is located in the next latitude ring after the tropical rainforest. North America, Northeast Asia and Europe are included in this type. The seasons are clearly defined, with four distinct seasons and a notable Winter; this allows for 4-6 frost-free months and 140-200 days of growth time. The weather is temperate, with temperatures ranging from -30° to 30° Celsius. It receives 75 - 150 cm of rain yearly, which is evenly spread throughout the year (Luka *et al.* 2011). Under the temperate forest, there are several subcategories as follows (Luka *et al.* 2011).

1. Evergreen broad - leaved fir and moist conifer -Mild Winters with concentrated rain and dry Summer.

2. Dry conifer - There is less precipitation and the forest is found at a higher elevation.

3. Mediterranean - A temperate region to the south of the temperate zone, centered on the coast. Almost every tree is evergreen.

4. Temperate broad-leaved rainforest - The climate is temperate, with mild Winters and high precipitation that is equally distributed throughout the year. Trees are perennially green.

C. Boreal Forest

The boreal forest is known as Taiga forest, which occurs between 50 and 60° of north latitude. This forest type is distributed in Eurasia and the vast span of North America, notably Siberia, Scandinavia, Alaska and Canada (Gritzner and Charles 2009). There are two seasons: a moist and pleasant Summer that lasts only a few weeks and a long, cold and dry Winter. Temperatures can drop as low as -40° C and rise as high as 20° C. There is less precipitation, roughly 40–100 cm per year and it is usually distributed as snow rather than rain (Burris *et al.* 2019). Because the canopy is dense and does not allow light to flow through, the understory is limited. Trees are evergreen conifers with needle-shaped leaves that thrive in cold climates. Plants grown in these forests are pine, spruce and fir.

2.3 Importance of forests

2.3.1 Economic importance

Humans have been depended on forests for a remarkable variety of products, services and benefits. Historically, forests have played a major role to influence patterns of economic development, supporting livelihoods, helping structure economic change and promoting sustainable growth. For millennia before the industrial revolution, forests, woodland and trees were the source of land for cultivation and settlement, of construction materials, of fuel and energy and indeed of food and nutrition as well (Williams 2002). Forests continue today to provide the high levels of commercial benefits to households, companies and governments that formed the initial impetus for protective statutes and policies. The FAO estimates that forest industries contribute to 1% of the global GDP in 2008 and also to 0.4% of the global labor force (FAO 2012). Forests also provide other sources of income and subsistence benefits, generate informal work opportunities and constitute reservoirs of economic values that help ameliorate shocks to household incomes, particularly in rural areas in poor countries (Chomitz and Kumari 1998). Forests draw their importance from the products and services they supply. Wood-based products make a considerable contribution to the world economy, amounting to some 2% of global gross domestic product and contributing to basic needs for energy and for material inputs to modern living in construction, furniture, communications and packing (FAO 1995). Tropical forests are particularly important in terms of species richness and endemic species concentration since they hold up to 90% of terrestrial biodiversity (Brooks *et al*. 2006).

2.3.2 Commercial values

By far the most important forest product is wood. Moreover, paper, lumber, plywood and other items are also obtained from wood. Firewood is the most essential source of energy for cooking and other purposes in most wooded areas of the developing world. On the other hand, non-industrial timber vegetation in forests and agroforestry systems with commercial value is referred to as non-timber forest products. Wild mushrooms, berries, ferns, tree boughs, cones, moss, maple syrup, honey and medicinal goods like cascara bark and ginseng are some of the most widely obtained nontimber forest products. NTFP is a political and economic category that highlights forest resources that are by-passed or disregarded in forest management as a viable source of revenue.

2.3.3 Cultural values

Forests encourage people to live healthy, active lifestyles by providing a variety of outdoor leisure options. They also benefit mental and spiritual health by forming bonds with others and interacting with nature. Forests play a role in protecting the health of our world and the well-being of its inhabitants, which grows as a result of recreational activities in forests (Morris 2003).

2.3.4 Ecological importance

The forest is responsible for transforming lifeless rock into a live habitat. Plants and animals in the forest establish themselves over thousands of years, creating a living cover of green. Forests are responsible for the formation of the majority of the soil of the Earth. When garden soil degrades, a forest grows over the old garden, replenishing the soil.

Forest plants help to conserve soil through root system. The movement of water across the land is controlled by the forest. Therefore, when it rains a lot, the trees help to keep the water trapped in the soil helping control floods. Water is stored in the branches, trunks, roots and leaves of these plants. Forest trees thus help to maintain soil moisture (Kricher 1997).

Forest trees can help maintain atmospheric moisture (Ingold 2007). By controlling atmospheric temperature forest can play role in occurrence of precipitation. Forests also have a significant impact on hydrological processes. Forests with high water absorption and retention capacity can sometimes convert unpredictable precipitation into a more consistent flow of water from catchment areas. As a result, if there are forests nearby, the risk of floods due to extreme weather and rainfall may be minimized (Collentine and Futter 2018).

Forests are also important components of biodiversity, both as individuals and as habitats for other species. Forests are home to some of the world's most biodiverse ecosystems and are expected to offer habitat for 90% of the threatened and endangered species of the world. Biodiversity has intrinsic worth as well as practical and economic benefits and it serves as the foundation for forest dwellers (Pillay *et al.* 2022).

Forests are one of the most complex and diverse ecosystems on the planet. They are the primary source of biological diversity and play a key role in the functioning of the ecosystems of the world. Forests are crucial for the provision of a number of ecological services and are key habitats for biodiversity. Tropical forests are particularly important in terms of species richness and endemic species concentration since they hold up to 90% of terrestrial biodiversity (Brooks *et al.* 2006). Forest ecosystems are principal source of biodiversity (Vizzari *et al.* 2015). Forests are necessary for life on Earth because they provide ecological services such as climate regulation and water resource management, as well as habitat for plants and animals. Plants are important sources of primary production and play an important role in ecosystem structure. As a result, forests provide provisioning, regulating and cultural services, allowing humans to meet their fundamental requirements while simultaneously contributing to the natural balance on Earth (Brockerhoff *et al.* 2017).

2.3.5 Forest as C-sinks

Forests are carbon sinks because they have the capacity to store atmospheric carbon dioxide in the trees and soil as they grow (Luyssaert *et al*. 2008). Trees are also carbon sources: when a tree decomposes, carbon is released into the atmosphere as carbon dioxide (Nowak *et al.*2002). Cutting down a forest can be led to release carbon into the atmosphere. Even if a forest stop growing, it still stores carbon. The carbon sequestration created by the trees of forest and soil prevents carbon from being released into the sky. As they expand, forests serve as both carbon sinks and carbon storage.

Wood and wood-based raw materials store carbon throughout their life cycles and can be used for long-term carbon storage, such as in wood construction. Cartons and paper products, on the other hand, are short-term carbon storages. Environmental or ecological activities that directly benefit humans are referred to as forest ecological services. Carbon sequestration, hydrological function preservation and protection and biodiversity conservation are only a few of the key ecological services (Dauvergne and Lister 2011).

Photosynthesis allows plants to collect carbon dioxide from the atmosphere and return oxygen to the environment. As a result, forests reduce carbon emissions and keep it out of the atmosphere, ensuring the suitability of the Earth for human life. As a result, forests might be thought of as the lungs of the Earth (Fishman and Kalish 1990).

2.3.6 Role of Forests in Climate regulation

Forests play four major roles in climate regulation. They currently contribute about one-sixth of global carbon emissions when cleared, overused, or degraded. Forests react sensitively to a changing climate and produce wood fuels as a benign alternative to fossil fuels when managed sustainably. Finally, they have the potential to absorb about one-tenth of global carbon emissions projected for the first half of this century into their biomass, soils and products. Forests store about one-tenth of global carbon emissions projected for the forests have a significant impact on climate change by influencing the amount of carbon dioxide in the atmosphere (Cheteu *et al.* 2010). Carbon is extracted from the atmosphere and absorbed in wood, leaves and soil as forests grow. Forests are referred to as one of the "carbon sinks" because they can absorb and store carbon for long periods of time. This carbon is kept in the forest environment, but when trees are burned, it can be released into the atmosphere (Malhi *et al*. 2002). Understanding the global carbon cycle and thus climate change, requires quantifying the significant functions of forests in absorbing, storing and releasing carbon (Schimel 1995).

2.4 Global distribution of forests

Forests vary in physiognomy, diversity, community makeup and life forms around the world. The total area of forest is 4.06 billion hectares and it is not evenly spread over the world (FRA 2020). Tropical forests cover 45% of the total forest area (FAO 2020). Only five countries, including Russia, Brazil, Canada, the United States of America and China, account for more than half of the forest area of the world. On the other hand, Australia, Congo, Indonesia, Peru, India and the rest of the world account for two-thirds of the forest of the world (66%). By climate realm and biological zone, there are five primary forests. The tropics account for the majority of the forest (45%), followed by the boreal (27%), temperate (17%) and subtropical areas (11%). These domains are further divided into terrestrial global ecological zones, 20 of which contain forest cover (FAO 2012, Buchhorn *et al*. 2019), as shown in Figure 2.1.

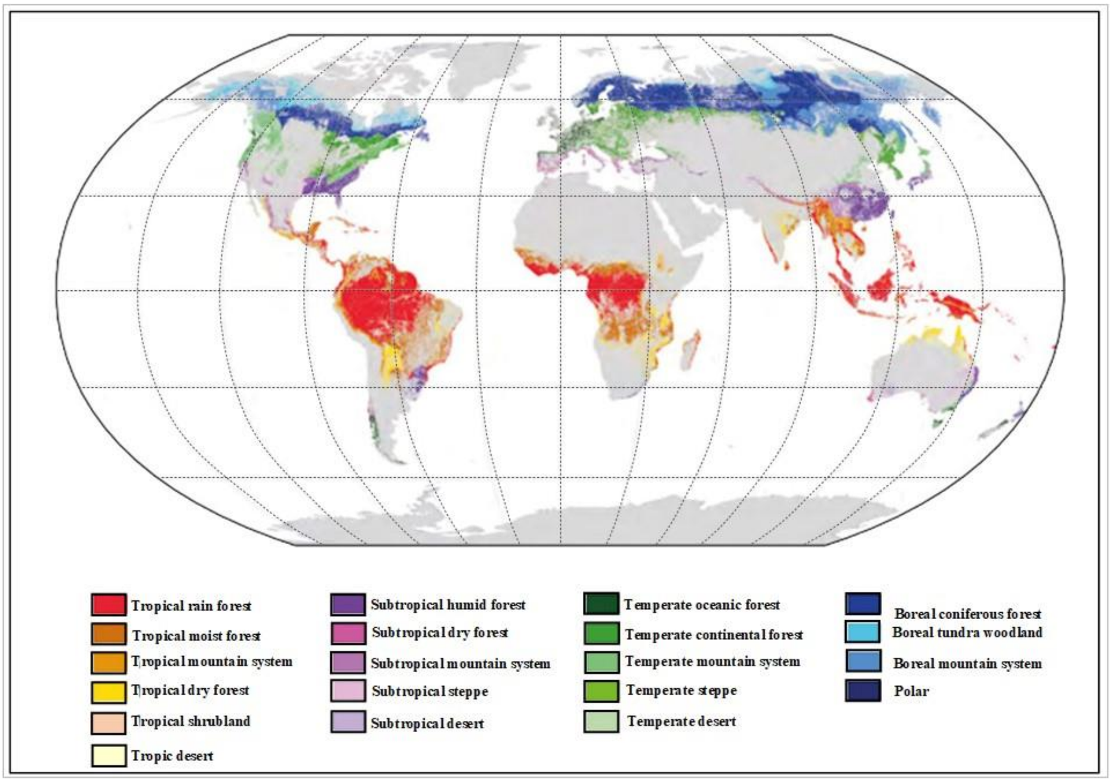

Figure 2.1: Map showing global forest cover of the world. Source: (FAO 2012, Buchhorn *et al.* 2019).

2.5 Deciduous forests of the world

A deciduous forest is a forest where the major constituent trees shed their leaves during the Winter or dry season to reduce the loss of water through transpiration. Moreover, a deciduous forest is a habitat where deciduous trees lose their leaves on a seasonal basis (Givnish 2002). Deciduous forests may be of several types such as temperate deciduous forests, tropical and subtropical deciduous forests, sometimes known as "dry forests"

(Jaramillo and Sanford 1995). Because of the large, flat leaves on the trees, these forests are also known as broad-leaf forests (Nunes 2012).

Deciduous forests are made up mostly of broad-leaved trees that lose all of their leaves in one season. These forests are seen in the Eastern North America, western Eurasia and northeastern Asia are three middle-latitude regions with a temperate climate typified by a Winter season and year-round precipitation (Kvaek *et al.* 2008). Along stream banks and around bodies of water, deciduous woodland also expands into more arid locations (Kolfschoten and Van 1995).

2.6 Deciduous forests in the South-east Asia

The structure and composition of dry forests in continental Southeast Asia differ significantly from those in the Neotropics (Rundel and Boonpragob 1995). In Asia, a patchwork of seasonal forest types exists, which is mostly governed by local elevation and moisture gradients (Bunyavejchewin *et al.* 2011, Rundel and Boonpragob 1995). Deciduous dipterocarp forests, a significant dry forest type in Southeast Asia, is limited to places with a total annual rainfall of 1,000–1,500 mm and a long dry season and is consequently characterized by large seasonal fluctuations in tree phenology gradients (Bunyavejchewin *et al.* 2011, Rundel and Boonpragob 1995). In the humid subtropics and along the equator between the tropics of Cancer and Capricorn, tropical deciduous forests can be found. Bangladesh, India, Pakistan, Nepal and Sri Lanka all have this deciduous type of forest (Nair 2007). In the countries of India, Pakistan, Nepal and Sri Lanka, open or closed forest covers around 40% of the subtropical area of the Earth, with tropical dry deciduous forest accounting for 42%, moist forest for 33% and wet forest accounting for 25% (Murphy and Lugo 1986). Sal forests, after the dominant species grow in both wet and dry environments. Sal forests can be found predominantly in South and Southeast Asia, from Assam to Punjab, along the foothills of the tropical Himalayas, in eastern Central India and on the Western Bengal Hills. Sal forests cover the greatest land of any Dipterocarpus, with an estimated 13 million hectares in India alone and over one million hectares in Bangladesh and Nepal combined (Poffenberger 2000).

2.7 Sal forests in the southeast Asia

Sal can be found in a variety of forest ecosystems in the southern Himalayan slopes in Nepal, Bhutan, India, Myanmar and Bangladesh, ranging in elevation from a few meters to 1500 meters above sea level (Gautam and Devoe 2006). Sal is found throughout northern and central India, divided by the Gangetic Plain (Pandey and Shukla 2003). It is found all throughout north, east and central regions of India. In Nepal, the largest Sal-growing region is the Terai (Webb and Sah 2003, Timilsina *et al.* 2007). *Shorea leprosula* is a Sal species that may be found in southern Thailand (Pattani), Peninsular Malaysia, Sumatra and North Borneo (Symington and Colin Fraser 1974). Sal woods are mostly found in central region of Bangladesh and are classified as tropical moist deciduous forest by Alam (1995). The plant is native to Myanmar, Bhutan, Bangladesh, Nepal and India, where it covers approximately 12 million hectares of forest (Tewari *et al.* 1995). In Bangladesh, Sal forests cover approximately 1,21,000 ha, accounting for roughly 32% of the total forest area. It is both economically and environmentally significant in the region.

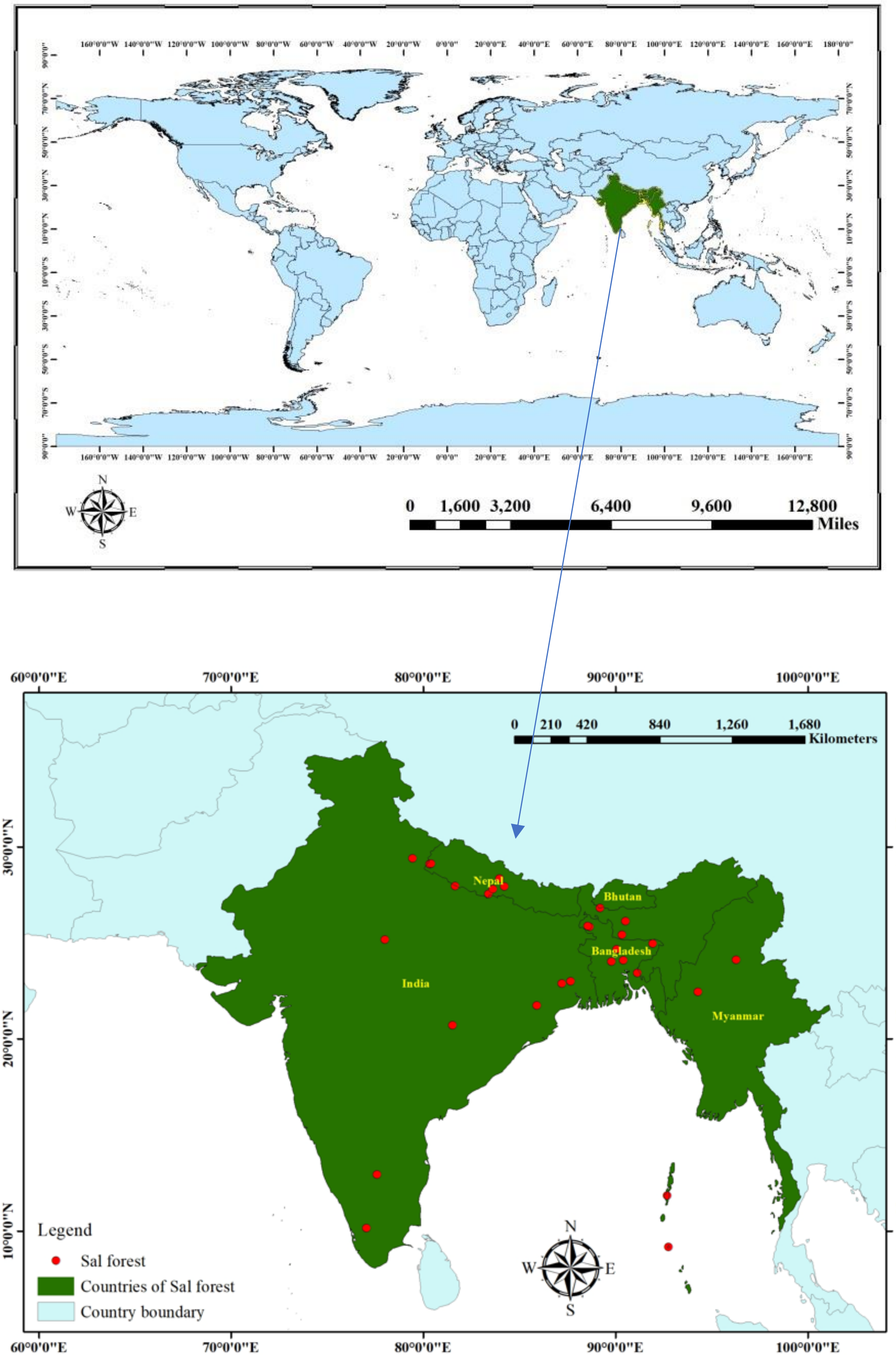

Figure 2.2: Map showing the countries where Sal forests are naturally grown.

2.8.1. Forests of Bangladesh

Bangladesh is a tropical country with a monsoon climate and is located between 20°34' and 26°38' north latitude and 80°01' and 92°41' east longitude in northeastern South Asia. The country is bordered on the west, north and northeast by India, on the Southeast by Myanmar and on the south by the Bay of Bengal. Tropical forest is defined as a forest that lies between the tropics of Cancer and Capricorn, according to the International Tropical Timber Agreement. Forest cover accounts for 10.2% of total land area, with 6,25,000 ha of forest plantations in 2000 (FAO 2005). Forestland covers 2.53 million hectares, or 17.5% of the total area of the country. The Bangladesh Forest Department (BFD) is responsible for the management of 1.53 million hectares of forestland in the country (Roy 2004). Natural forests of Bangladesh are regarded as one of the richest and most biologically diverse forest resources in the world due to their unique geo-physical location (Hossain 2001). This forest is thought to have around 5000 plant species (Sattar 1998). The forest provides habitat for plants and fauna, as well as a relaxing natural setting. As per the definition of FRA (Henry *et al.* 2021, FAO 2018), forest of Bangladesh cover in 2015 was 1,884,019 ha, or 12.8% of the total area of the country. This equates to 11.7 hectares per 1000 inhabitants. Forest cover is 14.1 percent when just terrestrial land area is included (i.e., ignoring river and lake area). Hill forest is the largest forest type in terms of area (4.6%), followed by shrubs with scattered trees (4.2%) and Mangrove forest (2.7%). Permanent crops cover half of the country and despite the fact that they are predominantly utilized for agriculture, they still have a tree cover of roughly 7%. Mangrove plantation had the largest increase in average tree cover (12%), followed by Mangrove forest (4%) and Rubber Plantation (2%). The highest decreases in tree cover occurs in Plain land forest i.e., Sal forest

(18%), Shifting Cultivation (14%) and Hill forest (7%) (Henry *et al*. 2021, BFI 2020). Table 2.1 depicts forest areas of Bangladesh under different management categories.

Table 2.1 Forest areas of Bangladesh under different management categories (Roy 2004, BFD 2012).

Types of forests	Area (million ha)	% Of country's total area
Managed forests by BFD	1.53	10.54
Unclassified State Forests	0.73	5.07
Village Forests	0.27	1.88
Total	2.53	17.49

According to Bangladesh Forest Department (2015) the entire forest land area of Bangladesh is around 2.62 million hectares. The Forest Department is responsible for the management of 1.6 million hectares of the total forest area (BFD 2015). The total forest area of Bangladesh is 1.429 million hectares, or 11% of the total land area of the country (FAO 2015). Plantation forest accounts for around 16% of the total forest area, while natural forest accounts for 84%. The three main types of forest in Bangladesh, are Hill forest, Mangrove forest and Sal forest, covering more than 70.8% of the total forest area (BFD 2016). Due to its unique geophysical location forests of Bangladesh are regarded as one of the most biologically diverse and abundant forest resources (Hossain 2001). Different natural heritages can be found in various parts of Bangladesh. The Sundarbans forest is in the southwest, the Sal forests are in the middle and the evergreen hill forests are in the southeast.

2.8.2 Forest types of Bangladesh

Bangladesh has a diverse range of forest types. Different natural heritages can be found in different parts of Bangladesh. Many factors influence the establishment of distinct forest types, including temperature, topography, aspect and gradient of hills, wind, microclimate, soil types and moisture in the soil, rainfall, humidity and the geography of the area (Das 1990). Tables 2.2 and 2.3 present statistics on forest area and forestlands maintained by the Forest Department of Bangladesh (Roy 2004, Khan *et al.* 2007).

Table 2.2 Different Forest types of Bangladesh (Roy 2004, Khan *et al.* 2007).

Forest types	Total area (Million ha.)	Area under tree cover (Million ha.)	% of total land under tree cover
Hill Forest	1.40	0.33	2.3
Mangrove Forest	0.74	0.46	3.2
Sal Forest	0.12	0.05	0.3
Village Forest	0.27	0.27	1.9
Total	2.53	1.11	7.7

Table 2.3 Forestlands managed by the Forest Department of Bangladesh **(**Roy 2004, Alam 2008)**.**

Forest types	Area (Million ha.)	% of total area
Hill Forests	0.67	4.65
Natural Mangrove Forests	0.60	4.09
Mangrove Plantations	0.14	0.97
Sal Forests	0.12	0.83
Total	1.53	10.54

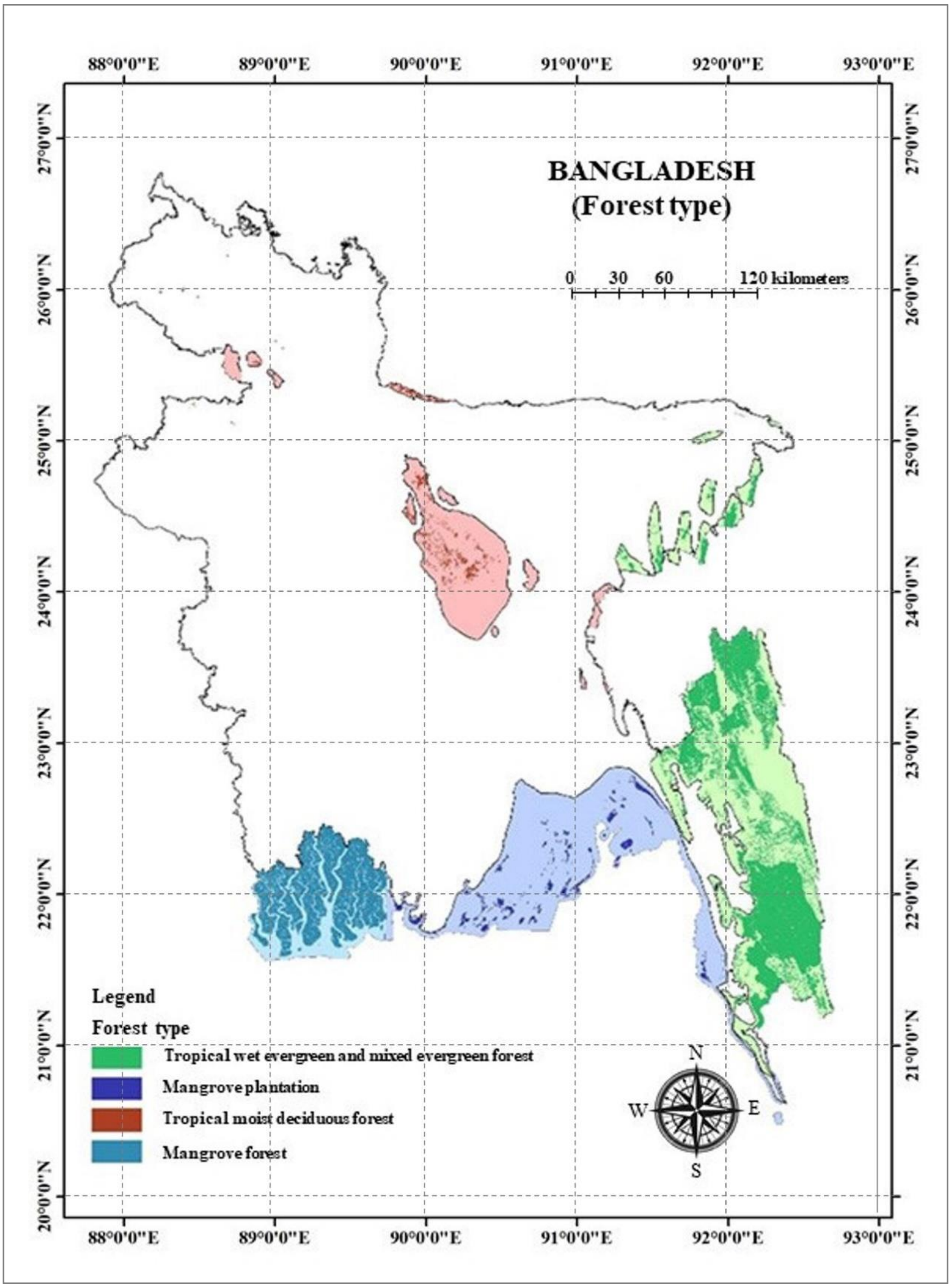

Figure 2.3: Map showing the distribution of different types of forests in Bangladesh.

2.8.2.1. Hill forests in Bangladesh

Hill forests can be found in hills and mountainous areas of Bangladesh. Hill forests cover 6,70,000 hectares, accounting for 4.65% of Bangladesh land area and 44% of all forestland maintained by the Forest Department (Khan *et al.* 2007, GOB 2010). This is one of most common forest types of Bangladesh. Rangamati, Bandarban, Khagrachari, Hill Tracts, Chittagong, Cox's Bazar, Sylhet, Maulvi Bazar and Habiganj districts have these forests. These forests are home to a great number of ecologically important tree, bamboo and shrub species. Hill forestss are home to a wide range of vegetation and fauna. Hill Forests are divided into two types based on topography, soil and climate:

(i) Tropical wet evergreen forests and

(ii) Tropical semi evergreen forests.

(i**)** Tropical wet evergreen forests

Tropical wet evergreen forests have a high amount of canopy (more than 75%) throughout the year (William *et al*. 1997). These species have a continuous canopy of at least 60% of the year (Prior *et. al*. 2003). They produce new leaves on a regular basis or on branches while shedding senescent leaves. Throughout the year, they never appear to be leafless (Rivera *et al.* 2002, Borchert 1994, Schongart *et al*. 2002). In these species vegetative buds break during the early or mid-dry season, just before or after leaf shedding occurs (Borchert 2000). The tropical wet evergreen forest grows in a region where the average annual temperature is around 25°-27°C, rainfall is about 250 cm, humidity exceeds 77% and the dry season is short. In Bangladesh, these forests are found in the Chittagong Hill Tracts (Khagrachari, Rangamati and Bandarban), Sylhet, Habigonj, Moulvibazer, Sunamganj, Cox's Bazar and Chittagong (Das 1990). Tropical moist evergreen forests predominate, with a diverse range of wildlife.

(ii) Tropical semi evergreen forests

Tropical semi evergreen forests are made up of a mix of moist evergreen and moist deciduous trees. The forest is deep and densely forested, with a wide diversity of both sorts of trees. This type of forest species has a brief period of deciduous growth (Gerhard *et al.* 1992). Species that are rarely, if ever, without green leaves and then only for a short time (Seghier *et al.* 2002, De Bie *et al.* 1998). Each species responds differently to leaf interchange, evergreenness, leaflessness and deciduousness, but all have a one-year leaf lifespan (Kushwaha and Singh 2005, Singh and Kuswaha 2005). This woodland receives 200-250 cm of rain every year. The average yearly temperature ranges from 24 to 27 degrees Celsius. The relative humidity level is around 75%. These forests occur in Cox‘s bazar, Chittagong, Rangamati, Khagrachari, Bandarban and Sylhet in less dry and hotter localities (BFD 2016).

2.8.2.2 Mangrove forests in Bangladesh

A mangrove plants are tiny shrub or tree that thrives in saline or brackish water along the coast (Saenger and Peter 2002). In the tropical and subtropical parts of the world, mangroves can be found in over 118 countries and territories (Sachin *et al.* 2020). In Bangladesh, there are both natural and manmade mangrove forests (Giri *et al.* 2015). The Sundarbans, a natural mangrove forest in Bangladesh, is the world's biggest mangrove region as well as the world's largest single block of tidal halophytic mangrove forest (Joshi and Ghose 2014). The Sundarbans is the world's biggest continuous productive mangrove forest, spanning southern region of Bangladesh and west Bengal state of India (Halder *et al.* 2021). The Sundarbans cover 62 percent of Bangladesh and the remaining 38 percent of West Bengal of India (Siddiqi 2001). The Sundarbans is a deltaic mangrove forest located southwest of Bangladesh and south of

West Bengal, India, that was produced around 7,000 years ago by the deposition of sediments from the Himalayan foothills through the Ganges River system (Khan *et al.* 2011). The Sundarbans East, founded in 1960, Sundarbans South and Sundarbans West, established in 1977, are three natural sanctuaries that face the Bay of Bengal. The sanctuaries have a total area of 1397 km^2. In 1997, UNESCO designated these sanctuaries as Natural World Heritage Sites, along with the Sundarbans (Khan 2011, BFD 2010). The Sundarbans World Heritage Site covers a total area of 1, 39,700 hectares. An estimate of 12.26 million cubic meters of timber resources (15 cm and above dbh) was found in 1998 forest inventory (Roy 2004). David Prain recorded a total of 245 genera and 334 plant species in 1903 (Prain 1903). Members of the Rhizophoraceae, Avicenneaceae, or Combretaceae characterize mangroves in various parts of the world. The Malvaceae and Euphorbiaceae families dominate the mangroves forest of Bangladesh (Hussain *et al.* 1994). The abundance of sundari (*Heritiera fomes*), gewa (*Excoecaria agallocha*), goran (*Ceriops decandra*) and keora (*Sonneratia apetala*) in the Sundarbans flora is notable.

2.8.2.3 Village forest in Bangladesh

A homestead, also known as a village forest, is a piece of land held by a family and used as a development and production unit for plants, animals and fish as part of an integrated farming system in which man, trees, cattle, soil and water are always in contact. It comprises the immediate vicinity of the residential unit. Homestead farming is an age-old practice in Bangladesh (Alam *et al.* 1988) that entails the intentional management of multipurpose trees and shrubs in close proximity to annual and perennial agri-cultural crops and, invariably, livestock within the compounds of individual houses; the entire crop tree-animal unit is intensively managed by family labor (Fernandes and Nair 1986). In the village woods, there are 2,70,000 hectares of trees. The homestead forests of Bangladesh are multi-story vegetation of shrubs, bamboos, palms and trees that generate a variety of resources for a variety of uses, including fuel, shelter, structural materials, fruits, feed and medicines (Motiur *et al*. 2006). Homestead forests meet a sizable share of the total demand for forest products. The village woodlots have an increasing supply of 54.7 million cubic meters, according to an inventory data (Roy 2004). In Bangladesh, there are no village woods given to inhabitants under the Forest Act (Pant 1990).

2.8.2.4 Deciduous forests in Bangladesh

The principal constituent trees in a deciduous forest shed their leaves throughout the Winter or dry season to prevent water loss through transpiration (de Souza *et al.* 2020). The Sal tree (*S. robusta*), is the dominating species in this type of forest, accounting for over 90% of the primary floral composition (Uddin *et al.* 2021). In Bangladesh, there are two types of Sal forests: moist deciduous and dry deciduous. Madhupur district has moist deciduous trees, while Dinajpur district has dry deciduous trees (Hossain *et al.* 2010). Sal woods are one of richest richest ecosystems when compared to other forests in Bangladesh. Sal woods cover 1,20,000 ha, accounting for 0.83 percent of the land area and 7.9% of forestland administered by the Forest Department (Roy 2004, Khan *et al.* 2007). Sal woods may be found in Bangladesh's Central and Northern districts (Alam 2008). A huge plantation effort is underway as part of the Social Forestry program, which is based on a benefit-sharing structure with local communities living in and around the forest region (Khan *et al.* 2007). Based on location, climatic conditions and interspecific exchanges, Sal forests exist in con-sociation and association (Chitale and Behera 2012). The ground floral diversity in the Sal forest is relatively high. Despite the fact that Sal is the dominant tree species in the Sal forest, around 500 undergrowth species have been identified in this forest (Hossain *et al.*

2013). In addition to trees and shrubs, the ground of Sal forest flora includes ferns, herbs, grasses and lianas (Gautam and Devoe 2006). The yearly rainfall in these woodland areas is typically around 2000 mm (Dey 2007).

2.8.3 Distribution of Sal forests in Bangladesh

Sal forests cover accounts for about 32% of the total forest acreage of our country (Mia *et al.* 2016). Gazipur, Tangail, Mymensingh, Cumilla, Dinajpur, Sherpur and Naogaon, are the most populous districts. Madhupur Sal forests also known as Madhupur Garh are the largest Sal forest belt of the country. These forests can only be found on gently elevated regions, never rising more than 15 meters above the floodplain. Many other significant natural tree species, known as Sal allies, can also be found in the woodlands (Hassan 2004). The forest is situated 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 with ferruginous nodules and manganese patches that belongs to the bio-ecological zone of Madhupur Sal Tract (Nishat *et al.* 2002). The soils have a mild to high acidic reaction and are deficient in organic matter and fertility (Alam 1995). The Madhupur Sal growing zone is included in the humid region according to Thornthwaite's standards (Ismail and Mia 1973). The meteorological features of this location over the last 30 years (BMD 2008), have been: annual rainfall 2030–2290 mm, annual temperature 10–34°C, humidity between 60 and 86 percent, daily sunshine 5–9 h, average maximum wind speed 16 km/h. (Rahman *et al.* 2009). Sal woods are one of the richest ecosystems when compared to other forests of this country.

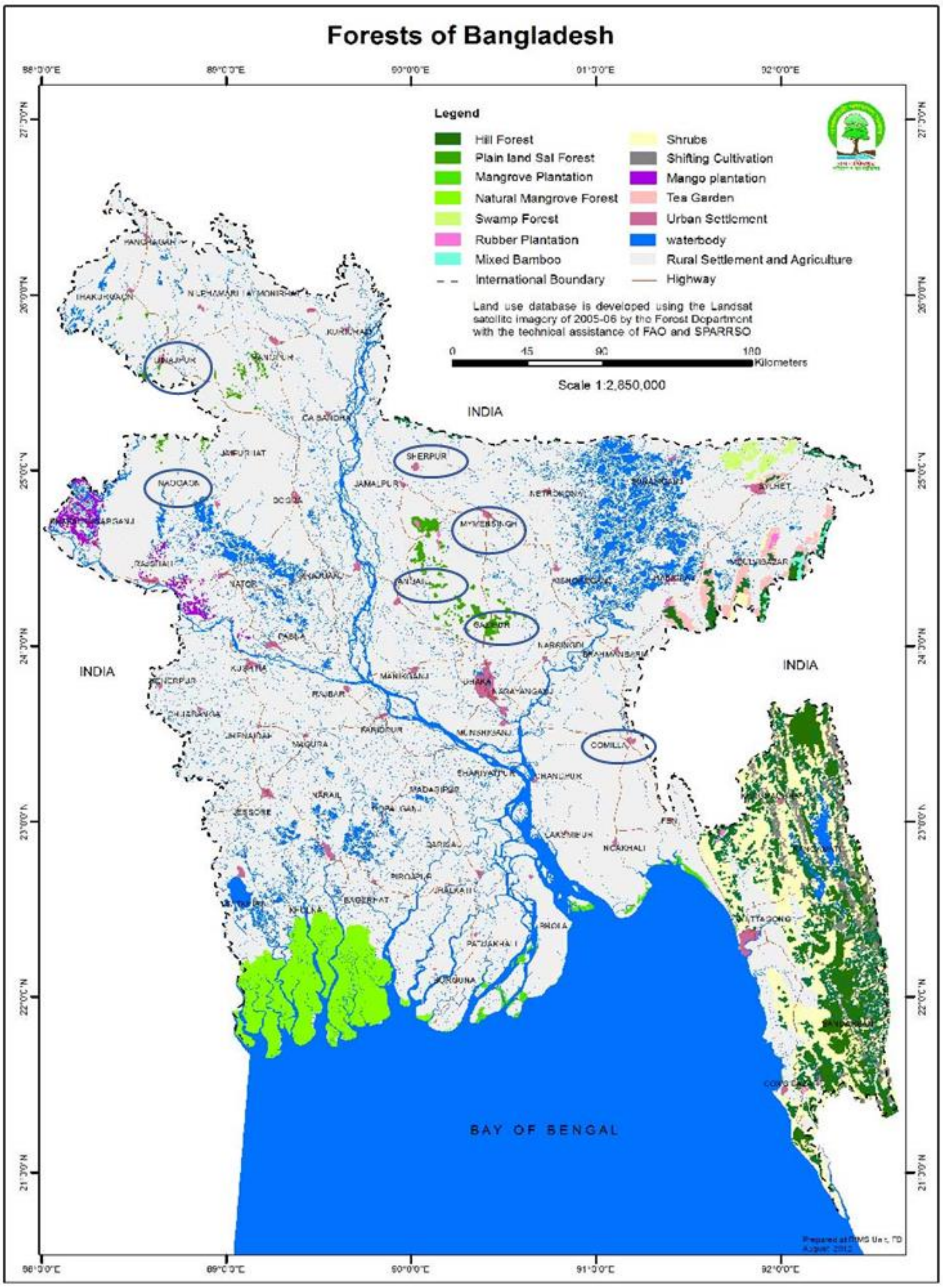

Figure 2.4: Map showing the distribution of Sal forests (Oval shape) in Bangladesh.

2.8.4 Madhupur Sal forest

Madhupur Sal forest is the largest natural Sal forest of Bangladesh. This forest is recognized as "Madhupur Garh" that comprises an area of 8436 ha. (DoE 2015, IUCN 2015). Madhupur National Park originated as the Madhupur Sal forest but was officially designated as a national park on February 24, 1982, despite the fact that the case for national park status had been made since 1962 (BFD 2015). Madhupur Sal forest is located in the Madhupur upazilla under Tangail district. Tangail Forest Division, which is part of the Mymensingh Forest Division, manages the Madhupur forest area. This one-of-a-kind natural forest is part of the tropical moist deciduous forest, which is rich in biodiversity. Madhupur Sal forests are also known as the inland Sal forests (Rashid *et al.* 1995). The tract is located between 23º50′ to 24°50′N latitude and 89°54′ to 90°50′E longitude, (Nishat *et al.* 2002). Madhupur Sal forest spans 17,932.15 hectares and is divided into four ranges: Madhupur, Aronkhola, Dokhola and Madhupur National Park (Khan *et al.* 2007). Pleistocene terraces and a recent alluvial floodplain make up the Madhupur tract. It is located in the middle of the Ganges-Brahmaputra-Meghna Delta. When dry, the soil is dense and hard, but when wet, it melts and becomes soft and tenacious. The soil in the Sal forest is a deep reddish-brown tint.

2.8.4.1 Floristic composition of Madhupur Sal forest

The Madhupur Sal forest contains some common plant species that are comparable to those found elsewhere (Chowdhury 1996). According to their development habits, the Madhupur Sal forest revealed a total of 174 plant species divided into 131 genera and 54 families, with roughly 102,17, 34 and 21 species categorized as tree, shrub, herb and climber, respectively (Malaker *et al.* 2010). In the Madhupur Sal forest, a total of 113 plant species have been identified as medicinal. There are 50 tree, 14 shrub, 32 herb and 17 climber species discovered to be used as medicinal plants (Malaker *et al*. 2010). In the Madhupur Sal forest, a total of four plant species have been identified as ornamental. Two trees, one shrub and one herb species were used as decorative plants (Malaker *et al*. 2010). In the Madhupur Sal forest, a total of 24 plant species have been identified as fruit plant species. Twenty-three tree and one shrub species were used as fruit plants (Malaker *et al.* 2010). In the Madhupur Sal forest, a total of 25 plant species have been identified as timber plant species (Malaker *et al.* 2010). In the Madhupur Sal forest, a total of 8 plant species have been recorded under miscellaneous plant species that included two trees (1 fodder and 1 rubber), one herb (1 fencing) and five climber species (3 cane, 1 packing and 1 alcohol) (Malaker *et al*. 2010).

2.8.4.2 Management of Madhupur Sal forest

In order to ensure biodiversity protection and conservation in the Protected Areas, the Forest Department has initiated three types of activities: (i) Buffer zone plantations, (ii) Core zone protection and (iii) expanding protected areas and declaring new areas when possible (Mia *et al.* 2012).

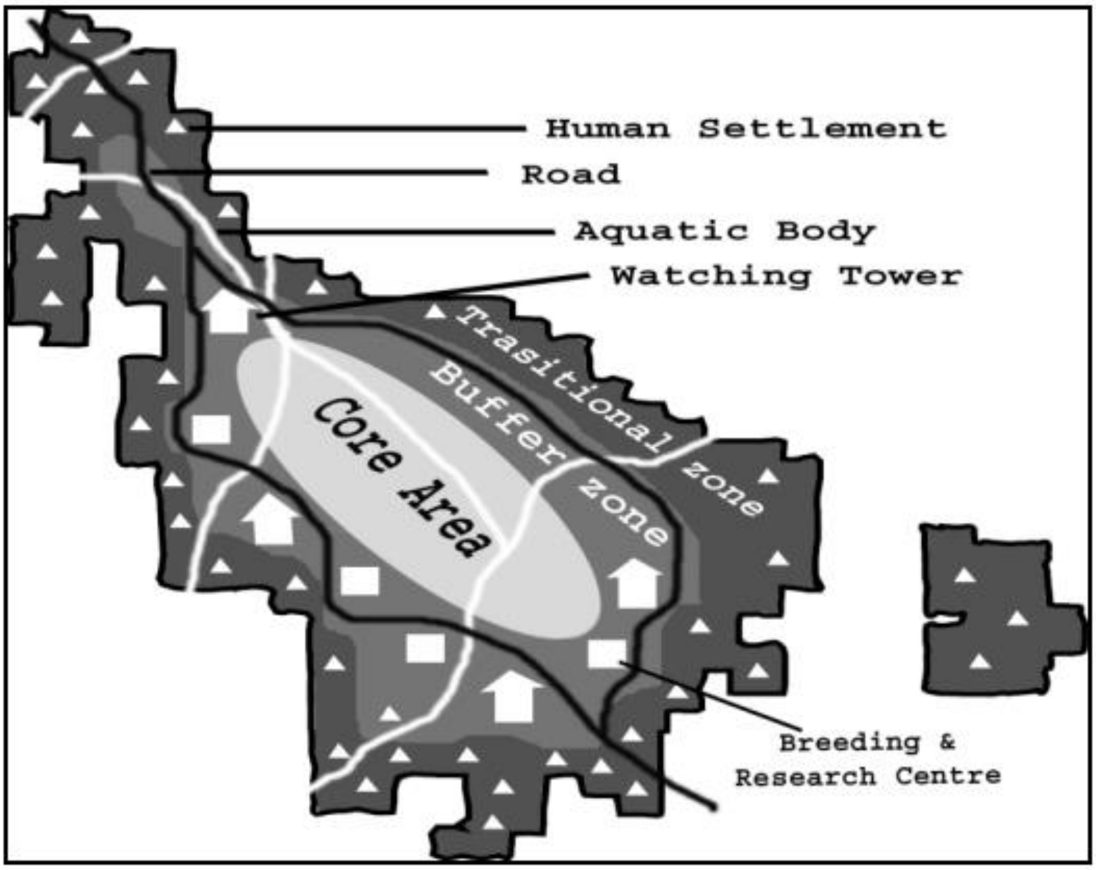

Figure 2.5: Map showing the Core zone and Buffer zone of Madhupur Sal forest.

Core zone

The innermost part of a park is known as the Core or restricted area. It is the zone where wildlife, including plants, is protected. This land might be used as a wildlife breeding ground. Human interference and control are severely limited here. Forest should be allowed to grow up naturally in this area. This area (about 3000 acres) is protected by erecting a durable wall within which no one, even forest service employees, is not permitted to access (Mia *et al.* 2012).

Buffer zone

Buffer zone usually surrounds and adjoins the management zones that allow for the long-term exploitation of natural resources. Tourist hotels and restaurants, small garden zones and traditional methods of collecting fallen timber, harvesting fruits, seasonal grazing of domestic stock and bamboo or grass cutting are all common activities in Buffer zones. Burning vegetation, chopping living trees, constructing buildings and planting trees are all prohibited in Buffer zones (Mia *et al.* 2012).

2.8.4.3 Major threats to Madhupur Sal forest

In the Madhupur forest area of the Tangail district, most of the Sal forests have recently been seriously disrupted by human activities such as illegal felling and encroachment by local people and Garo tribal community (Begum 2011). The Sal forest patches have been depleted to such an extent that they no longer represent the traditional Sal forest in most places. Due to shifting farming and the introduction of invasive species, natural Sal forests have become endangered (Gain 1998). The majority of the Sal forest has been degraded and encroached upon, or taken over for commercial or industrial rubber, Acacia, Eucalyptus, Pineapple, or exotic fuel wood plantations. Encroachers today own more than 66 percent of the entire area of these forests, relying mainly on the provision of wood and non-wood products (Hassan 2004). Despite the fact that the Madhupur Sal forests are protected, logging is widespread (Alam *et al.* 2008). In 1989, the Bangladesh government began agroforestry programs and the introduction of foreign species in response to competing land-use interests (Alam *et al*. 2008). The topography, geology and soil conditions all influence the spread of Sal forests (Chowdhury 2014, Rahman 2011).

From a social standpoint, Sal forest is one of the most important wooded areas in Bangladesh, where a diverse group of tribal people reside and rely on the forest for their entire subsistence. Due to overexploitation and the loss of natural habitats, many wild and semi-wild plant genetic resources are today more threatened than ever before. Many plant species have become rare and others are on the verge of extinction, as a result of over-exploitation and destructive harvesting of plant resources, particularly medicinal plants in the wild, by growing human populations (Malaker *et al*. 2010). Such a troubled but socioeconomically and environmentally vital forest ecosystem necessitates a holistic approach to its development, both for its medicinal plants and as a natural refuge for endangered animals.

Plantation with exotic trees

Due to commercial rubber monoculture plantings and ADB-funded "social forestry" in the form of woodlots (for the production of fuel wood) and agroforestry, the Madhupur Sal forest has been quickly depleted in recent years. The "social forestry" program, which began in 1989-1990, was preceded by a rubber monoculture, which wiped off a large portion of the Sal forest. Rubber plantations, in particular, are one of the most significant things that have permanently altered the Sal forest. In the Madhupur Sal forest, for example, 3,157.89 hectares were set aside for rubber production in the Tangail area (Gain 2005), while another 40,000 hectares of Sal woods were set aside for woodlots and agroforestry plantings under the Forestry Sector Project (GOB 2001). However, one of the most serious threats to the biodiversity of natural Sal forests is the introduction of various exotic species into plantation forestry (Gain 1998). Foreign invasions may result in a significant loss of biodiversity and species extinction, either directly or indirectly through exotic replacement. The Sal forest area has declined dramatically over the last forty years as a result of new plantations with foreign species (Hossain 2005), which neglect silvicultural principles and the impacts of invasive species on the Sal forest ecosystem. The Bangladesh government is attempting to reforest the land with invasive species such as *Acacia auriculiformis* and *Eucalyptus camaldulensis* (Rahman *et al*. 2010).

Cultivation of crop plants

In the Madhupur Sal forest area, large swaths of natural forest land have been converted into agricultural land and residences have been built. These regions produce pineapple, ginger, lemon, arum and banana, among other fruits and vegetables. These immature Sal timbers are being cut and sold at an alarming rate. Furthermore, land is bought and sold without being registered. Participatory agroforestry began in 1979 to protect the remnant forest, reclaim encroached land and supply the growing need for fuelwood (Hossain 2009). Agroforestry has become a common land use system in this area since then. On the basis of their major products, three types of agroforestry systems were recognized in the research area: pineapple (*Ananas comosus*) agroforestry, lemon (*Citrus lemon*) agroforestry and bananas (*Musa spp.*) agroforestry. Males made up the entire sample. Around 37% of the respondents belonged to ethnic communities, while 60% of the respondents were literate. For 73 percent of respondents, agroforestry was their principal source of income (Kibria and Saha 2011).

Pineapple agroforestry is one of the most common agroforestry practices in the study region, with a history dating back to the early 1980s. The main crop in this system is pineapple; secondary crops include turmeric (*Curcuma longa* L.), ginger (*Zingiber* *officinale*), papaya (*Carica papaya*), aurum (*Colocasia esculenta*) and various types of fruits such as jackfruit (*Artocarpus heterophyllus*), mango (*Mangifera indica*) and others. This system also included a variety of fast-growing wood species in addition to these crops. *Acacia auriculiformis* (Akashmoni), *Acacia mangium* (Mangium) and *Melia sempervirens* (Bokain). The forest department offers seedlings of timber species in participatory pineapple agroforestry.

The trend of lemon cultivation began in the early 1990s. Turmeric, ginger, papaya, aurum and various sorts of fruit species such as jackfruit, olive (*Elaeocarpus robustus*) and others are produced as secondary crops in this system. *Acacia auriculiformis*, *Acacia mangium*, *Melia sempervirens*, *Gmelina arborea* and other important timber species include akashmoni (*Acacia auriculiformis*), mangium (*Acacia mangium*), bokain (*Melia sempervirens*), gamar (*Gmelina arborea*) and others.

Banana agroforestry is the third type of agroforestry system. It began in the years 1985-86. Banana agriculture has ushered in a significant economic transformation in the region. It has become a simple method of bringing economic stability in a short period of time. Monoculture of bananas is prohibited by the department since it is extremely detrimental to the soil (Hossain 2009). Farmers are now aware of the negative consequences of banana monoculture. Residents in the area have recently expressed an interest in growing bananas in a mixed-culture setting.

Encroachment

Local impoverished and illegal timber dealers have typically spearheaded the encroachment and deforestation of forests. However, the Sal forests have recently been unlawfully taken by people, including politically and financially powerful individuals, groups and institutions (Iftekhar and Hoque 2005). A total of 8,869 hectares of forest area have already been encroached upon, with an estimated 100,000 encroachers (GOB 1992). In the Sal forest area, the invasion rate is around 1% per year (Iftekhar and Hoque 2005).

Illegal cutting

The Sal forest is decreasing at an alarming rate due to illegal cutting, causing a loss of biodiversity in the area (Haque 2007). Approximately, 25,101 ha. of the Madhupur Sal forest were unlawfully cut in the first part of this decade, accounting for about 12% of the Sal forest area (Gain 2005). Timber traffickers have taken advantage of the poor living conditions and lack of alternative income-generating options in the Sal forest areas to involve them in illegal forest cutting and other activities that are harmful to the Sal forest ecosystem (Safa 2005).

Urbanization and Industrialization

The forest is destroyed by urbanization. A number of significant urban settlements, including Gazipur, Tangail and Mymensingh, as well as Dhaka city, are located near the Sal forest areas. These urban towns have big populations and rapid population expansion. The expansion of road networks and other facilities as a result of such urban settlements degrades the quality of wildlife habitats. In the Sal forest sections of Mymensingh and Tangail, for example, two road network enhancement projects totaling 62.2 km have been completed (GOB 2008). This type of road building isolates wildlife populations from feeding sites and natural migration routes, limiting mating between larger groupings. Because road building has made the Sal forest more accessible, anthropogenic disturbances are more likely to occur in the forest. The Bangladesh Air Force erected a shooting range on around 405 hectares of Sal forest land (Gain 2005), causing noise pollution and posing a major threat to wildlife habitat.

Furthermore, industry has gradually expanded in the Sal forests area, affecting natural plant and animal species, particularly in Gazipur, Tangail and Mymensingh sites (Islam 2021).

2.8.4.4 Ecological significance of Madhupur Sal forest

Sal forests are important ecologically in the central region of Bangladesh (Rahman *et al.* 2010). Forest ecological services are those environmental or ecological processes that benefit humans directly. Forest ecosystems have three fundamental characteristics: structure, composition and function. Climate, terrain, soil and human and natural disturbances all affect these characteristics (Timilsina *et al.* 2007). Plant genetic resources are an important component of biodiversity that supports living systems on the planet. They are incalculably valuable worldwide assets for current and future generations; they are sources of improved yield and quality elements; and, in every way, they are the basic cornerstone of human existence (FAO 1984). Bangladesh, as part of center of plant diversity, the Indian Subcontinent, has a wealth of plant genetic resources (Vavilov 1926). These forests are home to various medicinal plants, including Hartaki (*Terminalia chebula*), Bohera (*Terminalia belerica*), Arjun (*Terminalia arjuna*) and Kurchi (*Holarrhena antidysentrica*). Many other medicinal herbs, such as Shothi (*Curcuma zedoaria*) and Bonada (*Curcuma amada*), flourish in the undergrowth of these woodlands (Khan 1990). However, a number of plant species are at risk of extinction in all or part of their distribution ranges due to population declines caused by overexploitation (Das 1987). Fruits, food, fodder, firewood, bamboo, canes and medicines have all been obtained from wild plant species. Furthermore, wild species have the potential to have desired genes and traits that are used in breeding programs to improve production and quality aspects, as well as to adjust to changing environmental conditions (Malaker *et al*. 2010).

Sal forest is one of the most important forest areas and it is home to a diverse group of tribal people that rely on it for their whole life. Such a disturbed but ecologically and environmentally important forest ecosystem necessitates a holistic approach to its development, both for its medicinal plants and natural habitat for endangered animals such as the Hoolock gibbon (*Hylobates hoolock*) and for international (as a dry and plain land tropical deciduous forest ecosystem) interest (Rahman 2010). They also provide a wide range of items, ranging from culinary plants to plants utilized in handicrafts. These forests are typically found near human settlements and are well suited to the extraction of forest products. Despite their extensive occurrence and importance from an ecological standpoint, there is little knowledge about the ecological characteristics of Sal Forest (Timilsina *et al.* 2007).

2.8.4.5 Economic importance of Madhupur Sal forest

Sal, the dominant plant in the Madhupur Sal forest, is a valuable timber tree with a wide range of applications. Beams, scantling, rafters, floor boards, piles, girders, electric poles, house posts, dugouts, wheel hubs, railway sleepers, wagon flooring, Buffers, break blocks and even ladders are made of this hard, heavy and durable wood Chapagain *et al.* 2021, Baldwin 2017). On tapping, the tree produces oleo-resin, also known as "Sal Drammer," which is widely used as incense and disinfecting fumigant, as well as for solidifying soft waxes for use in shoe polishes, carbon sheets, typewriters and ribbon. The resin is used as a peach replacement in boat caulking and as a lower-quality incense (Khan 1985, Alam *et al.* 2006). This is the only member of the Dipterocarpaceae family that can endure frost and adapt to a wide range of clinological, geological and soil conditions. Ayurvedic practitioners freely employ bark, leaves, fruits and resin, whereas Yunani doctors use resin and oil as medicine. The resin is an astringent that is used to treat dysentery, gonorrhea, poor digestion, toothaches, painful eyes, ulcers, wounds and as an aphrodisiac (Caius 1986). In Bangladesh, peasants commonly use the leaves as a substitute for plate in ceremonial occasions and used in native of Orissa eat 5 mg of powdered resin combined with hot milk orally to relieve chest discomfort and stomachache (Saxena *et al.* 1981). Agricultural implements, particularly ploughs, are sometimes made from the wood (Das 1984). In South Asia, seeds are frequently utilized as chicken feed (Ravindran and Blair (1991).

2.9 Biology of Sal

2.9.1 Taxonomy of Sal

Sal (*S. robusta* Roxb. *ex* Gaertn.) is a tropical tree species belonging to the family Dipterocarpaceae which consists of three sub-families, 17 genera and 511 spp. (Ashton *et al.* 1982). It is a hermaphrodite species which attains a height up to 30-35m and trunk (girth) diameter of up to 2.0-2.5 m (Surabhi *et al.* 2017).

The taxonomical classification of *S. robusta* is given below:

Kingdom: Plantae – Plants
Subkingdom: Tracheobionta
Super division: Spermatophyta
Division: Magnoliophyta
Class: Magnoliopsida
Subclass: Dilleniidae
Order: Theales
Family: Dipterocarpaceae
Genus: *Shorea* Roxb. *ex* Gaertn.

Species: *Shorea robusta* Roxb. *ex* Gaertn.

2.9.2 Vernacular names of Sal

Sal is known by several different names around the world. Names are found in Bengali (Sal, Shal, Sakhu), English (Sal), German (Salharzbaum, Sal-baum), Hindi (Borsal, Sala, Sagua, Sakhu, Sakhwa,Ssal, Shal), Nepali (Agrakh, Sakhua, Sal, Sakwa, Sakwa), Sanskrit (Shal, Sala, Saria) and in Trade name (Sal) and so on.

2.9.3 Habitat

Deciduous Sal forests can be found in a wide range of climates. It can be found in tropical moist deciduous, semi-evergreen and wet evergreen forests (Reddy *et al.* 2015).

2.9.4 Flowers

Yellowish-white flowers are arranged in large terminal or axillary racemose panicles. Flowers are sub-sessile, pendulous, hermaphroditic, and dichogamous with strong protogyny, 2.5 cm across and lack nectar. Sepals connate at the base, persist and elongate after fertilization of flowers to form wings, thus, facilitating wind dispersal of the samara fruit. The corolla is an inverted bowl structure. Petals are pale yellow with mild fragrance, but not showy. Each petal taper and the tapering are recurved and face upwards (Soni *et al*. 2013).

2.9.5 Fruits

Sal fruit is a samara with five wings, measuring about 1-2 cm in diameter, ovoid, indehiscent and enclosed by the accrescent calyx lobes. Sal fruiting occurs from February to July and the three expanded lobes or wings are c 4.5-6.0 × 0.8-1.5 cm, oblanceolate, obtuse and pubescent with 10- 12 fine nerves running the length (Fig. 2.6b). Fruit is a nut without the calyx (Kumar *et al.* 2015).

2.9.6 Shoots

Young stems and inflorescence of Sal plants are greyish, stellate and tomentose. Old tree bark is dark grey to dark brown in color, thick, rough and fissured longitudinally (Fig. 2.6c) (Muralidhara and Pullaiah 2007).

2.9.7 Leaves

Sal leaves are glabrous on the ventral surface, but can be scabrid or tomentose. The young leaves are pinkish or reddish in color, while the adult leaves are dark green to pale yellow in color (Fig 2.6d). The length and width of the leaves are approximately 12-30 cm and 8-15 cm, respectively. The leaves are ovate-oblong, briefly acuminate, base rounded or slightly cordate, sub-coriaceous, glabrous and shiny except for the puberulous nerves beneath, with 12-19 pairs of lateral nerves. Stipules are 0.8-1.0 cm long, somewhat falcate, tomentose and caduceus, while petioles are 2-3 cm long (Soni *et al.* 2013).

2.9.8 Propagation

Sal plants are propagated in a variety of ways, including seeds, seedlings and stem cuttings. Natural regeneration was also a factor, as were the species coppices (Sapkota *et al.* 2009).

2.9.9 Chromosome number

The number of chromosomes in Sal is 2n = 24 (Kumar and Subramanium, 1986, Kumar 1987).

Figure 2.6: Different plant parts of *Shorea robusta*: flower (a), fruit (b), shoot (c) and leaf (d). Photos captured from Madhupur Sal forest.

2.10. Regeneration mechanism of Sal plants

2.10.1 Reproductive organs

S. robusta is thought to be entomophilous or anemophilous (Bera *et al.* 1990) and it produces a lot of pollen (Bera *et al.* 1990, Chauhan *et al.* 1994). Pollen grains per anther range from 1,450 to 1,860, with an average of 1,700 grains per anther and 59,500 grains per flower. Fruit set after pollination of virgin stigmas with pollen grains maintained inside indicates that pollen grains are viable for beyond 50 hours (Atluri *et al.* 2004).

The stigma is slightly tridenticulate and the style is rather lengthy. It emerges around a day before the petals open and the stigma remains receptive for 50 hours, as seen by its viscidity and shimmering (Atluri *et al.* 2004). The fruit-set capability of stigmas of various ages in emasculated and protected flowers indicates a nearly identical receptivity time.

2.10.2 Blooming phenology

The species blooms only once a year, giving it a one-year flowering frequency (Ewusie *et al.* 1980). Blooming begins in late February, when the trees are leafless and continues through March, ending in early April, with little asynchrony amongst individual trees (Atluri *et al*. 2004). Blooming lasts 33–45 days (on average 35 days), with a peak of 7–13 days (av.10 days). It is hermaphrodite and, unlike other *Shorea* species, is wind pollinated, flowering primarily before the leaves emerge during dry seasons. It blooms in large quantities and strong winds cause pollen discharge (Atluri *et al.* 2004).

2.10.3 Seed

S. robusta seeds are ovoid in shape (eight millimeters in diameter), weigh up to two grams and have two shorter and three longer wings (Fig. 2.6b). (Jackson *et al.* 1994). Seed dissemination is aided by the wind and *S. robusta* seeds are tenacious, losing viability within a week of dropping to the ground (Tewari 1995).

2.11 Importance of Sal trees

2.11.1 Economic importance

Sal tree wood is robust, long-lasting and fire-retardant. Therefore, it is widely employed in the construction of houses, telephone and electrical poles, railway sleepers and boats, as well as furniture and other woodwork projects (Baldwin 2017). Sal dammar refers to the resin derived from Sal (Khan 1985). Paints and varnishes contain this substance. It is also used to caulk boats and ships and it is burned as incense in Hindu rites. Non-timber forest products such as feed, seed from oil, tannin and gum from bark (Narayanamurti *et al.* 1951) and leaves for plate manufacture are also produced by Sal forests (Chitale *et al.* 2012). After refinement, the seed oil is utilized for cooking.

2.11.2 Medicinal values

The available scientific research on *S. robusta* has shown that it is an important medicinal plant used in various medical treatments. Wani *et al.* (2012) revealed that the extracts of *S. robusta* possess significant analgesic properties. The methanolic and aqueous leaf extracts of *S. robusta* show analgesic activity with acetic acid-induced writhing and tail flick tests. The antipyretic activity of Sal was studied, and the results of this study demonstrated the antipyretic activity of *S. robusta* resin and supported its traditional therapeutic use in fever (Duddukuri *et al.* 2011). Furthermore, the preliminary phytochemical analysis revealed that the aqueous extract possesses tannins, flavonoids, cardiac glycosides and steroids, which are involved in the antibacterial activity (Duddukuri *et al.* 2011). The methanolic and aqueous leaf extracts of *S. robusta* show anti-inflammatory activity in the carraganeen and dextran-induced paw method and the cotton-pellet-induced granuloma model (Jyothi *et al.* 2008, Wani *et al.* 2012, Chattopadhyay *et al.* 2012). *S. robusta* resin possesses significant gastroprotective activity, supporting the traditional use of resin preparations and contributing to its pharmacological validation (Muthu *et al.* 2013). *S. robusta* resin has a stronger and broader spectrum of antimicrobial activity against a number of pathogenic microorganisms (Murthy *et al.* 2011).

2.11.3 Religious importance of Sal trees

Sal has a spiritual significance in Hinduism. According to Hindu legend, Vishnu favors the Sal tree (quoted from a book titled "Sacred Trees"). Its name, shala, shaal, or sal, is derived from a Sanskrit word (literally "home"), which denotes that it is made of wood. Sarna Burhi, a goddess associated with sacred Sal tree groves, is worshipped by some Bengali traditions (Porteous 2001). The tree is also mentioned in the Ramayana, where Lord Rama is asked to pierce seven Sals in a row with a single arrow (which is later used to kill Vali and still later to behead Ravana's brother Kumbhakarna) at the request of deposed monkey king Sugreeva for proof that he can kill Sugreeva's older half-brother Vali. Typical Nepali pagoda temple architectures with very rich wooden carvings may be seen in the Kathmandu Valley of Nepal and most of the temples, such as Nyatapol Temple (Nyatapola), are made of bricks and Sal tree wood.

Sal has a lot of meaning in Buddhism. The ephemeral flowering of the Sal tree is utilized in Buddhism as a symbol of impermanence and the fleeting nature of brilliance (Giamo 2003). According to Buddhist legend, Queen Maya of Sakya gave birth to Gautama Buddha while on route to her grandfather's kingdom in Lumbini, Nepal, while gripping the branch of a Sal or Ashoka tree in a garden (Buswell *et al.* 2013, Nyanatusita 2010). Sal has a meaningful value in Japanese Buddhism.

2.12 Constraints of Regeneration of Sal plants in Madhupur Sal forest

2.12.1 Natural problems with Sal plants

This plant is vulnerable to a well-known plant borer that can cause significant harm (Sen-Sarma and Thakur 1994). In 1899, the heartwood borer was discovered as a pest on Sal. Crown sickness, dead bark on the upper surface and leafless branches are all symptoms of the Sal heartwood borer (*Hoplocerambyx spinicornis* Newn.) (Jesudasan 2011). **S**eeds are recalcitrant and show wind-driven dispersal (Tewari 1995). Seeds lose their viability within a week after dropping to the ground. Despite the fact that the plants produce abundant blooms and fruits in the plains and foothills, natural regeneration is weak (Pawar *et al.* 2012, Pattanaik *et al.* 2015). Furthermore, dryness causes widespread mortality or die-back during the seedling stage (Kandya *et al*. 2006).

2.12.2 Anthropogenic constraints with Sal plants

The anthropogenic disturbances in the Madhupur Sal woods are so complex that a single metric cannot accurately reflect the level of disturbance. In terms of wood supply and competing land uses, the forests are under a lot of stress. Natural resources are overexploited due to high population density and unequal land distribution (60% of people are landless) (Pagiola 2004). Due to shifting farming and the introduction of invasive species, natural Sal forests have become endangered (Gain 1998). One study shows that encroachers own more than 66% of the entire area of these forests, relying mainly on the provision of wood and non-wood products (Hassan 2004). Despite the fact that the Madhupur Sal forests are protected, logging is widespread (Alam *et al.* 2008). In 1989, in response to competing land-use interests, the government launched agroforestry programs and introduced foreign plants (Alam *et al*. 2008). Paddy is typically grown in the depressions. Forest border marking and maintenance are particularly challenging because homesteads, cultivable land and woods are all intermingled together. The Garo ethnic group (also known as the Mandis) has lived in these forests for millennia and is considered a forest people (Gain 1998). More than 66 percent of the Sal forests have been removed, with 88,000 encroachers in control (Hassan 2004). Other anthropogenic disturbances observed include grazing, trash sweeping or regeneration cutting, soil disturbances, shifting agronomy and logging.

2.13 Regeneration

The process of regenerating, renewing, or repairing something, especially after it has been destroyed or lost, is known as regeneration. Regrowth is a near-synonym (Goss 2013). Plants have a remarkable capacity for regeneration, as sessile organisms that must repair damage caused by a variety of biotic and abiotic stressors. When placed on growth conditions containing high quantities of plant hormones, they can efficiently mend cuts and wounds, totally regenerate an excised root tip and produce new organs and tissues (Birnbaum and Sanchez Alvarado 2008, Sugimoto *et al.* 2011).

Regeneration mechanism of plants

The term regeneration is used to describe the regrowth of a portion of an organism. Tissue, organs and other bodily components that have been damaged or destroyed in animals or plants can sometimes be regenerated. Some animals can recover a full leg or tail. Similarly, some plants can recover a full body while others may regenerate only a portion of their body (Sugimoto *et al.* 2011). Environments that have been harmed or destroyed, such as forests or grasslands that have been ravaged by fire, can regenerate (Kull 2000).

Wounding causes all three types of plant regeneration, showing that this is the initial signal. Alterations in hormone biology result from this wound signal, which leads to changes in gene expression. The chemical nature of the wound signal, however, is unknown. It is likely that the signal differs throughout tissues or organs or under different wounding situations because it is a complicated blend of numerous substances. This is due to the fact that injury can produce distinct forms of regeneration depending on which tissues/organs are destroyed or separated. Several plausible factors have been postulated in studies on wounds, including plasma transmembrane potential, Ca_2+, reactive oxygen species, plant hormones and alterations in several metabolic pathways (Leon *et al.* 2001, Maffei *et al.* 2007). Because the wound signal promotes both regeneration and defense, its signal transduction pathway could be quite complicated.

To recuperate from injury, plants have evolved tremendous regeneration abilities. Plant regeneration research is important because the mechanisms behind plant regeneration are linked to fundamental research in numerous domains as well as the creation of widely used plant biotechnology (Delporte *et al.* 2012). Tissue regeneration, organogenesis and somatic embryogenesis are the three basic types of regeneration seen in higher plants (Bennici *et al.* 2004).

The health and vitality of a forest are determined by its regeneration state and a healthy forest ensures strong future regeneration. The existence of distinct age groups of seedlings, saplings and trees determines a regenerative and productive forest (Chauhan *et al.* 2008). Regeneration is monitored to see if it satisfies the goal of sustainable forest management, namely whether a forest's productive potential and biological variety are preserved (Lutze *et al.* 2004).

2.14 **Phenology**

Phenology is the study of periodic events of biological life cycles and how they are influenced by seasonal and interannual climate variations, as well as habitat conditions (Kristensen *et al.* 2019, Morisette *et al.* 2009). Phenology refers to the occurrence of life-cycle events on a regular basis and it is currently receiving a lot of attention because the consequences of global change on phenology are so obvious. Phenology is a science that studies these events and ties their annual variations to climate change. However, phenology is studied in a variety of fields, each with its own unique viewpoint (Visser *et al.*).

2.15 Leaf Phenology

Plant leaf phenology is the study of annual life-cycle events in plants, from bud break and leaf expansion in the Spring to leaf coloration and leaf drop in the fall, as detected by ground-based visual observation on individuals in the field or by satellite remote sensing of land surface vegetation (Zhang *et al.* 2003, Polgar and Primack 2011, Xie *et al*. 2015)

In tropical trees, leaf phenology is important because it reflects the influence of evolution and environment on plant characteristics and in turn has substantial implications for plant functioning (Singh and Kushwaha 2005, Reich 204). Most tropical woody plants generate new leaves and flowers in bursts rather than continuously and the presence of new leaves, flowers and fruits varies seasonally in most tropical forest ecosystems. This patterning indicates that phenological changes are responses to biotic or abiotic influences. Individual plant species' phenological activity may be staggered or clustered depending on biotic variables (Van Schaik *et al*. 1993). The duration and intensity of seasonal dryness determine the phenology of trees in the dry tropics. The extent to which trees are subjected to drought varies greatly, depending on temperature and soil water availability, as well as tree attributes such as roots depth (Van Schaik *et al.* 1993).

Sal changes foliage around the Spring equinox in the middle of the dry season, in contrast to the co-existing deciduous tree species, which produce new leaves after varied leafless intervals during the dry–hot Summer (May–June), just before the rainy season begins (Kushwaha *et al.* 2005). Deciduous species leaf out shortly before or with the commencement of the rainy season, whereas evergreen species leaf out in the middle of the dry season (Medina *et al*. 1995). *Shorea* cannot be classified as a deciduous plant because of its Spring leaf flushing, significant leaf exchange and substantial canopy re-establishment during the hottest and driest months of the year (March–June). Ability of Sal, like many evergreen species, to swiftly rehydrate the stem during the dry season is reflected in its leaf flushing and flowering during the mid-dry portion of the annual cycle. Leaf falls and twigs with a high-water potential are required for subsequent leafing (Borchert *et al*. 2002). During the dry season, leaf-exchanging Sal plants are constrained to moderately damp areas and maintain a high-water potential (Rivera *et al*. 2002). Sal has a deep root system that allows it to access subsurface water (Joshi *et al.* 1980)

Sal plant is important both economically and ecologically for providing timber products and maintaining biodiversity (Pandey and Geburek 2009). In Bangladesh, with a total area of about 1,20,000 ha, the deciduous Sal forests are considered as one of the richest ecosystems with about 500 undergrowth species (Alam 2008, Alam 1995).

Sal is a major tree species in both wet and dry tropical deciduous forests in India (Champion and Seth 1968). Due to the evergreen vs deciduous dilemma, the nature of

S. robusta in terms of leaf phenology has been questioned (Troup 1921). While some researchers have classified *S. robusta* as a deciduous (Kirtikar and Basu 1975, Cooke 1958, Tiwari 1995) or semi-deciduous species (Bor 1953), others have classified it as an evergreen species (Borchert 2000, Krishnaswamy and Mathauda 1954, Singh and Singh 1992). Sal has been described as deciduous or as a transitional species between evergreen and deciduous by Joshi (1980). The lifespan of leaves is important because it represents a number of eco-physiological characteristics (Reich 1992). Evergreen species, for example, have longer leaf lifespans, deeper root systems, earlier leaf flushing during the dry season, higher stem water potential and greater ability to rehydrate the stem during the dry season, lower resource requirements to support leaf turnover and longer duration of photosynthetic activity at lower rates when compared to deciduous species (Borchert *et al.* 2002, Eamus and Prior 2001, Medina 1995, Chapin *et al.* 1996). Leaf phenology is crucial in tropical plants because it displays the influence of evolution and environment on plant traits, which has significant consequences for plant function (Reich 2004, Shankar 2001). *S. robusta* has been paradoxically described as deciduous, semi- deciduous, or evergreen species depending on the percentage of leaf fall and leaf initiation at different seasons of the year (Singh and Kushwaha 2005, Rich *et al.* 2004). Such variation in functional properties through leaf phenology has been attributed to environmental factors including soil moisture, rainfall, drought, temperature and rooting depth (van Schaik *et al.* 1993). Therefore, it is important to study the leaf phenological nature of Sal plants which is relevant for better management and conservation of deciduous Sal forests.

2.16 Nutritional Adaptation of leaf of Sal plants

Nutrients are chemicals that are required for organisms to grow effectively in any ecosystem (Costa *et al.* 2018). There are two kinds of nutrients: macronutrients and micronutrients. Macronutrients are required in relatively large amounts, while micronutrients are required in relatively small amounts (Shukla *et al.* 2014). N (Nitrogen), P (Phosphorus) and K (Potassium) are the most important macronutrients for plant growth and function.

Nitrogen is the most common mineral nutrient that is required by all living organisms for protein synthesis. It is an important component of chlorophyll and thus required for photosynthesis. Plants obtain nitrogen by absorbing nitrate or ammonium ions through their roots (Dordas and Sioulas 2008). Phosphorus is the most essential nutrient for all living organisms. Plants require P for normal growth and maturity (Lynch 2011). Foliar P concentration, like N, is related to the content of photosynthesis-related chlorophyll and carboxylation enzymes (Duursma and Marshall 2006). In plants, P is essential for respiration, energy storage and transfer, cell division, cell enlargement and a variety of other processes. According to Aerts and Chapin (2000), N:P ratios greater than 16 indicate P deficiencies, while ratios less than 14 indicate N deficiencies. Potassium is a necessary plant nutrient that must be consumed in large amounts for optimal growth and reproduction (Jones and Jacobsen 2005). It performs a number of functions in plants. K regulates the opening and closing of stomata, making it essential for photosynthesis and CO_2 uptake (Liaqat *et al.* 2022). It also has a significant impact on the regulation of water levels. K is required for Adenosine Triphosphate formation and enzyme activation. It influences plant shape, size, color and other properties.

Plants use a variety of mechanisms to adapt to their surroundings. Many factors influence plant adaptation, distribution and net primary productivity, including water and plant nutrients (Wright *et al.* 2001, Ordonez *et al.* 2009). Plant functional traits reflect how plants adapt to physical environment variation and biotic interactions. As a result, including functional traits will aid in the mechanistic understanding of plant community assembly and ecosystem functioning, which should improve predictions of the effects of environmental changes, such as disturbances and climate change, on biodiversity, species distributions and ecosystem processes (Adler *et al.* 2013, McGill *et al.* 2006).

The amount of leaf nutrients such as nitrogen (N), phosphorus (P) and potassium (K) in green leaves and old yellow leaves will help to understand the mechanism of nutrient availability during the dry period (December-January) when leaf fall starts in Sal plants and that gives an indication of leaf response to nutrient variability in the leaf falling period.

Leaves play key roles in plant function and long-term adaptation to the environment (Royer *et al.* 2008). Tree species adjust to variable micro-habitat conditions and often show different leaf strategies. Leaf strategy primarily denotes adaptations in leaf dynamics controlling the ability of a tree species to utilize resources (e.g., water, nutrients and CO_2) in relation to its ability to conserve the same (Singh and Kushwaha 2005). Plant species growing in seasonal systems commonly exhibit mechanisms to deal with extended dry periods when water is in short supply. Such adaptations consist of multiple traits at leaf and whole plant levels that reduce carbon assimilation due to a strong control of stomatal conductance (Meinzer *et al*. 1999, Prior *et al.* 2004, Franco *et al.* 2005).

The resorption of nutrients from senescing leaves is an important component of plants' nutrient conservation strategy (Milla *et al.* 2005). Nutrient absorption is greater in senescing leaves than in stems or roots. Woody plants have lower nutrient absorption from their stems and roots than non-woody plants. Deciduous plants are more efficient than evergreen plants at reabsorbing leaf nutrients prior to senescence. Furthermore, reproductive efforts have been shown to increase nutrient resorption (Brant and Chen 2015). Nitrogen resorption efficiency decreases and phosphorus resorption efficiency increases along a latitudinal gradient of terrestrial biomes as temperature and precipitation increase; however, latitudinal patterns reflect the influences of several coupling factors such as genetic variation, climate, soil and disturbance history. Experiments with nutrient fertilization have shown that increased soil fertility reduces nutrient resorption (Brant and Chen 2015). One of the conservation mechanisms in plants that can increase nutrient use efficiency is nutrient withdrawal from senescing leaves towards developing tissues or internal stores for future use (Vitousek 1982, Aerts 1996, Yuan and Chen 2015). Nutrient absorption occurs throughout the life cycle of leaf (Leopold 1961, Ackerly and Bazzaz 1995). A significant proportion usually occurs shortly before abscission (Ares and Gleason 2007, Karlsson 1997, May and Killingbeck 1992) reported that nutrient resorption from old leaves significantly contributed to plant fitness in terms of growth and reproduction in the deciduous tree *Quercus ilicifolia*. This can be expressed quantitatively as the plant's nutrient resorption efficiency or proficiency (Killingbeck 1996, Yuan *et al.* 2005). Nutrient resorption influences nutrient cycling in plants and soils and determines how old leaf nutrients are partitioned between plant internal re-cycling and soil microbial decomposition pathways (Aerts 1997). Nutrient resorption prolongs nutrient residence time in plants while also influencing litter decomposition, soil nutrient availability, nutrient uptake, plant competition and overall resource use efficiency (Vitousek 1982, Garkoti and Singh 1994, Aerts and Chapin 2000, Escudero and Mediavilla 2003, McGroody *et al.* 2004, Hikosaka 2005, Ares and Gleason 2007). Nutrient levels in senesced leaves, or nutrient resorption proficiency, differ between species, ecosystems and soil fertility levels (Killingbeck 1996, Yuan and Chen 2015). According to Killingbeck (1996), there is a minimum level of nutrient reduction that species can achieve in their senescing leaves. Therefore, the study of leaf traits on the basis of nutrient availability in green leaves and yellow leaves was relevant to enhancing knowledge about the adaptation mechanisms of leaf nutrients of Sal plants.

CHAPTER 3

MATERIALS AND METHODS

3.1 Effects of forest management on regeneration of Sal plants

3.1.1 Study of regeneration through vegetation survey

3.1.1.1 Geographical location of the study sites

Two different sites namely the Core zone and the Buffer zone in the Madhupur Sal forest under Madhupur subdistrict (Upazilla) of Tangail district were selected in the present study. The Core zone and the Buffer zone were selected from Rasulpur and Jangalia areas, respectively. Each 3 permanent plots from the Core zone and Buffer zone of the Madhupur Sal forest were selected with a minimum distance of 50 m from each plot. A total of each 12 quadrats from the Core zone and Buffer zone were selected in four seasons namely Spring, Summer, Autumn and Winter of the year. The study was carried out from 2018 to 2019.

The selected sampling quadrats of the Core zone located in Rasulpur were distributed between 24.690125°–24.690510°N latitude and 90.132363°–90.133745°E longitude. The selected sampling quadrats of the Buffer zone located in Jangalia were distributed between 24.642357°–24.643105°N latitude and 90.081972°–90.082127°E longitude (Table 3.1).

Table 3.1 Geographical location of the permanent plots of the Core zone in Rasulpur and Buffer zone in Jangalia of Madhupur Sal forest for seasonal study.

Plots	Core zone (Rasulpur)		Buffer zone (Jangalia)	
	Latitude (°N)	Longitude (°E)	Latitude (°N)	Longitude (°E)
1	24.690125°N	90.133745°E	24.643105°N	90.082127°E
2	24.690502°N	90.133182°E	24.642785°N	90.082107°E
3	24.690510°N	90.132363°E	24.642357°N	90.081972°E

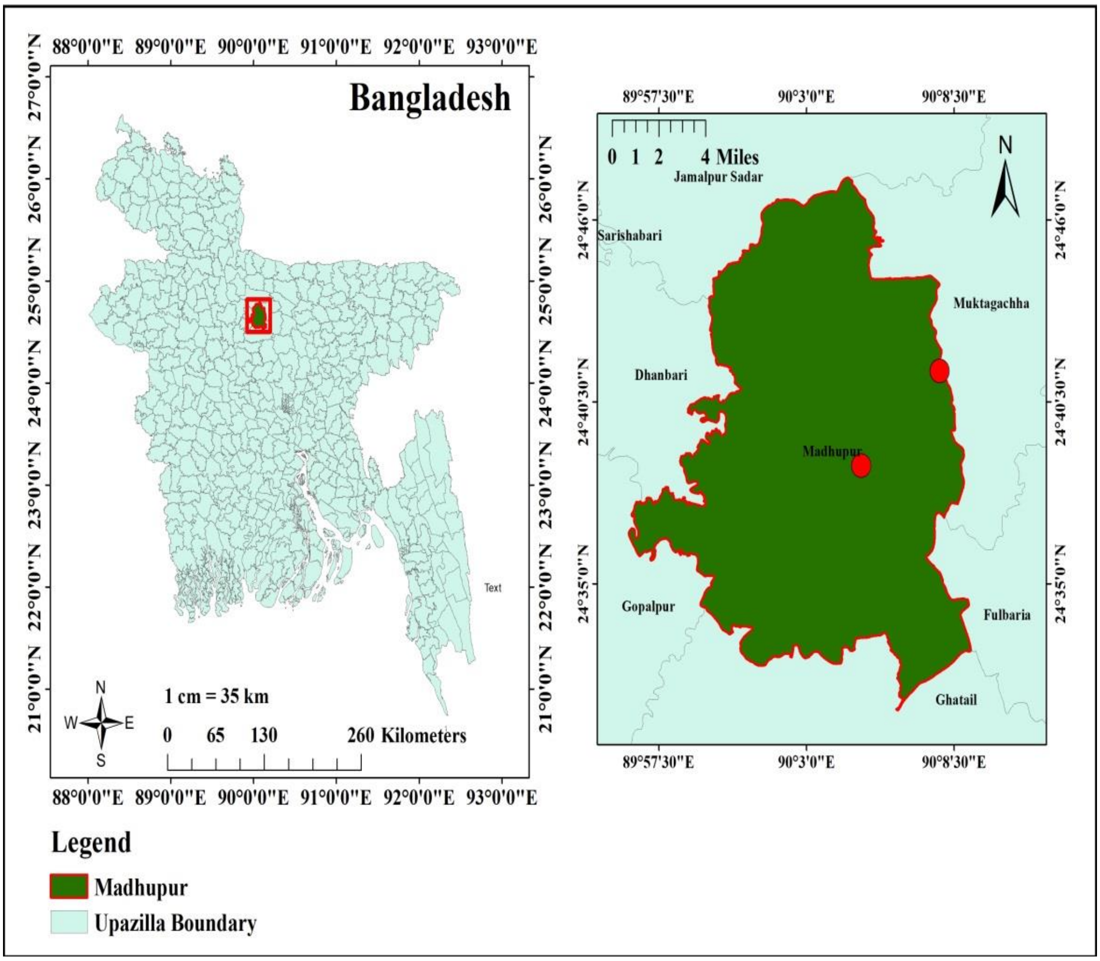

Figure 3.1: GIS (Geographic Information System) map showing the geographical location of the study sites.

3.1.1.2 Climatic condition of the study sites

Rainfall

The climatic conditions are relatively uniform over the deciduous Madhupur Sal forest area. Rainfall is not evenly distributed throughout the year in this Sal forest area. The annual average rainfall during the last decade (2011–2020) was 1649 mm in this Sal forest area (www.worldweatheronline.com). The maximum rainfall occurs from April to October and from November to March, rainfall is almost zero. At least 80% of the rainfall occurs from May to October (rainy season) and the remaining amount of rainfall occurs mostly from March to April. The maximum monthly average rainfall of 313.17 mm was seen in July and the minimum monthly average rainfall of 3.4 mm was seen in January in the Madhupur Sal forest area (during 2011-2020). In the studied year 2019, the average yearly rainfall was 1643 mm and in 2020, the average yearly rainfall was 2557 mm over the forest area. The maximum monthly average rainfall of 311.2 mm was seen in July, 2019, but the maximum monthly average rainfall of 595.5 mm was seen in June, 2020. The minimum monthly average rainfall of 0.7 mm was seen in December of 2019, but the minimum monthly average rainfall of 0 mm was seen in December, 2020 (www.worldweatheronline.com).

Temperature

The annual average temperature during the last decade (2011–2020) was 28.63°C in the Madhupur Sal forest area (www.worldweatheronline.com). The maximum monthly average temperature of 32.6°C was seen in May and the minimum monthly average temperature of 22.1°C was found in January over the forest area (2011-2020) (www.worldweatheronline.com). In the study year 2019, the yearly average temperature was 29°C and in 2020, the average yearly temperature was 28.25°C in this forest area (www.worldweatheronline.com). A maximum monthly average temperature of 34°C was seen in May of 2019, but a maximum average temperature of 32°C was seen in April and May of 2020. A minimum average temperature of 23°C was seen in December, 2019, but a minimum average temperature of 21°C was seen in January 2020 over the Madhupur Sal forest area (www.worldweatheronline.com).

Humidity

The annual average humidity during the last decade (2011-2020) was 64% in the Madhupur Sal forest area (www.worldweatheronline.com). The maximum monthly average humidity of 80.1% was seen in July and the minimum monthly average humidity of 42.8% was seen in February over the forest area during 2011-2020). In the studied year 2019, the yearly average humidity was 63% and in 2020, the average yearly humidity was 64.2% in this forest area. The maximum average humidity of 78% was seen in July and September 2019, but the maximum average humidity of 81% was seen in July 2020. The minimum monthly average humidity of 43% was seen in March 2019, but the minimum monthly average humidity of 44% was seen in March 2020 over the Madhupur Sal forest area (www.worldweatheronline.com).

Table 3.2 Average temperature, precipitation and humidity of the study site at different months and seasons of the study period (www.worldweatheronline.com).

Month	Year	Temp. (°C)	Rainfall (mm)	Humidity (%)	Seasons	Average Temp. (°C)	Average Rainfall (mm)	Average humidity (%)
Mar.	2018	31	21.83	41	Spring	31.67	150.61	54.33
Apr.	2018	32	159.5	55				
May	2018	32	270.4	67				
Jun.	2018	33	226.38	70	Summer	32.00	248	75.00
Jul.	2018	31	265	75				
Aug.	2018	32	252.9	74				
Sep.	2018	31	131.31	70	Autumn	29.00	54.4	63.33
Oct.	2018	29	28.1	64				
Nov.	2018	27	3.8	56				
Dec.	2018	23	35.4	55	Winter	24.00	16	49.33
Jan.	2019	24	1.1	47				
Feb.	2019	25	11.5	46				

3.1.1.3 Vegetation of the study sites

Some studies report that 70%–75% of the trees are Sal (*Shorea robusta*) in the Madhupur Sal forest (Malakar *et al.* 2010). A total of 174 plant species were recorded under 131 genera and 54 families in Madhupur Sal forest and of these species, about 102 species are trees, 17 species are shrubs, 34 species are herbs and 21 species are climbers (Malakar *et al.* 2010). Some species have been planted artificially and *S. robusta* is the most dominant tree species all over the forest area (Hossain *et al.* 2010, Kashem *et al.* 2015). Vegetation of the Madhupur Sal forest show seasonal variation were shown in (Figures 3.2 - 3.5).

Figure 3.2: Photo of Madhupur Sal forest taken during Spring season of the year 2018.

Figure 3.3: Photo of Madhupur Sal forest taken during Summer season of the year 2018.

Figure 3.4: Photo of Madhupur Sal forest taken during Autumn season of the year 2018.

Figure 3.5: Photo of Madhupur Sal forest taken during Winter season of the year 2019.

3.1.1.4. Soil properties of the study sites

The soil of the Madhupur Sal forest is reddish-brown in color throughout the forest area. The soil of this forest is acidic in nature and the pH range is from 5.2 to 5.5 (Dhar and Mridha 2006). In the forest area, the texture of the soil is generally sandy loam, though somewhere it is silty loam. The soil is compact and hard in dry conditions, but it melts with the rainfall and becomes soft. The organic matter content in surface soil ranges is low (<1.5%) under grassland and it is moderate (2-5%) under forest cover (Coppin *et al.* 2004). This soil contains concretionary mottlings or indurated concretions in the subsoil and substratum (Banglapedia 2010). The Sal forest areas which consist of high lands are locally called "Chala" and relatively low land areas are called "baid". Local people cultivate agricultural crops, especially paddy in some low-land areas of the Sal forest. The Chalas, containing forests, are inextricably mixed up with homesteads and cultivations (Rahman 2003). The soil of the forest land contains all the necessary nutrients like Mg, Fe, Na, Cl, K, N, P and so on which are essential for the growth of plants (Hossain *et al.* 2010, Kashem *et al.* 2015).

3.1.1.5 Topographic condition of the study sites

Different topographies are found in the Madhupur Sal forest. The area consists of plain land, plain lowland, cultivated land and forest land. Two tribal peoples, the *Koch* and the *Mande*, live in the Madhupur Tract, whose livelihood depends on forest resources. The altitude of the Madhupur Sal forest is about 20 m above the mean sea level (Khan and Ahsan 2011).

3.1.1.6 Vegetation survey by using quadrats

Twenty four quadrats each 12 in the Core zone and Buffer zone, were laid down at 50 m intervals in 4 different seasons, namely Spring, Summer, Autumn and Winter. The number of plants was counted within each quadrat. A 10 × 10 m^2 quadrate was placed in each location of the Core zone and Buffer zone of the Madhupur Sal forest to count plants and collect soil samples. In total, 24 quadrats of two study zones were established. Within each plot, data were sampled on smaller plots fixed in the field. The quadrat size, such as 10 m × 10 m for trees, 5 m × 5 m for shrubs and 2 m × 2 m for herb species, were laid down (Fig. 3.6).

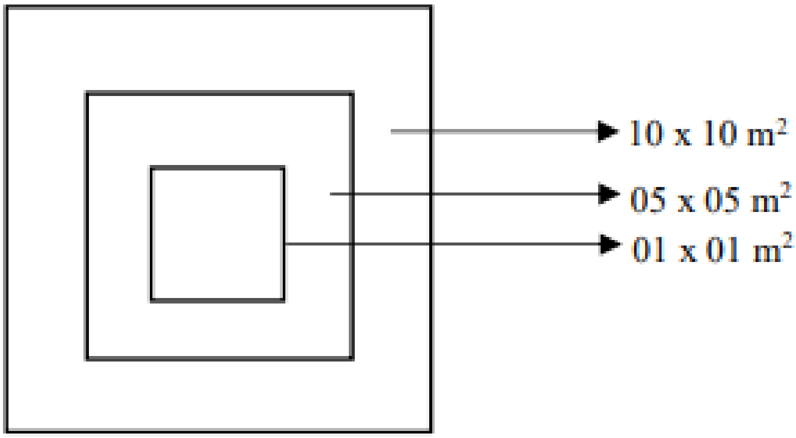

Figure 3.6: A sample plot

To understand the regeneration pattern of *S robusta*, the population structure was investigated based on girth classes, including seedlings and saplings. The total number of individuals belonging to these girth classes was calculated. This database is further used to determine the trend of establishment and growth of *S. robusta*. Then, individuals with a height of more than 200 cm were identified at the species level and their DBH (diameter at breast height) was measured. Based on the height of each individual, tree species were grouped into seedlings (individuals with a height of between 0 cm and 10 cm), saplings (individuals with a height of between 10 cm and 200 cm) and trees (individuals with a height of more than 200 cm).

Table 3.3 Girth classes based on the DBH (diameter at breast height) of Sal plants (Ralhan *et al*. 1982).

Girth class	Range of DBH (cm)
A	0-10 (seedlings)
B	>10-20 (saplings)
C	>20-40
D	>40-60
E	>60-80
F	>80-100
G	>100-120
H	>120-140
I	>140-160
J	>160-180 and above

3.1.1.7 Phytosociological analysis

The Importance Value Index (IVI) was measured to know the dominance of the species on the basis of relative frequency, relative abundance and relative density. The relative values of frequency, abundance and density for each single species were used to calculate IVI per plot according to the following formula:

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

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

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

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

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

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

Importance Value Index (IVI) = Relative Frequency + Relative Abundance + Relative Density.

3.1.2 Study of regeneration by growing Sal plants in the field condition

3.1.2.1 Selection of sites for growing Sal plants

The Madhupur Sal forest was selected to understand the regeneration mechanisms through seed germination of Sal plants and to compare the regeneration status of Sal plants between disturbed area of the Buffer zone and relatively undisturbed area of the Core zone in the Madhupur Sal forest. The study was carried out from June 2020 to May 2021. In the Madhupur Sal forest, the Core zone and Buffer zone were selected from Rasulpur and Jangalia, respectively. Eeach 3 plots from the Core zone and the Buffer zone of the Madhupur Sal forest were selected, with a minimum distance of 50 m from each plot. The size of each plot was 4m x 4m.

3.1.2.2 Collection of Sal Seeds

Seeds of Sal plants were collected on June 15th, 2020 from Madhupur Sal forest. Sal seeds lose their viability within nearly about 7 days after falling from trees. Seeds were, therefore, collected immediately after seed fall occurred. Seeds were collected from the selected Sal trees and the old fallen seeds were removed from the collected seeds.

3.1.2.3 Sowing seed

Seeds were sown in the plots one day later after collection from the field and a total of 100 seeds were sown in each plot. In total, 600 seeds were sown in 6 plots. The place where seeds were sown was marked with bamboo sticks so that it was possible to monitor the status of the germination of the seeds.

3.1.2.4 Data collection

Data on seed germination and the growth of seedlings and saplings was collected periodically from both the Core and Buffer zones. Data collection started after 30 days of sowing seeds in the plots. The survival rate and growth rate of the germinated seeds and seedlings were noted. The survival rate and growth rate of the germinated seedlings were studied every month during the study period. Soil moisture content was also measured during the study period.

3.1.2.5 Statistical analysis

Two-way ANOVA was performed in order to examine the effects of forest management (Core zone vs Buffer zone), seasons and their interactions on the vegetation structure and regeneration status of Sal plants. The JMP 4.0 software (SAS Institute, Carry, NC, USA) was used to analyze the data.

3.2 Study of leaf phenology of Sal

3.2.1 Study of leaf phenology of Sal by leaf counting

3.2.1.1 Study site description

Two different sites those were different in geographical and climatic conditions in Bangladesh were selected for this study. These were the Madhupur Sal forest under

Tangail district and the Charkai Sal forest under Dinajpur district. The studied plot of Madhupur Sal forest was near to the Charaljani Forest Research Center in Baribaid mouza of Baribaid union council under Madhupur Sub-district. The other plot of Charkai Sal forest was near to the Charkai Forest Research Center in Debipur mouza of Khanpur union council under Birahmpur sub-district. This study was carried out from January of 2019 to July of 2021.

The selected sampling plot of the Charaljani Forest Research Center was at 24.631°N latitude, 90.060°E longitude and another selected sampling plot of the Charkai Forest Research Center was at 25.420°N latitude, 88.999°E longitude (Figure 3.7).

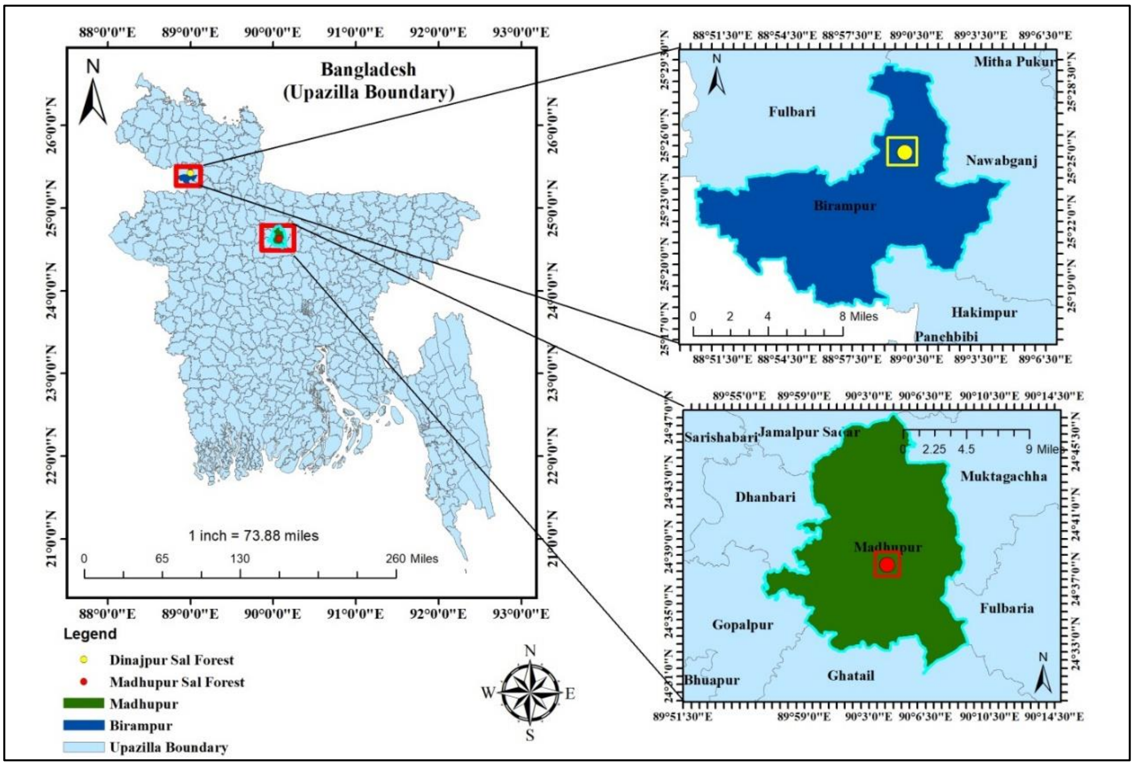

Figure 3.7: Map showing the location of the two study sites located in the Madhupur Sal forest, Tangail and the Charkai Sal forest, Dinajpur**.**

Madhupur Sal forest

Sections 3.1.1.1 to 3.1.1.5 have already discussed about the Madhupur Sal forest.

Charkai Sal forest

Charkai Sal forest is situated in Khanpur union of Birampur upazila under Dinajpur district. The total area of this forest is 191.15 acres and this forest area is under three mouzas. The names of these three mouzas are Sundulpur, Debipur and Dhanjuri-Khalishahor. Among the 191.15 acres, 73 acres are under the Dhanjuri-Khalishahor mouza, 55 acres are under the Sundulpur mouza and the remaining area is under the Debipur mouza. The Charkai Sal forest is located approximately 57 kilometers away from Dinajpur district town. The office of the Bangladesh Forest Research Institute is situated in this forest, namely the Charkai Forest Research Center. The East Pakistan Forest Department handed over the total land area of this forest to the East Pakistan Forest Research Laboratory in 1968 (Source: BFRI). Seasonal variation in leaf phenology is shown in Figure3.8.

Figure 3.8: Photographs showing the leaf condition of the selected Sal trees during Spring (a), Summer (b), Autumn (c) and Winter (d).

3.2.1.2 Climatic condition of Charkai Sal forest

Rainfall

The climatic conditions are relatively uniform over the deciduous Charkai Sal forest area. Rainfall is not evenly distributed throughout the year in this Sal forest area. The annual average rainfall of the last decade (2011-2020) is 1314 mm in this Sal forest area (www.worldweatheronline.com). The maximum rainfall occurs from April to October and rainfall is almost zero from November to March. At least 80% of the rainfall occurs from June to October (rainy season) and the remaining amount of rainfall occurs mostly from March to May. The maximum monthly average rainfall of 269 mm was seen in September and the minimum monthly average rainfall of 1.5 mm was seen in December in the Charkai Sal forest area (2011-2020). In the study year 2019, the average yearly rainfall was 1387 mm and in 2020, the average yearly rainfall was 2181 mm of this forest area. The maximum monthly average rainfall of 427.7 mm was seen in July of 2019, but the maximum monthly average rainfall of 591.4 mm was seen in June of 2020. The minimum monthly average rainfall of 0.3 mm was seen in December of 2019, while that of 0 mm was seen in December of 2020 (www.worldweatheronline.com).

Temperature

The annual average temperature of the last decade (2011–2020) was 28.9°C in this Sal forest area (www.worldweatheronline.com). The maximum monthly average temperature of 32.5°C was seen from May to June and the minimum monthly average temperature of 22.1°C was seen in January over the forest area (2011-2020). In 2019, the yearly average temperature was 28.5°C and in 2020, the yearly average temperature was 28.42°C in the forest area. A maximum monthly average temperature of 33°C was seen in June, 2019, but a maximum monthly average temperature of 32°C was seen in April and May, 2020. The minimum monthly average temperature of 23°C was seen from December to January of 2019, but the minimum average temperature of 21°C was seen in January, 2020 over the Charkai Sal forest area (www.worldweatheronline.com).

Humidity

The annual average humidity during the last decade (2011–2020) was 61% in the Charkai Sal forest area (www.worldweatheronline.com). The maximum monthly average humidity of 78.4% was seen in September and the minimum monthly average humidity of 34.5% was seen in March over the forest area during 2011-2020. In 2019, the yearly average humidity was 61.25% and in 2020, that was 59.5% in this forest area. The maximum monthly average humidity 78% was seen in September, 2019, but the maximum average humidity 82% was seen in September 2020. The minimum monthly average humidity 36% was seen in March 2019, but the minimum monthly average humidity of 34% was seen in March 2020 over the Charkai Sal forest area (www.worldweatheronline.com).

3.2.1.3 Vegetation of Charkai Sal forest

Though Sal is the single most important tree species in this forest, many undergrowth species have been seen in association with Sal. The special type of microclimate prevailing in the Sal forest ecosystem, with a relatively higher mean annual temperature and greater rainfall, particularly during the rainy season, facilitates the rich association of undergrowth diversity in this forest type. Many plant species have been planted in this Sal forest in recent years. Important planted species are Palm oil, Agar, Lombu, Akashmoni, Jali bet, Khoier, Babla, Chapalish, Cevit, Loha kath and Nalita.

3.2.1.4 Soil properties of Charkai Sal forest

The soil of this forest is reddish in color and the soil becomes muddy in the rain and becomes hard in the sun. In the dry season, the soil of this forest becomes much harder. The pH range is 6.5-7 of the soil in the forest, which is acidic in nature (Jake *et al.* 2020).

3.2.1.5 Topographic condition of Charkai Sal forest

Different topographies are found in the Charkai Sal forest. The forest area consists of plain land, plain low-land, cultivated land, forest land and habitats. The altitude of the Charkai Sal forest is about 20 m above the mean sea level. One tribal people namely Santal lives in the Charkai Sal forest, which was a small part of its livelihood depends on the forest. About 2500 Santal people and 3000 migrated Bengali Muslim people live in the forest (BFRI).

3.2.1.6 Selection of Sal plants for counting leaves

Fully matured Sal plants with a minimum of 30 cm of DBH (Diameter at Breast Height) were selected in both the two forests in order to count the number of leaves per twig. Ten Sal plants were chosen in each of the two selected Sal forests for counting leaves.

3.2.1.7 Methods of counting leaves

Ten mature trees (> 30 cm DBH) were selected in each of the two selected Sal forests. Then, four well-illuminated twigs per plant were chosen. Selected trees and twigs were numbered and marked with metal tags and colors (Figure 3.9). Recently-growing shoots of last-order branches were selected for counting leaves. Leaf initiation, leaf flushing, leaf maturation and leaf falling were studied by observing color and counting the number of leaves per twig. Leaves were studied every month from January 2019 to July 2021.

Figure 3.9: Photos showing the procedure for leaf counting in the selected Sal plants of the study sites.

3.2.1.8: Leaf collection

Fully expanded mature leaves were collected from the selected Sal plants in the polythene bags in airtight condition. Six leaves from each plant were selected randomly for the analysis of functional traits (Figure 3.10-11). Thus, a total of 120 (6 leaves × 10 plants × 2 forests) leaves were studied in this study.

3.2.1.9 Determination of leaf traits

Measurement of leaf length

ImageJ Ver: k 1.45 software was used to determine the length of the leaves. Six fresh leaves of each plant from the selected Sal plants were randomly picked from the leaf samples. Then, using a ruler, leaves were put across a plain glass sheet. A camera (Canon EOS 1500D) was used to capture the image of the leaves. This allowed for the collection of a single photograph of each of the six leaves for each sample. The leaf length of each image was then measured using the software ImageJ. ImageJ opened the captured image. The scale was then set in centimeters (cm) from the “analyze” menu using the width tool from the scale bar. The color image was then converted to grayscale (8 bits) using the image menu. To acquire the red leaf image, the image was adjusted in the threshold. The wand tool was used to select the red leaf image and the image data was then added to the ROI manager window from the analyze menu. Then, by clicking on the Measure box, the result was analyzed.

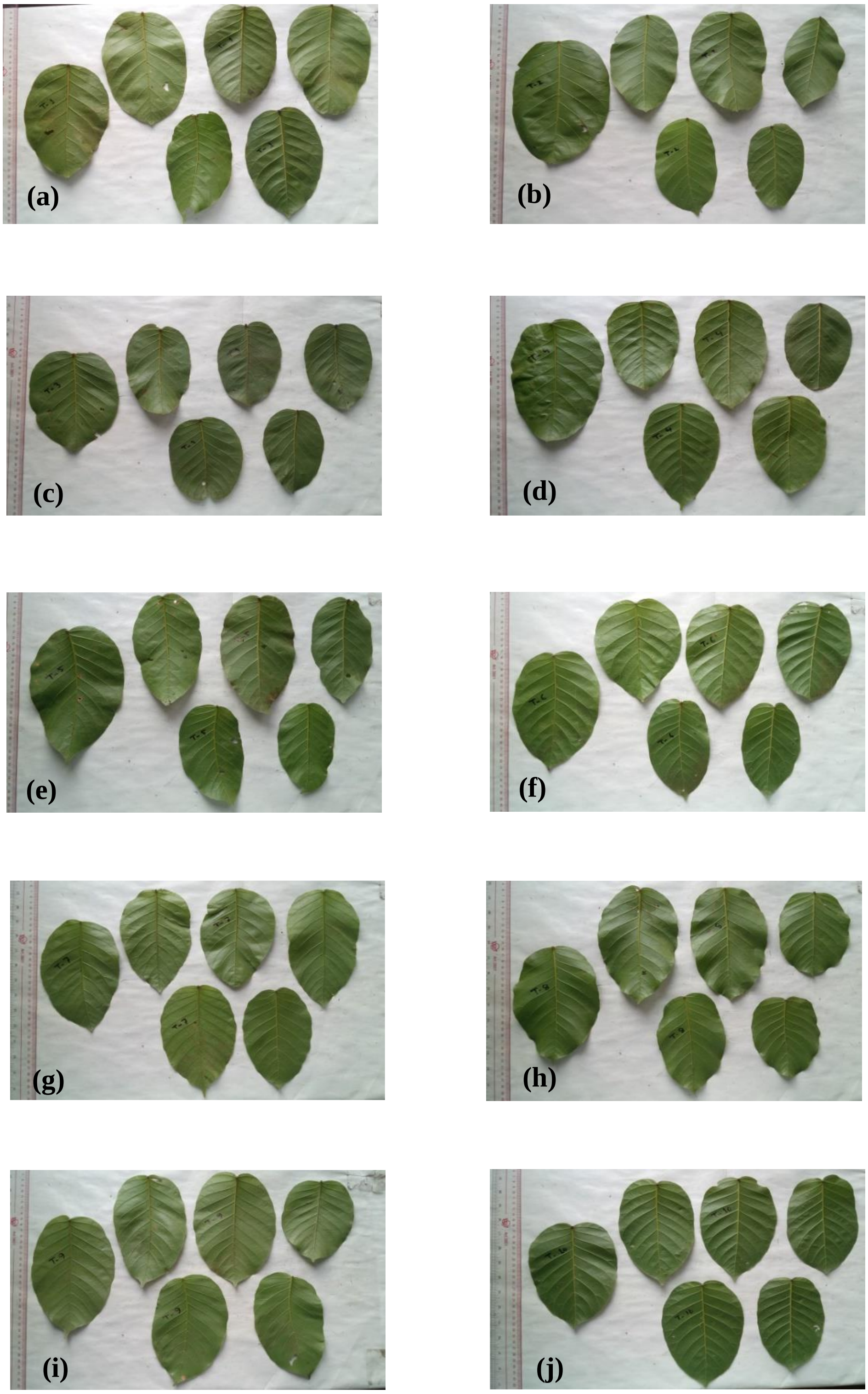

Figure 3.10: Images of mature leaves of the ten selected Sal plants of Madhupur Sal forest collected for the study of leaf traits (a-j).

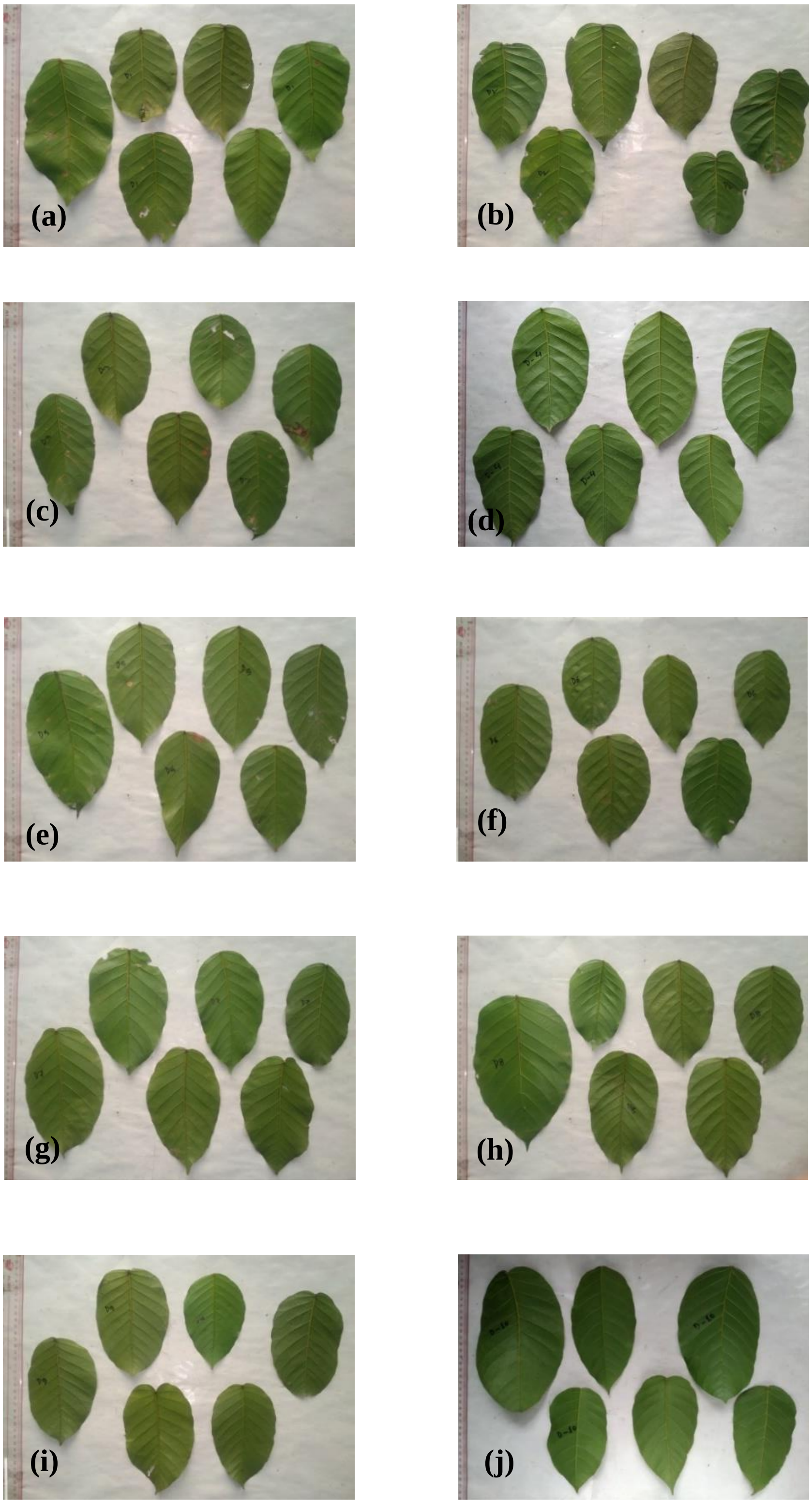

Figure 3.11: Images of mature leaves of the ten selected Sal plants of Charkai Sal forest collected for the study of leaf traits (a-j).

Determination of leaf breadth

After the measurement of the leaf length, the leaf breadth was measured. Leaf breadth was measured using the same software ImageJ Ver: k 1.45 in similar method from the same image which was used for measuring leaf length. Measurements were expressed in cm.

Determination of leaf perimeter

After the measurement of leaf length and leaf breadth, the leaf perimeter was measured using the same software ImageJ Ver: k 1.45 in similar method from the same image. The unit of the leaf perimeter was in cm.

Determination of Leaf Area

The same image and software (ImageJ Ver: k 1.45) were used for the determination of leaf area. The unit of leaf area was expressed in cm^2.

Leaf breadth, leaf perimeter and leaf area were analyzed in the same way that was already explained in the previous section "Measurement of leaf length."

Determination of fresh weight, turgid weight and dry weight

Fresh weight, turgid weight and dry weight were determined following the standard protocol as designed elsewhere (Akter *et al*. 2021).

Determination of Specific Leaf Area

The one-sided area of a fresh leaf, divided by its oven-dry mass, is known as the "Specific Leaf Area" (SLA). The particular leaf area is determined by measuring the leaf area as previously mentioned. It was calculated by dividing the leaf area of the measured leaves by their dry mass. The following formula was used to determine SLA:

$$\mathrm{SLA} = \frac{\text{Leaf area}}{\text{Leaf dry weight}}$$

Determination of Relative Water Content

A total of six leaves were weighed. To prevent evaporation, the leaves were covered immediately. The fresh weight was calculated using the weight of the leaves. The leaves were then immersed in deionized water overnight to keep the samples away from physiological activity through physical growth and respiration suppression. The leaves were wiped using tissue paper after 24 hours and their reweight was taken. This weight was a turgid weight. After that, the leaves were kept in the oven for 24 hours at 80 degrees Celsius. The dry weight was taken after 24 hours. The following formula is used to determine RWC:

$$\mathrm{RWC} = \frac{\mathrm{FW-DW}}{\mathrm{TW-DW}}$$

Where,

FW=Fresh Weight

TW=Turgid Weight

DW=Dry Weight

Determination of Leaf Dry Matter Content

To determine the leaf dry matter content (LDMC), the fresh weight of leaves was taken. After that, the leaves were kept at 80 degrees Celsius in an oven for 24 hours. The dried weight of the leaf was divided by the fresh weight of the leaf. The following formula was used to determine LDMC:

$$\mathrm{LDMC} = \frac{\mathrm{DW}}{\mathrm{FW}}$$

Determination of Leaf Water Content

Leaf water content (LWC) per unit area was determined as leaf fresh weight minus dry weight, divided by leaf area. The following formula is used to determine LWC:

$$\mathrm{LWC} = \frac{\mathrm{FW-DW}}{\mathrm{Leaf\ Area}}$$

Determination of leaf chlorophyll content

Leaf chlorophyll content was measured by a chlorophyll meter (SPAD-502Plus, Konica, Minolta, Japan). This machine gives the relative chlorophyll content of leaf. In order to determine the chlorophyll content of leaves, 6 fully expanded mature leaves were selected per plant. Then, each chlorophyll content was measured for each leaf. After that, the average chlorophyll content of six leaves was taken. The machine was calibrated before measuring.

Study of stomata by following impression technique

Leaf was gently spread over a plain field of glass sheet. A thick swath of clear nail polish was painted on the ventral side of the leaf. After the nail polish had dried, the peel of the nail polish swath was taken away gently from the leaf completely. A cloudy impression of the leaf surface attached to the nail polish was found. One drop of glycerin was put on and then the leaf impression was kept on a clean slide, covered with a cover slip and observed under a microscope. A photograph of the field of leaves under the microscope (Axio Lab. A1 Microscope, Carl Zeiss Microscopy GmbH, Germany) was taken. In each image, stomatal length (µm) was taken for each of six randomly selected leaves.

Measurement of stomata length

The length of the stomata was measured using ImageJ Ver: k 1.45 software. The captured image was opened by ImageJ. After that, the scale bar scale was set by the line width tool in micrometer (µm) from the "analyze" menu. The selected line data was added in the ROI manager window from the analyze menu. Then, the result was analyzed by clicking on the Measure box.

Measurement of stomata breadth

The breadth of the stomata was measured using ImageJ Ver: k 1.45 software. Measurements were expressed in micrometer (µm).

Measurement of stomatal density

For the measurement of stomatal density (number mm^{-2}), the number of stomata

per unit area (mm^{-2}) was counted from the images at a magnification of 10 × 40 and visual field area = (32×22) sq. µm. Stomatal density was calculated by the following formula:

Area of FOV (Field of View) = πr^2

Stomatal density = number of stomata in entire FOV / area (mm^2)

Determination of Stomatal Pore Index

Stomatal Pore Index is an integrative metric that reflects leaf stomatal conductance by combining stomatal density and stomatal length. SPI increases stomatal conductance and photosynthetic capacity in the leaves. The following formula was used to determine the SPI (percentage):

$$\text{SPI} = \text{Stomatal density} \times \text{Stomatal length}^2 \times 10^{-4}$$

3.2.1.10 Analysis of soil sample

Soil was collected from 0-10 cm depth using augur (Figure 3.12). Air tight polythene bags were used to collect and preserve soil. Soil was analyzed immediately after collection from the field.

Figure 3.12: Photos showing the procedure of soil collection.

Determination of soil pH

The pH of the soil was measured in the laboratory within 24 hours of its collection from the field. The pH of the soil was measured in suspension with distilled water (2:1, v: w). In a beaker, ten grams of soil was placed and 25 ml of distilled water was added to produce a suspension by shaking well. The suspension was held for a while to allow the particles to settle. The pH meter (Hanna pH meter, pHeP) was calibrated with a known pH. Then, the pH values were recorded for each of the soil samples.

Determination of soil electrical conductivity

Soil electrical conductivity was measured in the lab 24 hours after it was collected from the field. The conductivity of the soil was measured in suspension with distilled water (5:1, v: w). In a beaker, ten grams of soil was placed and 50 milliliters of distilled water was added to produce a suspension by shaking well. The suspension was kept for a while to allow the particles to settle. The conductivity meter was calibrated with a known conductivity. Then, the conductivity values were recorded for each of the soil samples.

Determination of soil moisture content

For the purpose of determining soil moisture content, 10 g of fresh soil was placed in an aluminum foil cup and placed in an oven at 80 °C for 24 hours. The following formula was used to calculate the moisture content of the soil:

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

Where,

F= Weight of fresh soil

D= Weight of dry soil

3.2.2 Effects of soil moisture on the deciduousness of Sal plants

3.2.2.1 Seed collection

Seeds of Sal plants were collected on June 15th, 2019 from the Madhupur Sal forest. After collection from the forest floor, the seeds were kept in jute bags and then brought to the laboratory.

3.2.2.2 Seedbed preparation

The seedbed was prepared at the Charaljani Forest Research Centre, Madhupur. The polybag (18 cm × 13 cm) was filled with 800 g of forest soil amended with 20% organic fertilizer and 1% DAP (diammonium phosphate). One seed per polybag was sown for germination (Figure 3.13). Seeds were kept for germination in the seedbed of the Charaljani Forest Research Centre, Tangail. Eight-month-old saplings were transferred to the Botanical Garden, Department of Botany, University of Dhaka.

Figure 3.13: Photos showing the seedlings of Sal plants grown in the seed bed.

3.2.2.3 Preparation of experimental pots

Experimental pots were prepared at the Botanical Garden, Department of Botany, University of Dhaka. A total of 45 clay-made pots (15 inches in diameter) were taken (Figure 3.14). Each pot was filled with 9 kg of soil, leaving a space of 1.5 inches on the top side of the pot for watering. No organic or chemical fertilizers were added to the soil. One Salsapling was planted in each pot.

Figure 3.14: Photos showing the experimental pot with soil and seedlings of Sal plants.

3.2.2.4 Setting of experimental pots under treatments

Pots were placed under a tent made of transparent polythene paper (Figure 3.15). All 45 pots with planted Sal saplings were grouped into 3 for the application of water treatments: 1.5 litters of water was applied to the plots after 3, 5 and 7-days of intervals. Saplings were planted in March 2020 and data collection was done from April 2020 to July 2021.

Figure 3.15: Photo showing the experimental pots with seedlings under tent.

3.2.2.5 Data collection

Leaf initiation, leaf flushing, leaf maturation and leaf falling were studied by observing color and counting the number of leaves per plant. The number of total leaves, including old and new leaves, was counted every month. Sapling height and branch number, as well as morphological, physiological and anatomical traits of leaves, were investigated. Soil moisture content, pH and electrical conductivity were also measured every month. The temperature, humidity and light intensity of the experimental site were measured for 12 months. Data was collected within the first week of every month.

3.2.2.6 Methods of Leaf counting

Leaf initiation, leaf flushing, leaf maturation and leaf falling were studied by observing color and counting the number of leaves per plant. The number of total leaves, old leaves and new leaves were counted every month from April 2020 to July 2021.

3.2.2.7 Determination of leaf traits

Fully expanded mature leaves were collected from the randomly selected four Sal plants of each three groups in the polythene bags in air-tight condition. Five leaves per plant were selected randomly. Then, five leaves from each plant were analyzed for functional traits. Thus, a total of 60 (5 leaves × 4 plants × 3 groups) leaves were studied during this study.

Measurement of leaf length

ImageJ Ver: k 1.45 software was used to determine the length of the leaves. Five fresh leaves of each plant from the selected Sal plants were randomly picked from the leaf samples. Then, using a ruler, 5 fresh leaves were put across a plain glass sheet. A camera was used to capture the image of the leaves (Canon EOS 1500D). This allowed for the collection of a single photograph of each of the six leaves for each sample. The leaf length of each image was then measured using the software ImageJ. ImageJ opened the captured image. The scale was then set in centimeters (cm) from the “analyze” menu using the width tool from the scale bar. The color image was then converted to grayscale (8 bits) using the image menu. To acquire the red leaf image, the image was adjusted in the threshold. The wand tool was used to select the red leaf image and the image data was then added to the ROI manager window from the “analyze” menu. Then, by clicking on the Measure box, the result was analyzed.

Determination of leaf breadth

After the measurement of leaf length, the leaf breadth was measured. Leaf breadth was measured using the same software ImageJ Ver: k 1.45 in similar method from the same image which was used for measuring leaf length. Measurements were expressed in cm.

Determination of leaf perimeter

After the measurement of leaf length and leaf breadth, the leaf perimeter was measured using the same software ImageJ Ver: k 1.45 in similar method from the same image. The unit of the leaf perimeter was in cm.

Determination of Leaf Area

Same image and the same software ImageJ Ver: k 1.45 were used for the determination of leaf area. The unit of leaf area was used in cm^2.

Leaf breadth, leaf perimeter and leaf area were analyzed by the same way that was already described in a previous section “Measurement of leaf length”.

Determination of fresh weight, turgid weight and dry weight

Fresh weight, turgid weight and dry weight were determined following the standard protocol.

Determination of Specific Leaf Area

The one-sided area of a fresh leaf, divided by its oven-dry mass, is known as the Specific Leaf Area (SLA). The particular leaf area is determined by measuring the leaf area as previously mentioned. It was calculated by dividing the leaf area of the measured leaves by their dry mass. The following formula is used to determine SLA:

$$\text{SLA} = \frac{\text{Leaf area}}{\text{Leaf dry weight}}$$

Determination of Relative Water Content

A total of five leaves were weighed. To prevent evaporation, the leaves were covered immediately. The fresh weight was calculated using the weight of the leaves. The leaves were then immersed in deionized water overnight to keep the samples away from physiological activity through physical growth and respiration suppression. The leaves were wiped using tissue paper after 24 hours and their reweight was taken. This weight was a turgid weight. After that, the leaves were kept in the oven for 24 hours at 80 degrees Celsius. The dry weight was taken after 24 hours. The following formula was used to determine RWC:

$$\text{RWC} = \frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}}$$

Where,

FW=Fresh Weight

TW=Turgid weight

DW=Dry weight

Determination of Leaf Dry Matter Content

To determine the leaf dry matter content (LDMC), the fresh weight of five leaves was taken. After that, the leaves were kept at 80 degrees Celsius in an oven for 24 hours and dry weight of five leaves was taken. The dried weight of the leaf was divided by the fresh mass of the leaf. The following formula was used to determine LDMC:

$$\text{LDMC} = \frac{\text{DW}}{\text{FW}}$$

Where,

FW=Fresh Weight

DW=Dry weight

Determination of Leaf Water Content

Leaf water content (LWC) per unit area was determined as leaf fresh mass minus dry mass, divided by leaf area. The following formula is used to determine LWC:

$$\mathrm{LWC} = \frac{\mathrm{FW-DW}}{\mathrm{Leaf\ Area}}$$

Where,

FW=Fresh Weight

DW=Dry weight

Determination of leaf chlorophyll content

Leaf chlorophyll content was measured by a chlorophyll meter (SPAD-502Plus, Konica, Minolta, Japan) (Figure 3.16). This machine gives the relative chlorophyll content of leaf. In order to determine the chlorophyll content of leaves, 5 fully expanded mature leaves were selected per plant. Then, chlorophyll content was measured for each plant. After that, the average chlorophyll content of 5 leaves was taken (Figure 3.17). The machine was calibrated before measurement.

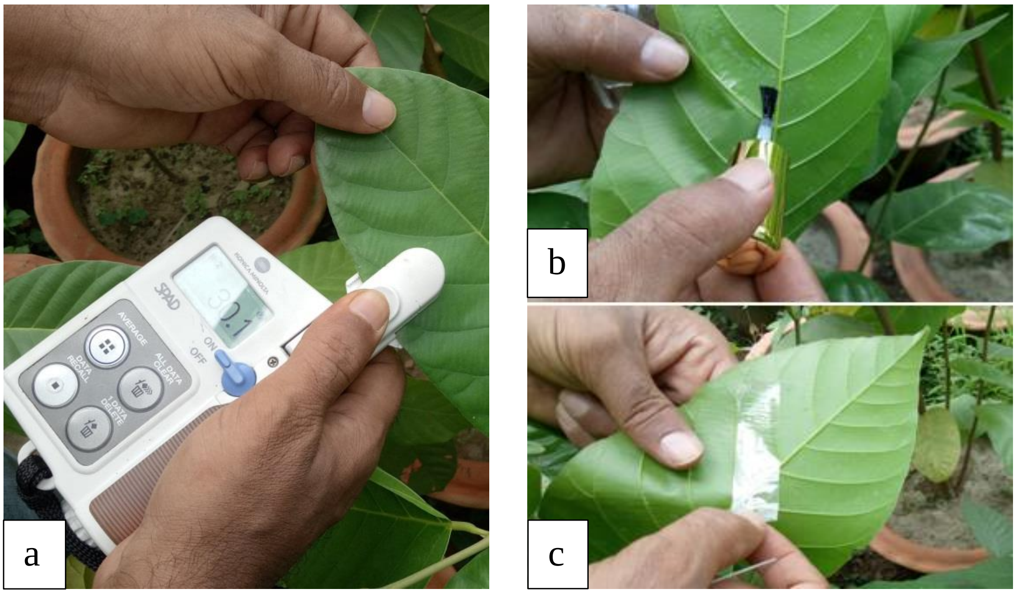

Figure 3.16: Photos showing the measurement of chlorophyll (a) and slide preparation for the study of stomata (b-c).

Study of stomata using impression technique

Leaf was gently spread on a plain field of a glass sheet. A thick swath of clear nail polish was painted on the ventral side of the leaf. After the nail polish had dried, the peel of the nail polish swath was taken away gently from the leaf completely. A cloudy impression of the leaf surface attached to the nail polish was found. One drop of glycerin was put on and then the leaf impression was kept on a clean slide, covered with a cover slip and observed under a microscope. A photograph of the field of leaves under the microscope (Axio Lab. A1 Microscope, Carl Zeiss Microscopy GmbH, Germany) was taken. In each image, stomatal length (µm) was taken for each of five randomly selected leaves per plant.

Measurement of stomatal length

The length of the stomata was measured using ImageJ Ver: k 1.45 software. The captured image was opened by ImageJ. After that, the scale bar scale was set by the line width tool in micrometer (µm) from the "analyze" menu. The selected line data was added in the ROI manager window from the analyze menu. Then, the result was analyzed by clicking on the Measure box.

Measurement of stomatal breadth

The breadth of the stomata was measured using ImageJ Ver: k 1.45 software. Measurements were expressed in micrometer (µm).

Measurement of stomatal density

For the measurement of stomatal density (number mm^{-2}), the number of stomata

per unit area (mm^{-2}) was counted from the images at a magnification of 10 × 40 and visual field area = (32×22) sq. µm. Stomatal density was calculated by the following formula:

Area of FOV (Field of View) = πr^2

Stomatal density = number of stomata in entire FOV / area (mm^2)

Determination of Stomatal Pore Index

Stomatal Pore Index is a stomatal density and stomatal length integrative parameter that reflects leaf stomatal conductance. Increased SPI leads to higher stomatal conductance and photosynthetic capacity in leaves. The SPI (%) was calculated by the following formula.:

SPI = Stomatal density × Stomatal $\text{length}^2 \times 10^{-4}$

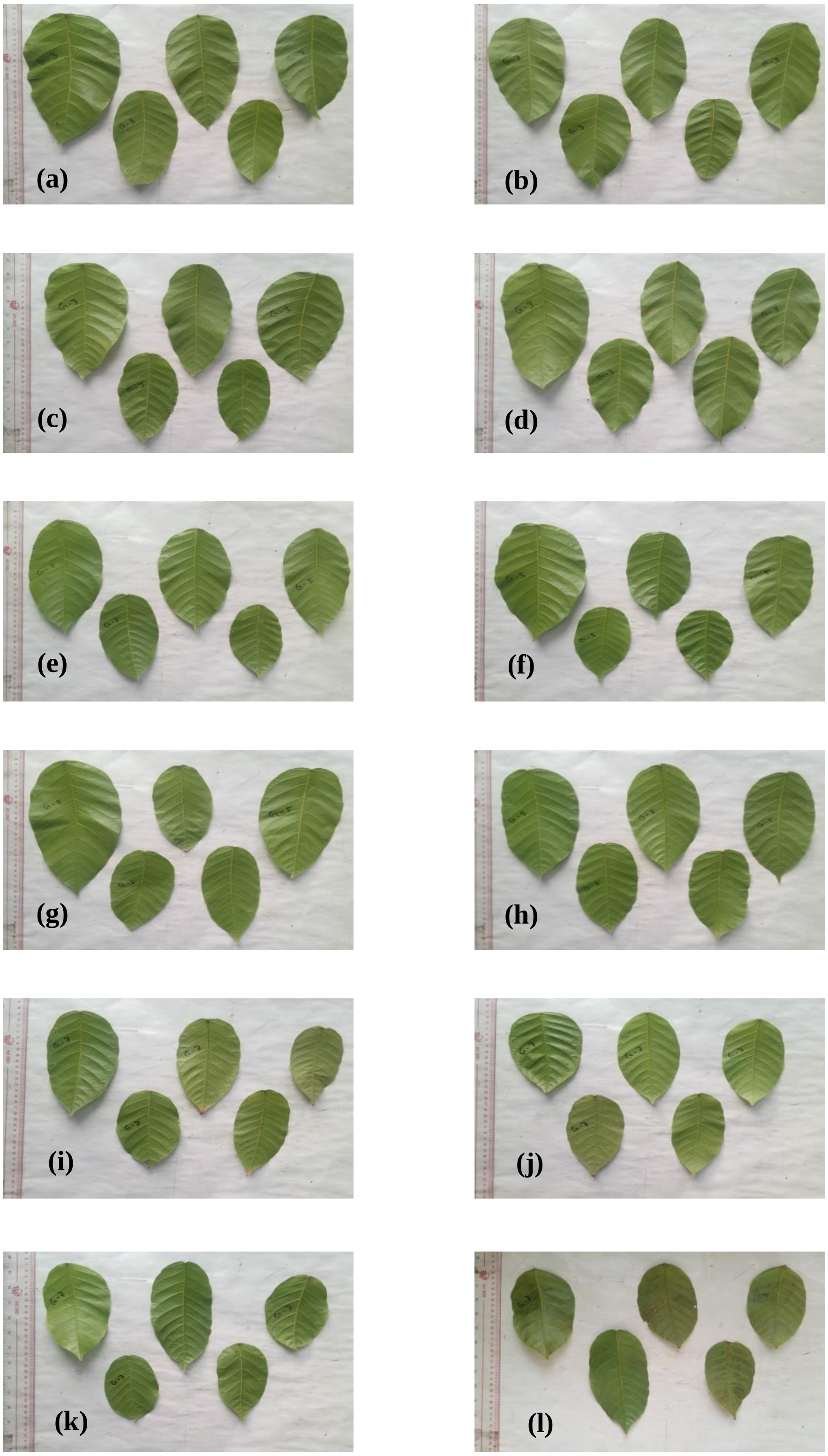

Figure 3.17: Images (a-l) of leaves of Sal plants selected in the present study for the analysis of functional traits.

3.2.2.8 Analysis of soil sample

Collection of soil samples

Identical soil collected from the Botanical Garden, University of Dhaka, was used in this experiment to grow plants in the pot. Soil was analyzed for its characteristics before taking into the pot. Soil moisture, electrical conductivity and pH were measured every month during the study period of one year. Soil was collected from a depth of 0–10 cm using a metal spoon. Air-tight polythene bags were used to collect and preserve soil samples. The soil was analyzed immediately after collection from the experimental pots.

Determination of soil pH

The pH of the soil was measured in the laboratory within 24 hours after its collection from the field. The pH of the soil was measured in suspension with distilled water (2:1, v: w). In a beaker, ten grams of soil were placed and 25 ml of distilled water was added to produce a suspension by shaking well. The suspension was held for a while to allow the particles to settle it down. The pH meter (Hanna pH meter, pHeP) was calibrated with known pH. Then, the pH values were recorded for each of the soil sample.

Determination of soil electrical conductivity

Soil electrical conductivity was measured in the laboratory within 24 hours after it was collected from the field. The conductivity of the soil was measured in suspension with distilled water (5:1, v: w). In a beaker, ten grams of soil was placed and 50 milliliters of distilled water were added to produce a suspension by shaking well. The suspension was kept for a while to allow the particles to settle down. The electrical conductivity meter was calibrated with a known conductivity. Then, the conductivity values were recorded for each of the soil samples.

Determination of soil moisture content

For the purpose of determining soil moisture content, 10 g of fresh soil was placed in a cup made of aluminum foil paper and placed in an oven at 80 °C for 24 hours. The following formula was used to calculate the moisture content of the soil:

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

Where,

F= Fresh soil weight

D= Dry soil weight

3.3 Nutritional adaptation of Sal plants

3.3.1 Collection of leaf

Fully expanded mature green leaves and old yellow leaves were collected in airtight polythene bags from each 10 selected Sal plants in Madhupur Sal forest and Charkai Sal forest. Fully expanded mature green-colored leaves and yellow-colored old leaves were collected at the end of December 2021 (Figure 3.18-3.19). Leaf samples were collected between the hours of 10 am and 12 pm from both sites. The collected leaf samples were brought to the Ecology and Environment Laboratory, Department of Botany, at the University of Dhaka for further analyses within the shortest possible time. A hundred green-colored fresh leaves and a hundred yellow-colored old leaves were selected randomly from both forests for the analysis of chlorophyll and other nutrients. The leaves were then wiped off with a tissue to take the chlorophyll reading.

Thus, a total of 200 green and 200 old leaves were studied during this study. The leaves were then air-dried for the analysis of other nutrients. Thus, a total of 400 leaves were analyzed for nutritional traits.

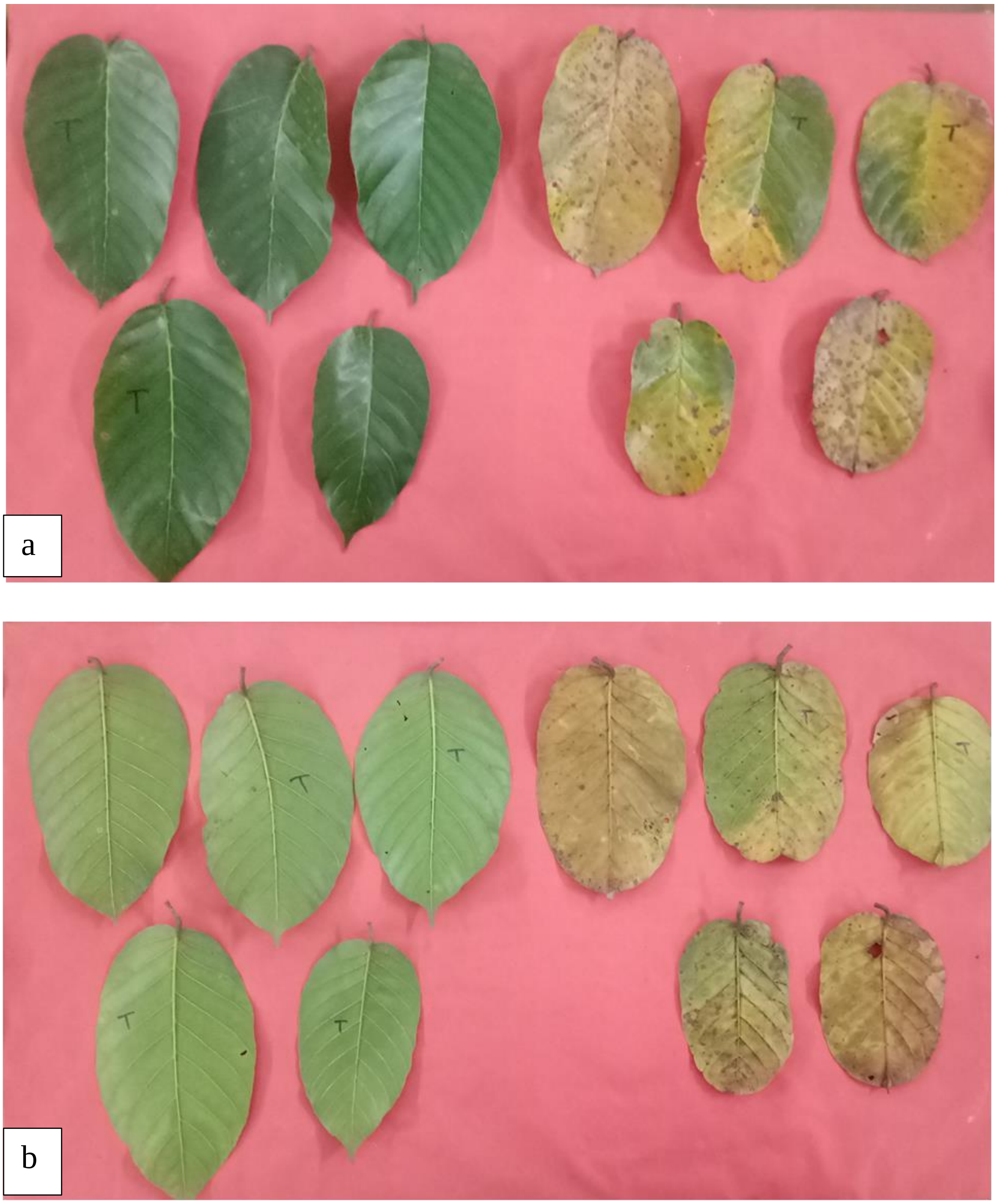

Figure 3.18: Image of green leaves and yellow leaves (a = ventral side, b = dorsal side) of Madhupur Sal forest which were studied during this study period for leaf nutrients.

Figure 3.19: Image of green leaves and yellow leaves (a = ventral side, b = dorsal side) of Charkai Sal forest which were studied during this study period for leaf nutrients.

3.3.2 Determination of leaf chlorophyll content

Leaf chlorophyll content was determined with the help of a chlorophyll meter (SPAD-502Plus Konica, Minolta, Japan). In order to measure chlorophyll contents of leaves, 5 fully expanded youngest leaves were selected per plant. The machine was calibrated.

3.3.3 Determination of leaf nutrients

3.3.3.1 Determination of total Nitrogen (N) in leaf

Leaf total nitrogen was determined by following the Kjeldahl method (Black 1965). For the determination of total leaf nitrogen, a 500 ml clean Kjeldahl flask was taken, where 0.25 g of the finely powdered leaf was taken. Then 2 ml of distilled water was added to it and shaken and then was left for 20 minutes. Ten ml of concentrated H_2SO_4 was added and mixed thoroughly. The flask was heated over a low flame in a digestion chamber for 15 minutes. When white fumes of H_2SO_4 appeared, the flask was removed from the heater and 3 g of catalyst (digestion mixture) was added to raise the boiling temperature of H_2SO_4 digestion to accelerate the reaction. Then, the flask was placed over the heater and the temperature was increased. The digestion was kept for 4 hours until the digest was clear. Then, it was kept for cooling. When the digestion became cold, it was diluted with distilled water and finally made volume up to 100 ml in a volumetric flask with distilled water. Then, 10 ml of extract was distilled with 10 ml of 40% NaOH using a micro Kjeldahl distillation apparatus with an equal volume of NaOH. The distillate was collected in 10 ml of 2% H_3BO_3 until the volume was about 50 ml. About 60 ml of distillate (ammonium borate) was collected in a 125 ml conical flask containing 10 ml of boric acid with a mixed indicator. Then, the distillate was titrated against the standard H_2SO_4. The endpoint was indicated by the pink color of the solution. A blank experiment was done simultaneously using all the chemicals except the leaf.

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

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

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 plant sample

f = Normality factor of N/100 H_2SO_4 = 0.0118

W = Weight of leaf sample

3.3.3.2 Determination of total Phosphorus (P) content in leaf

Total leaf phosphorus was determined by the vanadomolybdate yellow color method (Jackson 1973). The determination of total phosphorus was conducted by five steps. The steps are digestion, filtration, cooler development, preparation of the standard solution and absorbance by spectrophotometer. For digestion, a 45 ml beaker was taken and washed with distilled water. Then, 0.25 g of the finely chopped air-dried leaf was taken. After that, 10 ml of nitric acid (HNO_3) was added to the beaker and placed on the hot plate. It should be kept in a hot plate until the liquid was dried. A few minutes 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. After complete digestion, filtration was done. In the digestion beaker, distilled water was added and filtrated with filter paper until the final volume of filtration was 50 ml. For color development, a 25 ml volumetric flask was taken. Then, 2 ml of filtrated sample was taken in a volumetric flask. After that 5 ml of mixed solution (A+B) was added. The final volume was made to be 20 ml with distilled water. A standard solution was prepared in five different concentrations. They were 0, 1, 2.5, 5, 7.5 and 10 ppm. In a 25 ml volumetric flask for 0, 1, 2.5, 5, 7.5 and 10 ppm concentration, 0 ml, 1 ml, 2.5 ml, 5 ml, 7.5 ml and 10 ml of standard solution were taken in different volumetric flasks, respectively. After that, 5 ml of mixed solution (A+B) was added. The final volume was made to be 20 ml with distilled water. The absorbance was measured in a spectrophotometer. At first, the spectrometer (wave length 400 to 490 nm) was made standard with five standard solutions. Then, the absorbance of a standard solution was taken. After that, the absorbance of the sample solution was taken. The absorbance of the sample was transformed into concentration. For measuring sample concentration, a 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 the following formula:

$$\%\text{ of total phosphorus (P)} = \frac{(\text{ppm from st. curve } \times 20 \times 50 \times 100)}{\text{Vol. taken for colour} \times \text{Wt. of leaf} \times 10^6}$$

3.3.3.3 Determination of total Potassium (K) content in leaf

The digest solution prepared for the determination of phosphorus was also used for the determination of potassium (Piper 1950). K_2SO_4 was used to prepare five standard solutions (0, 2.5, 5, 10, 15 and 20 ppm). A flame photometer (Gallenkamp) was used to determine absorbance. A standard curve was drawn using the absorbance of five concentrations. The concentration of sample K was calculated using this standard curve.

$$\%\ \text{of total potassium (K)} = \frac{(\text{ppm from st. curve } \times 10 \times 50 \times 100)}{(\text{wt. of sample} \times 5 \times 10^{6}\ )}$$

CHAPTER 4

RESULTS

4.1 Effects of forest management on regeneration of Sal plants

4.1.1 Study of regeneration through vegetation survey

The effects of forest management and seasons on the number of species, plant density (density of tree species, density of shrub species and density of herb species) and the density of only Sal plants in the Core zone and Buffer zone of Madhupur Sal forest are shown in Table 4.1. The number of species ($P = 0.0005$), density of plants ($P = <0.0001$) density of tree species ($P = 0.0001$), density of herb species ($P = <0.0001$) and density of Sal plants ($P = <0.0001$) of the Core zone and Buffer zone of Madhupur Sal forest were significantly affected by seasons but not by management and their interactions. However, only the density of shrub species in the study area was significantly ($P = 0.0024$) affected by management of Madhupur Sal forest.

Table 4.1 Two-way ANOVA statistics on the effects of management (Core zone and Buffer zone) and seasons (Spring, Summer, Autumn and Winter) on the vegetation structure of the Madhupur Sal forest.

Parameters	Source of variation	df	F ratio	P value
Number of species	Management	1	1.2101	0.2876
	Season	3	10.4538	0.0005
	Management x Season	3	1.0084	0.4147
Density plant	Management	1	2.8764	0.1093
	Season	3	21.5329	<.0001
	Management x Season	3	0.2697	0.8463
Density of tree species	Management	1	3.8404	0.0677
	Season	3	13.4088	0.0001
	Management x Season	3	0.3596	0.783
Density of shrub species	Management	1	13.022	0.0024
	Season	3	0.999	0.4187
	Management x Season	3	0.2699	0.8461
Density of herb species	Management	1	0.4959	0.4914
	Season	3	20.4842	<.0001
	Management x Season	3	0.3998	0.755
Density of Sal plants	Management	1	1.5085	0.2371
	Season	3	16.9222	<.0001
	Management x Season	3	0.4395	0.7279

The effects of forest management and seasons on the density of Sal plants under different girth classes of Madhupur Sal forest are shown in Table 4.2. The seasonal effect was highly significant (P = <0.0001) in the 0–10 cm girth class. Management effect was significant in the > 10–20 cm (P = 0.0513) girth class as well as highly significant in the > 60–80 cm (P = 0.0001) and > 80–100 cm (P = <0.0001) girth classes in the Madhupur Sal forest.

Table 4.2 Two-way ANOVA statistics on the effects of management (Core zone and Buffer zone) and seasons (Spring, Summer, Autumn and Winter) on the density of Sal plants under different girth classes in the Madhupur Sal forest.

Girth class (cm)	Source of variation	df	F ratio	P value
0-10	Management	1	3.8527	0.0673
	Season	3	20.6583	<.0001
	Management x Season	3	0.4673	0.7092
>10-20	Management	1	4.4393	0.0513
	Season	3	0.0738	0.9732
	Management x Season	3	0.0386	0.9895
>20-40	Management	1	0.8	0.3844
	Season	3	0	1.00
	Management x Season	3	0	1.00
>40-60	Management	1	0	1.00
	Season	3	0	1.00
	Management x Season	3	0	1.00
>60-80	Management	1	25.6	0.0001
	Season	3	0	1.00
	Management x Season	3	0	1.00
>80-100	Management	1	38.4	<.0001
	Season	3	0	1.00
	Management x Season	3	0	1.00
>100-120	Management	1	4	0.0628
	Season	3	0	1.00
	Management x Season	3	0	1.00

The mean values of the effects of management and seasons on the number of species in four different seasons are shown in Figure 4.1. The number of species was relatively higher in the Buffer zone than in the Core zone in Spring (14 vs 12), Summer (16.67 vs 14.33) and Autumn season (14 vs 12.67). However, it was opposite in Winter where the species number was higher in the Core zone (9.33) than in the Buffer zone (7.67).

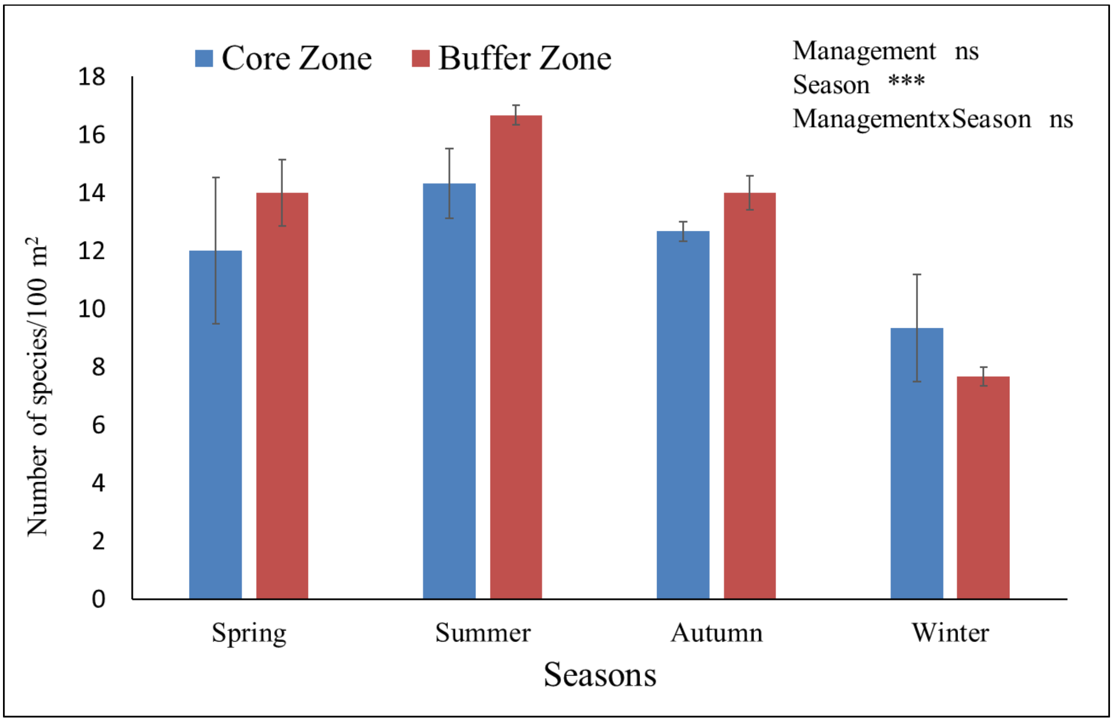

Figure 4.1: Mean value (± SEM) of the number of species of the Core zone and Buffer zone of the Madhupur Sal forest during Spring, Summer, Autumn and Winter seasons.

The mean values of the effects of management and seasons on the density of plants in four different seasons in the Core zone and Buffer zone are shown in Figure 4.2. Plant density was significantly lower in the Winter season than in the other three seasons. Plant density was higher in the Buffer zone than in the Core zone in all four seasons studied.

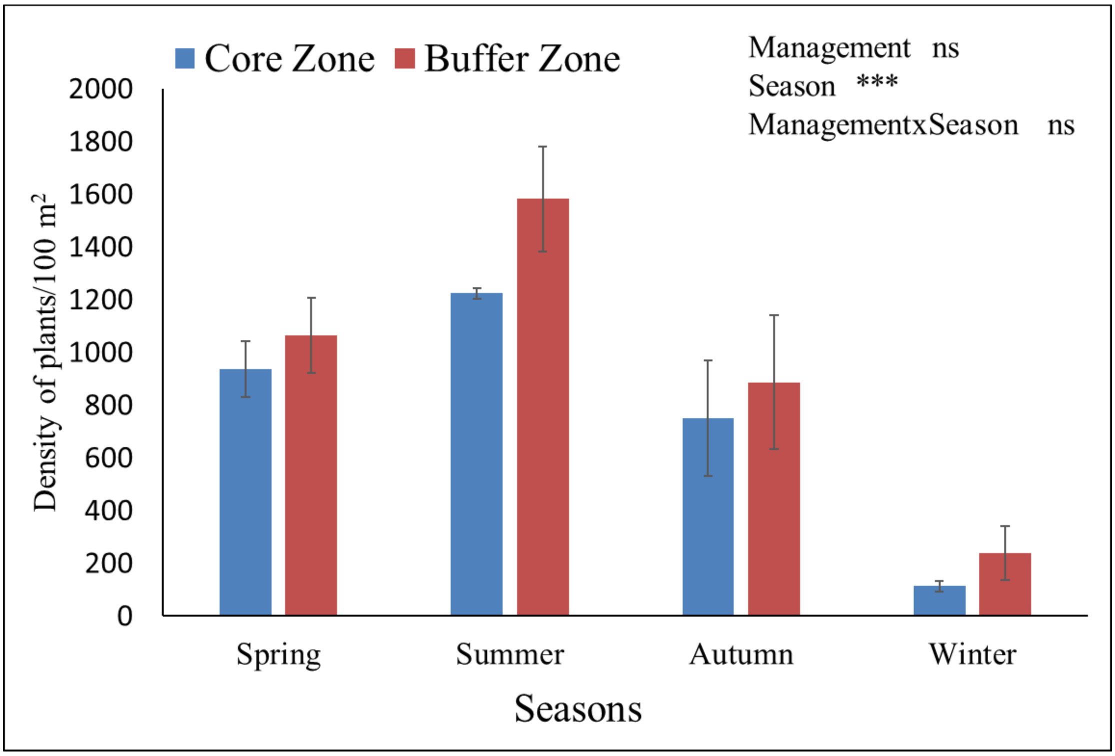

Figure 4.2: Mean value (± SEM) of the density of plants in the Core zone and Buffer zone of the Madhupur Sal forest during Spring, Summer, Autumn and Winter seasons.

The mean values of the effects of management and seasons on the density of tree species in four different seasons of the Core zone and Buffer zone are shown in Figure 4.3. The density of tree species was significantly lower in Winter than in other three seasons of the study period. The density of tree species was higher in the Buffer zone than in the Core zone in all four seasons studied.

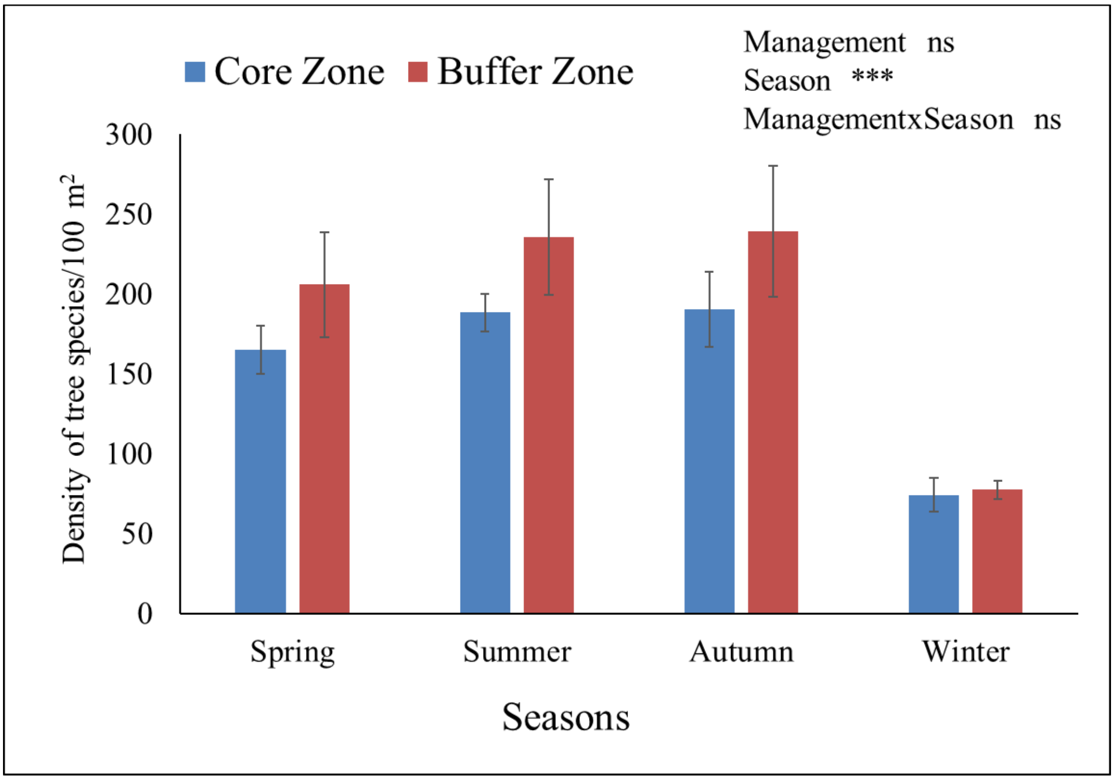

Figure 4.3: Mean value (± SEM) of the density of tree species of the Core zone and Buffer zone of Madhupur Sal forest during Spring, Summer, Autumn and Winter seasons.

The mean values of the effects of management and seasons on the density of shrub species in four different seasons of the Core zone and Buffer zone are shown in Figure 4.4. The density of shrub species was higher in the Buffer zone than in the Core zone in all four seasons studied.

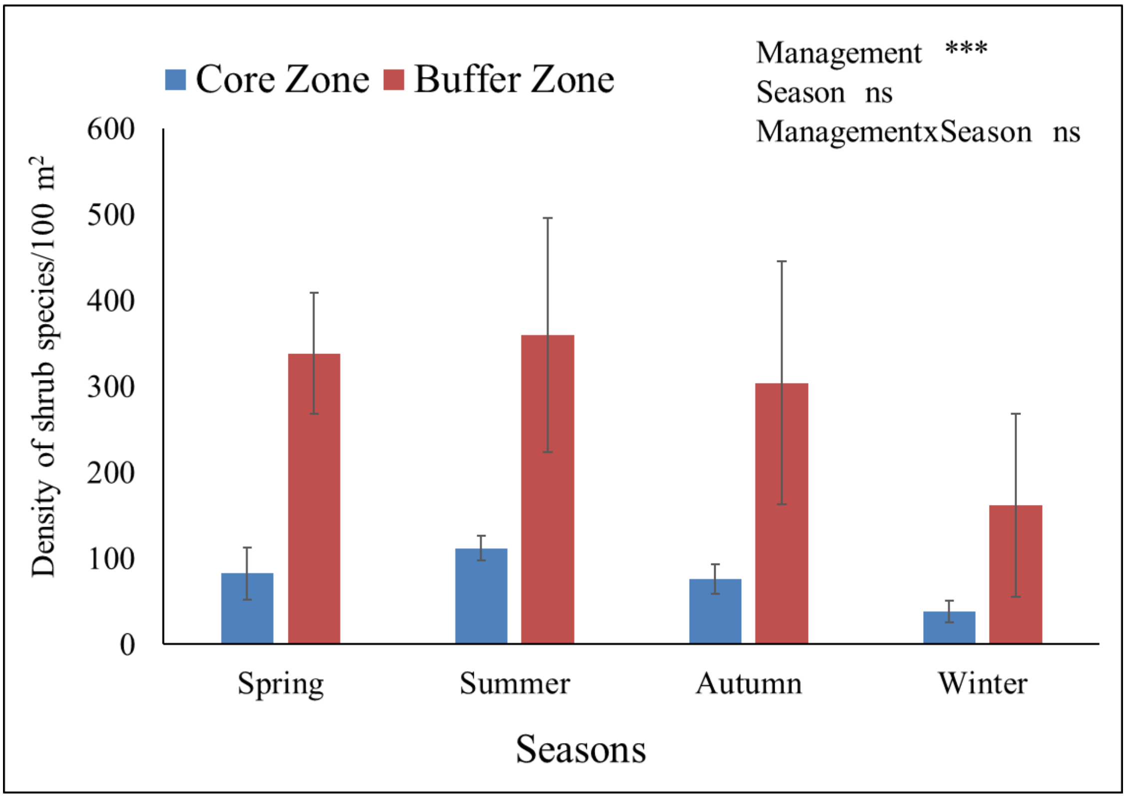

Figure 4.4: Mean value (± SEM) of the density of shrub species in the Core zone and Buffer zone of the Madhupur Sal forest during Spring, Summer, Autumn and Winter seasons.

The mean values of the effects of management and seasons on the density of herb species in four different seasons of the Core zone and Buffer zone are shown in Figure 4.5. The density of herb species was relatively higher in the Core zone than in the Buffer zone in the Spring and Autumn seasons, but in the Summer season the density of herbs was higher in the Buffer zone than in the Core zone. The density of herb species was almost zero in the Winter season in both zones.

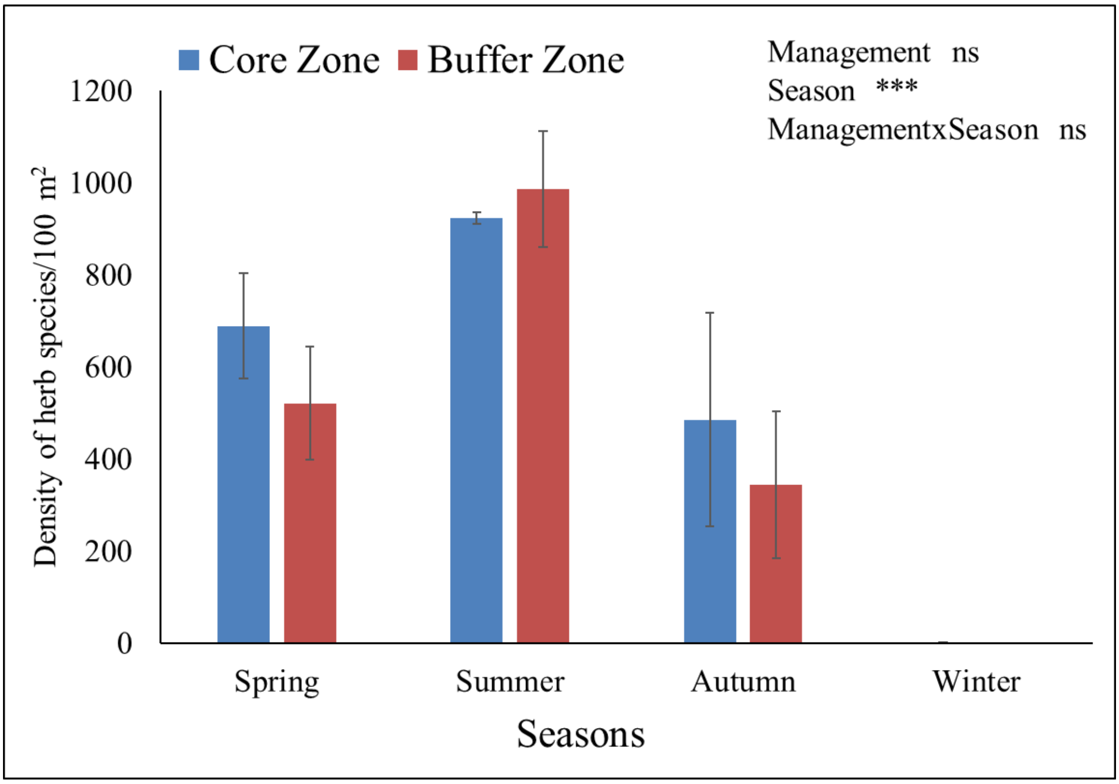

Figure 4.5: Mean value (± SEM) of the density of herb species in the Core zone and Buffer zone of the Madhupur Sal forest during Spring, Summer, Autumn and Winter seasons.

The mean values of the effects of management and seasons on the density of Sal trees in four different seasons in the Core zone and Buffer zone are shown in Figure 4.6. The density of Sal trees was significantly lower in Winter than in other three seasons. The density of Sal trees was higher in the Buffer zone than in the Core zone in the Spring (119.67 vs 106.67), Summer (155.33 vs 122.33) and Autumn (176.33 vs 145.67) seasons, but the density of Sal trees was higher in the Core zone than in the Buffer zone during the Winter season (32.0 vs 24.67).

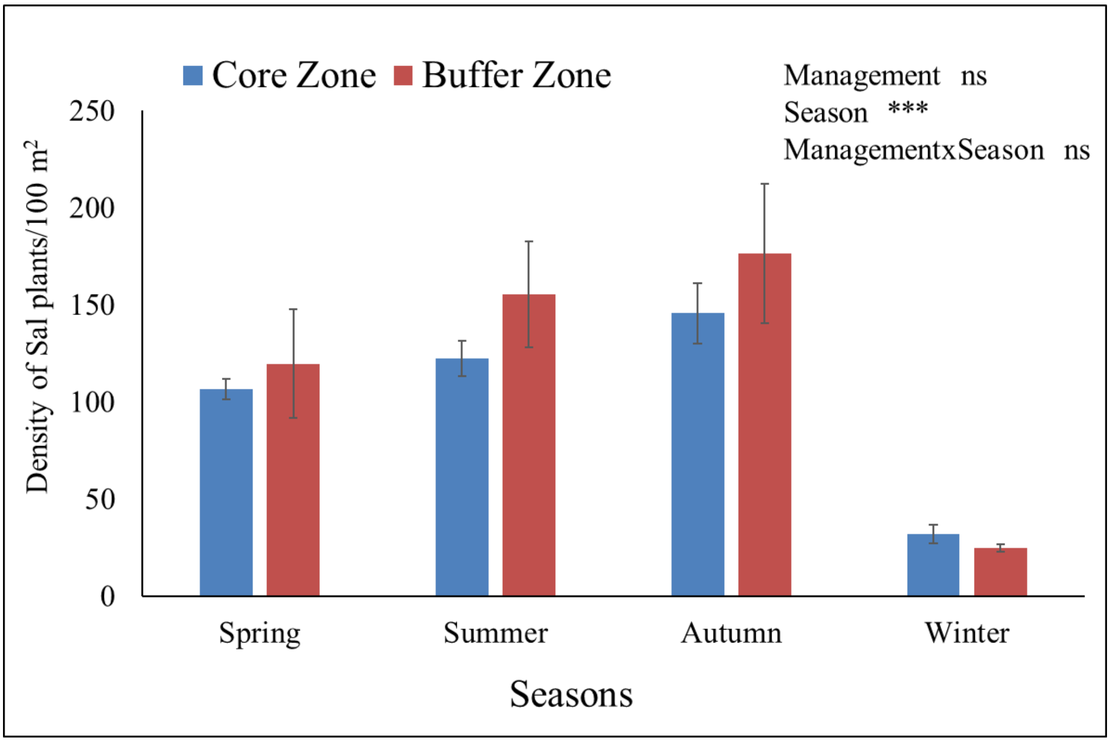

Figure 4.6: Mean value (± SEM) of the density of Sal trees of the Core zone and Buffer zone of the Madhupur Sal forest during Spring, Summer, Autumn and Winter seasons.

The mean values of the effects of forest management and seasons on the density of Sal plants under different girth classes in the Core zone and Buffer zone are shown in Figure 4.7. The maximum number of Sal plants in the 0-10 cm girth class was seen in the Autumn season and that was the minimum in the Winter season in both the management areas. The density of Sal plants in the 0-10 cm girth class was higher in the Buffer zone than in the Core zone in all four seasons studied and it was very low in the Winter season in both zones (Figure 4.7a). The density of Sal plants in the 10-20 cm girth class was higher in the Core zone than in the Buffer zone in all four seasons studied and it was very low in the Winter season in the Buffer zone (Figure 4.7b). The density of Sal plants in the 20-40 cm girth class (Figure 4.7c) and in the 60-80 cm girth class (Figure 4.7e) was also higher in the Core zone than in the Buffer zone in all four seasons studied. The density of Sal plants in the 80-100 cm girth class (Figure 4.7f) was higher in the Buffer zone than in the Core zone in all four seasons studied, though the number of Sal plants in this girth class was very small.

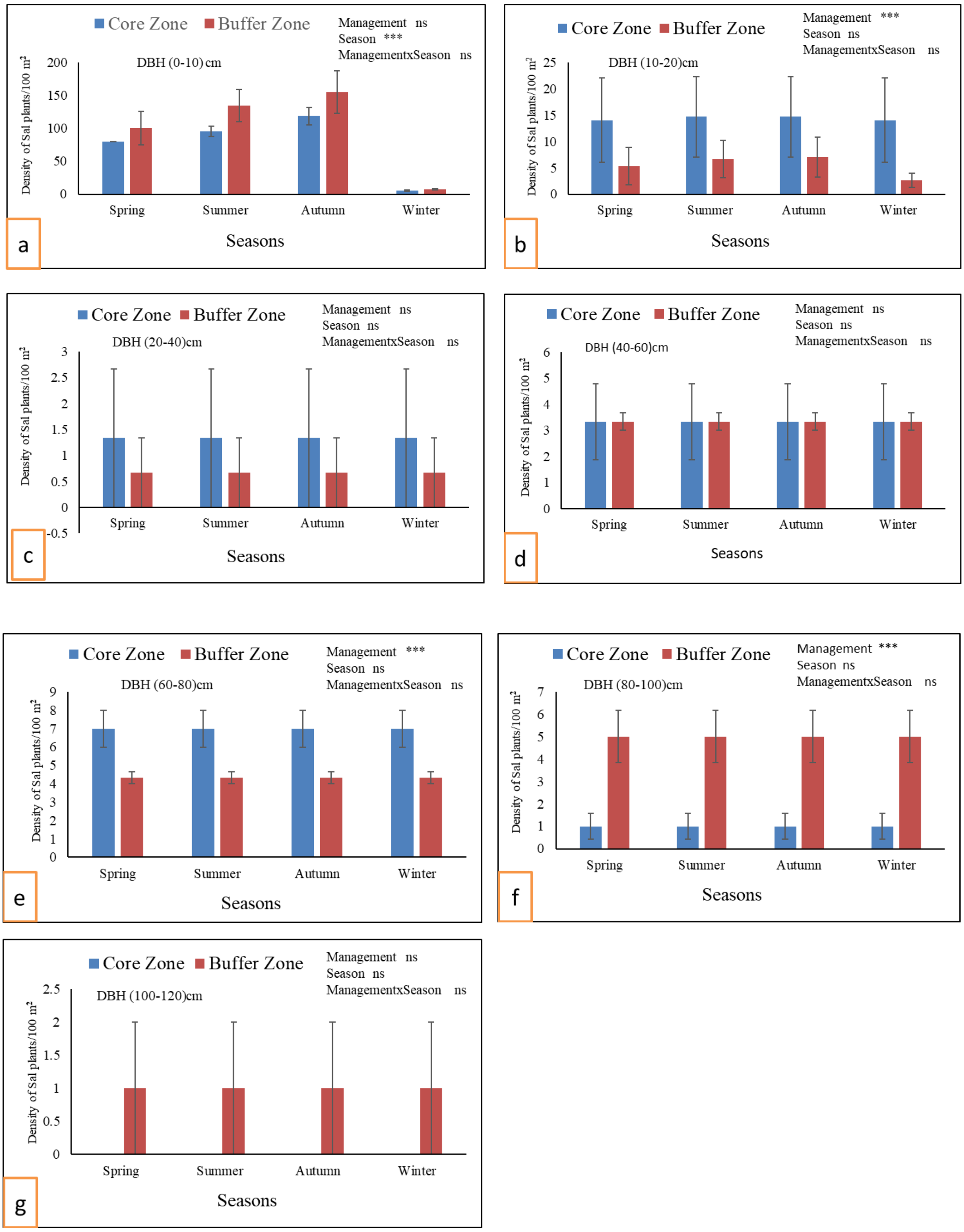

Figure 4.7: Mean value (± SEM) of the density (number of plants/quadrat) of Sal plants under different girth classes in the Core zone and Buffer zone of Madhupur Sal forest during Spring, Summer, Autumn and Winter seasons.

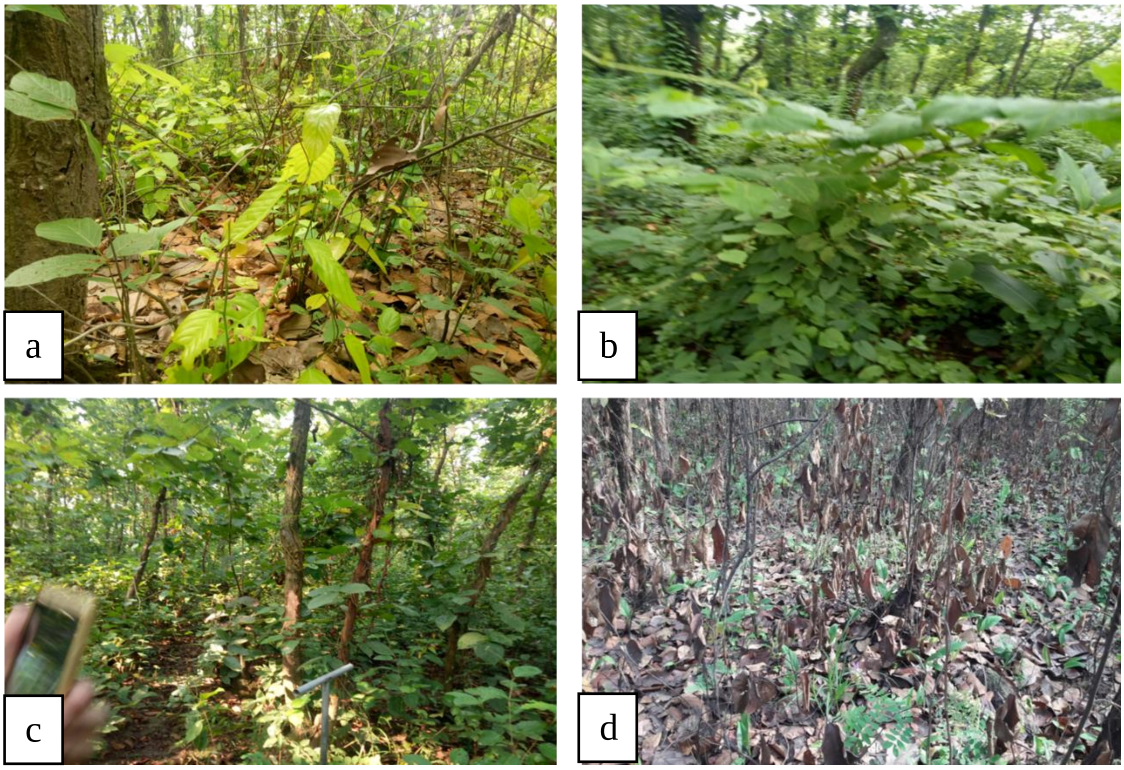

Figure 4.8: Photos showing the vegetation of Sal forest during Spring (a), Summer (b), Autumn (c) and Winter (d) seasons.

Phyto-sociological association among the plant species in the Spring season of the Core zone is shown in Table 4.3. A total of 23 plant species were recorded in this season. Among the species observed, 13 were trees, 4 were shrubs and 6 were herbs in habit. Among the tree species, *S. robusta* Roxb. *ex* Gaertn. showed the highest IVI value (129.14), followed by *Randia dumetorum* (Retz.) Lam. (32.83), *Syzygium grande* (Wight.) Walp. (27.481) and *Mallotus philippensis* (18.24). These data indicated that *S. robusta* Roxb. *ex* Gaertn. was the dominant tree species over other species in the Core zone of Madhupur Sal forest during the Spring season. Among the shrubs, *Clerodendrum infortunatum* L. showed the highest IVI value (113), followed by *Urena lobata* L. (65), *Calamus viminalis* Willd. (63.66) and *Glycosmis pentaphylla* (Retz.) A. DC (58.33). Among the herb species, *Axonopus compressus* (Sw.) P. Beaub. showed the highest IVI value (144.80), followed by *Cyperus* sp. (57.87), *Curcuma zedoaria* Rosc. (46.20) and *Kyllinga brevifolia* Rottb. (21.57).

Table 4.3 Importance Value Index (IVI) of the Core zone of the Madhupur Sal forest during the Spring season (2018).

Sl. no.	Scientific name	Local name	Family	IVI
Trees				
1	*Shorea robusta* Roxb. *ex* Gaertn.	Sal	Dipterocarpaceae	129.14
2	*Randia dumetorum* (Retz.) Lam.	Monkata	Rubiaceae	32.83
3	*Syzygium grande* (Wight.) Walp.	Jam	Myrtaceae	27.48
4	*Mallotus philippensis*	Shinduri	Euphorbiaceae	18.24
5	*Dipterocarpus turbinatus*	Garjan	Dipterocarpaceae	17.65
6	*Randia longiloba*	Randia	Rubiaceae	16.98
7	*Dillenia indica*	Bon chalta	Dilleniaceae	12.99
8	*Toona ciliata*	Toon	Meliaceae	8.99
9	*Zizyphus mauritiana*	Boroi	Rhamnaceae	8.99
10	*Albizia procera* (Roxb.) Benth.	Koroi	Mimosaceae	7.66
11	*Bauhinia acuminata*	Bauhinia	Fabaceae	6.99
12	*Tectona grandis*	Segun	Lamiaceae	6.33
13	*Butea monosperma* (Lam.) Taub.	Polash	Fabaceae	5.66
Shrubs				
1	*Clerodendrum infortunatum* L.	Vaat	Lamiaceae	113
2	*Urena lobata* L.	Bonokra	Malvaceae	65
3	*Calamus viminalis* Willd.	Bet	Palmae	63.66
4	*Glycosmis pentaphylla* (Retz.) A. DC	Motkila	Rutaceae	58.33
Herbs				
1	*Axonopus compressus* (Sw.) P.Beaub.	Carpet ghas	Gramineae	144.80
2	*Cyperus* sp.	Cyperus	cyperaceae	57.87
3	*Curcuma zeoderia* Rosc.	Shathi	Zingiberaceae	46.20
4	*Kyllinga brevifolia* Rottb.	Shabujnirbisa	Cyperaceae	21.57
5	*DiosCorea bulbifera* L.	Banalu	DiosCoreaceae	16.12
6	*Pteris* sp	Pteris	Pteridaceae	13.40

Phyto-sociological association among the plant species in the Summer season of the Core zone is shown in Table 4.4. A total of 23 plant species were recorded in this season. Among the species observed, 13 were trees, 4 were shrubs and 6 were herbs in habit. Among the tree species, *S. robusta* showed the highest IVI value (129.99), followed by *Randia dumetorum* (Retz.) Lam. (36.08), *Syzygium grande* (Wight.) Walp. (25.05) and *Albizia procera* (Roxb.) Benth. (19.97). These data indicated that *S. robusta* was the dominant tree species over other species in the Core zone of Madhupur Sal forest during the Summer season. Among the shrubs, *Clerodendrum infortunatum* L. showed the highest IVI value (81.60), followed by *Calamus viminalis* Willd. (80.87), *Urena lobata* L. (79.40) and *Glycosmis pentaphylla* (Retz.) A. DC (58.11). Among the herb species, *Axonopus compressus* showed the highest IVI value (138.74), followed by *Cyperus* sp. (67.50), *Curcuma zedoaria* Rosc. (43.32) and *Pteris* sp. (21.53).

Table 4.4 Importance Value Index (IVI) of the plant species observed in the Core zone of the Madhupur Sal forest during the Summer season (2018).

Sl. no.	Scientific name	Local name	Family	IVI
Trees				
1	*Shorea robusta* Roxb. *ex* Gaertn.	Sal	Dipterocarpaceae	129.99
2	*Randia dumetorum* (Retz.) Lam.	Monkata	Rubiaceae	36.08
3	*Syzygium grande* (Wight.) Walp.	Jam	Myrtaceae	25.05
4	*Albizia procera* (Roxb.) Benth.	Koroi	Mimosaceae	19.97
5	*Dipterocarpus turbinatus*	Gorjan	Dipterocarpaceae	16.48
6	*Randia longiloba*	Randia	Rubiaceae	15.29
7	*Dillenia indica*	Bon chalta	Dilleniaceae	15.28
8	*Toona ciliata*	Toon	Meliaceae	8.72
9	*Mallotus philippensis*	Shinduri	Euphorbiaceae	8.12
10	*Cinnamomum iners* Reinw.	Tejbohu	Lauraceae	6.93
11	*Bauhinia acuminata*	Bauhinia	Fabaceae	6.33
12	*Zizyphus mauritiana*	Boroi	Rhamnaceae	5.96
13	*Tectona grandis*	Segun	Lamiaceae	5.73
Shrubs				
1	*Clerodendrum infortunatum* L.	Vaat	Lamiaceae	81.60
2	*Calamus viminalis* Willd.	Bet	Palmae	80.87
3	*Urena lobata* L.	Bonokra	Malvaceae	79.40
4	*Glycosmis pentaphylla* (Retz.) A. DC	Motkila	Rutaceae	58.11
Herbs				
1	*Axonopus compressus* (Sw.) P. Beaub.	Carpet ghas	Poaceae	138.74
2	*Cyperus* sp.	Cyperus	Cyperaceae	67.50
3	*Curcuma zeoderia* Rosc.	Shathi	Zingiberaceae	43.32
4	*Pteris* sp.	Pteris	Pteridaceae	21.53
5	*Kyllinga brevifolia* Rottb.	Shabujnirbisa	Cyperaceae	15.55
6	*Dioscorea bulbifera* L.	Banalu	Dioscoreaceae	13.33

Phyto-sociological association among the plant species in the Autumn season of the Core zone of the Madhupur Sal forest is shown in Table 4.5. A total of 22 plant species were recorded in this season. Among the species observed, 12 were trees, 4 were shrubs and 6 were herbs in habit. Among the tree species, *S. robusta* showed the highest IVI value (154.18), followed by *Syzygium grande* (22.96), *Randia dumetorum* (17.80) and *Albizia procera* (16.24). These data indicated that *S. robusta* was the dominant tree species over other species in the Core zone of Madhupur Sal forest during the Autumn season. Among the shrubs, *Calamus viminalis* showed the highest IVI value (124.37), followed by *Glycosmis pentaphylla* (69.32), *Urena lobata* L. (59.58) and *Clerodendrum infortunatum* L. (46.71). Among the herb species, *Axonopus compressus* (Sw.) P. Beaub. showed the highest IVI value (121.79), followed by *Cyperus* sp. (98.81), *Pteris* sp. (25.79) and *Kyllinga brevifolia* (22.46).

Table 4.5 Importance Value Index (IVI) of the plant species observed in the Core zone during the Autumn season of the Madhupur Sal forest (2018).

Sl.no.	Scientific name	Local name	Family	IVI
Tree				
1	*Shorea robusta* Roxb. *ex* Gaertn.	Sal	Dipterocarpaceae	154.18
2	*Syzygium grande* (Wight.) Walp.	Jam	Myrtaceae	22.96
3	*Randia dumetorum* (Retz.) Lam.	Monkata	Rubiaceae	17.80
4	*Albizia procera* (Roxb.) Benth.	Koroi	Mimosaceae	16.24
5	*Dipterocarpus turbinatus*	Garjan	Dipterocarpaceae	15.28
6	*Mallotus philippensis*	Shinduri	Euphorbiaceae	15.07
7	*Dillenia indica*	Chalta	Dilleniaceae	14.68
8	*Randia longiloba*	Randia	Rubiaceae	12.26
9	*Grewia nervosa* (Lour) G. Panigrahi	Datoi	Malvaceae	9.84
10	*Toona ciliata*	Toon	Meliaceae	8.02
11	*Cinnamomum iners* Reinw.	Tejbohu	Lauraceae	7.42
12	*Tectona grandis*	Segun	Lamiaceae	6.21
Shrubs				
1	*Calamus viminalis* Willd.	Bet	Palmae	124.37
2	*Glycosmis pentaphylla* (Retz.) A. DC	Glycosmis	Rutaceae	69.32
3	*Urena lobata* L.	Bonokra	Malvaceae	59.58
4	*Clerodendrum infortunatum* L.	Vaat	Lamiaceae	46.71
Herbs				
1	*Axonopus compressus* (Sw.) P. Beaub.	Carpet ghas	Gramineae	121.79
2	*Cyperus* sp.	Cyperus	Cyperaceae	98.81
3	*Pteris* sp.	Pteris	Pteridaceae	25.79
4	*Kyllinga brevifolia* Rottb.	Shabujnirbisa	Cyperaceae	22.46
5	*Legume* sp.	Legume	Fabaceae	17.73
6	*Curcuma zeoderia* Rosc.	Shathi	Zingiberaceae	13.38

Phyto-sociological association among the plant species in the Winter season of the Core zone of the Madhupur Sal forest is shown in Table 4.6. A total of 17 plant species were recorded in this season. Among the species observed, 13 were trees, 3 were shrubs and 1 were herbs in habit. Among the tree species, *S. robusta* showed the highest IVI value (84.40) followed by *Syzygium grande* (38.85), *Dipterocarpus turbinatus* (29.08) and *Randia longiloba* (24.01). These data indicated that *S. robusta*.was the dominant tree species over other species in the Core zone of Madhupur Sal forest during the Winter season. Among the shrubs, *Clerodendrum infortunatum* L. showed the highest IVI value (138.80), followed by *Calamus viminalis* Willd. (80.97) and *Glycosmis pentaphylla* (80.22). Among the herb species, only *Pteris* sp. was found.

Table 4.6 Importance Value Index (IVI) of the plant species observed in the Core zone of the Madhupur Sal forest during the Winter season (2019).

Sl.no.	Scientific name	Local name	Family	IVI
Trees				
1	*Shorea robusta* Roxb. *ex* Gaertn.	Sal	Dipterocarpaceae	84.40
2	*Syzygium grande* (Wight.) Walp.	Jam	Myrtaceae	38.85
3	*Dipterocarpus turbinatus*	Garjan	Dipterocarpaceae	29.08
4	*Randia longiloba*	Randia	Rubiaceae	24.01
5	*Randia dumetorum (*Retz.) Lam.	Monkata	Rubiaceae	22.22
6	*Mallotus philippensis*	Shinduri	Euphorbiaceae	22.02
7	*Dillenia indica*	Bon chalta	Dilleniaceae	20.21
8	*Toona ciliata*	Toon	Meliaceae	12.60
9	*Zizyphus mauritiana*	Boroi	Rhamnaceae	12.60
10	*Albizia procera* (Roxb.) Benth.	Koroi	Mimosaceae	10.07
11	*Bauhinia acuminata*	Bauhinia	Fabaceae	8.80
12	*Butea monosperma* (Lam.) Taub.	Polash	Fabaceae	7.53
13	*Tectona grandis*	Segun	Lamiaceae	7.53
Shrubs				
1	*Clerodendrum infortunatum* L.	Vaat	Lamiaceae	138.80
2	*Calamus viminalis* Willd.	Bet	Palmae	80.97
3	*Glycosmis pentaphylla* (Retz.) A. DC	Motkila	Rutaceae	80.22
Herb				
1	*Pteris* sp.	Pteris	Pteridaceae	300

Phyto-sociological association among the plant species in the Spring season of the Buffer zone of the Madhupur Sal forest is shown in Table 4.7. A total of 20 plant species were recorded in this season. Among the species observed, 9 were trees, 4 were shrubs and 7 were herbs in habit. Among the tree species, *S. robusta* showed the highest IVI value (127.85) followed by *Randia dumetorum* (43.30), *Syzygium grande* (30.91) and *Mallotus philippensis* (22.56). These data indicated that *S. robusta* was the dominating tree species over other species in the Buffer zone of Madhupur Sal forest during the Spring season. Among the shrubs, *Clerodendrum infortunatum* L. showed the highest IVI value (102.23), followed by *Urena lobata* L. (85.29), *Calamus viminalis* (64.95) and *Glycosmis pentaphylla* (47.52). Among the herb species, *Axonopus compressus* showed the highest IVI value (134.02), followed by *Curcuma zeoderia* (46.16), *Trifolium repens* L. (43.38) and *Cyperus* sp. (33.64).

Table 4.7 Importance Value Index (IVI) of plants in the Buffer zone of the Madhupur Sal forest during the Spring season (2018).

Sl.no.	Scientific name	Local name	Family	IVI
Tree				
1	*Shorea robusta* Roxb. *ex* Gaertn.	Sal	Dipterocarpaceae	127.85
2	*Randia dumetorum* (Retz.) Lam.	Monkata	Rubiaceae	43.30
3	*Syzygium grande* (Wight.) Walp.	Jam	Myrtaceae	30.91
4	*Mallotus philippensis*	Shinduri	Euphorbiaceae	22.56
5	*Ziziphus oenoplia* (L.) Mill.	Bonboroi	Rhamnaceae	22.17
6	*Grewia nervosa* (Lour.) G Panigrahi	Datoi	Malvaceae	22.17
7	*Albizia procera* (Roxb.) Benth.	Koroi	Mimosaceae	12.72
8	*Dillenia indica*	Bon chalta	Dilleniaceae	9.14
9	*Tectona grandis*	Segun	Lamiaceae	9.14
Shrubs				
1	*Clerodendrum infortunatum* L.	Vaat	Lamiaceae	102.23
2	*Urena lobata* L.	Bonokra	Malvaceae	85.29
3	*Calamus viminalis* Willd.	Bet	Palmae	64.95
4	*Glycosmis pentaphylla* (Retz.) A. DC	Motkila	Rutaceae	47.52
Herbs				
1	*Axonopus compressus* (Sw.) P. Beaub.	Carpet ghas	Poaceae	134.02
2	*Curcuma zeoderia* Rosc.	Shathi	Zingiberaceae	46.16
3	*Trifolium repens* L.	Ampin	Fabaceae	43.38
4	*Cyperus* sp.	Cyperus	Cyperaceae	33.64
5	*Musa acuminata*	Bonkola	Musaceae	21.04
6	*DiosCorea bulbifera* L.	Banalu	DiosCoreaceae	11.05
7	*Pteris* sp.	Pteris	Pteridaceae	10.67

Table 4.8 shows the Phyto-sociological association among the plant species in the Summer season of the Buffer zone of the Madhupur Sal forest. A total of 23 plant species were recorded in this season. Among the species observed, 10 were trees, 4 were shrubs and 9 were herbs in habit. Among the tree species, *S. robusta* showed the highest IVI value (140.21) followed by *R. dumetorum* (35.90), *Syzygium grande* (26.44) and *Mallotus philippensis* (24.28). These data indicated that *S. robusta* was the dominant tree species over other species in the Buffer zone of Madhupur Sal forest during the Summer season. Among the shrubs, *Clerodendrum infortunatum* L. showed the highest IVI value (130.80), followed by *Calamus viminalis* Willd. (80.06), *Urena lobata* L. (55.48) and *Glycosmis pentaphylla* (33.64). Among the herb species, *Axonopus compressus* showed the highest IVI value (94.54), followed by *Cyperus sp.* (59.56). *Curcuma zeoderia* Rosc. (33.02) and *Mimosa pudica* L. (29.83).

Table 4.8 Importance Value Index (IVI) of plants in the Buffer zone of the Madhupur Sal forest during the Summer season (2018).

Sl.no.	Scientific name	Local name	Family	IVI
Tree				
1	*Shorea robusta* Roxb. *ex* Gaertn.	Sal	Dipterocarpaceae	140.21
2	*Randia dumetorum* (Retz.) Lam.	Mon kata	Rubiaceae	35.90
3	*Syzygium grande* (Wight.) Walp.	Jam	Myrtaceae	26.44
4	*Mallotus philippensis*	Shinduri	Euphorbiaceae	24.28
5	*Ziziphus oenoplia* (L.) Mill.	Bonboroi	Rhamnaceae	21.58
6	*Grewia nervosa* (Lour.) G. Panigrahi	Datoi	Malvaceae	17.22
7	*Albizia procera* (Roxb.) Benth.	Koroi	Mimosaceae	11.62
8	*Dillenia indica*	Bon chalta	Dilleniaceae	7.92
9	*Eugenia* sp.	Kharajora	Apocynaceae	7.92
10	*Tectona grandis*	Segun	Lamiaceae	6.87
Shrubs				
1	*Clerodendrum infortunatum* L.	Vaat	Lamiaceae	130.80
2	*Calamus viminalis* Willd.	Bet	Palmae	80.06
3	*Urena lobata* L.	Bonokra	Malvaceae	55.48
4	*Glycosmis pentaphylla* (Retz.) A. DC	Motkila	Rutaceae	33.64
Herbs				
1	*Axonopus compressus* (Sw.) P. Beaub.	Carpet ghas	Poaceae	94.54
2	*Cyperus* sp.	Cyperus	Cyperaceae	59.56
3	*Curcuma zeoderia* Rosc.	Shathi	Zingiberaceae	33.02
4	*Mimosa pudica* L.	Lozzaboti	Fabaceae	29.83
5	*Trifolium repens* L.	Ampin	Fabaceae	23.60
6	*DiosCorea bulbifera* L.	Ban alu	DiosCoreaceae	15.46
7	*Kyllinga brevifolia* Rottb.	Shabujnirbisa	Cyperaceae	15.46
8	*Musa acuminata*	Bonkola	Musaceae	14.44
9	*Pteris* sp.	Pteris	Pteridaceae	14.05

IVI value of the identified plant species in the Autumn season of the Buffer zone of the Madhupur Sal forest is shown in Table 4.9. A total of 22 plant species were recorded in this season. Among the species observed, 10 were trees, 4 were shrubs and 8 were herbs in habit. Among the tree species, *S. robusta* showed the highest IVI value (154.33) followed by *Randia dumetorum* (30.45), *Syzygium grande* (27.05) and *Mallotus philippensis* (16.99). These data indicated that *S. robusta* was the dominant tree species over other species in the Buffer zone of Madhupur Sal forest during the Autumn season. Among the shrubs, *Clerodendrum infortunatum* L. showed the highest IVI value (114.91), followed by *Calamus viminalis* Willd. (87.66), *Urena lobata* L. (60.43) and *Glycosmis pentaphylla* (36.98). Among the herb species, *Cyperus* sp. showed the highest IVI value (93.80), followed by *Axonopus compressus* (91.18). *Curcuma zeoderia* Rosc. (25.33) and *Pteris* sp. (21.95).

Table 4.9 Importance Value Index (IVI) of the plants of the Buffer zone of the Madhupur Sal forest during the Autumn season (2018).

Sl.no.	Scientific name	Local name	Family	IVI
Trees				
1	*Shorea robusta* Roxb. *ex* Gaertn.	Sal	Dipterocarpaceae	154.33
2	*Randia dumetorum* (Retz.) Lam.	Monkata	Rubiaceae	30.45
3	*Syzygium grande* (Wight.) Walp.	Jam	Myrtaceae	27.05
4	*Mallotus philippensis*	Shinduri	Euphorbiaceae	16.99
5	*Grewia nervosa* (Lour) G. Panigrahi	Datoi	Malvaceae	16.99
6	*Ziziphus oenoplia* (L.) Mill.	Bonboroi	Rhamnaceae	15.37
7	*Albizia procera* (Roxb.) Benth.	Koroi	Mimosaceae	11.85
8	*Zizyphus mauritiana*	Boroi	Rhamnaceae	11.34
9	*Dillenia pentagyna* Roxb.	Bon chalta	Dilleniaceae	8.30
10	*Tectona grandis*	Segun	Lamiaceae	7.29
Shrubs				
1	*Clerodendrum infortunatum* L.	Vaat	Lamiaceae	114.91
2	*Calamus viminalis* Willd.	Bet	Palmae	87.66
3	*Urena lobata* L.	Bonokra	Malvaceae	60.43
4	*Glycosmis pentaphylla* (Retz.) A. DC	Glycosmis	Rutaceae	36.98
Herbs				
1	*Cyperus* sp.	Cyperus	Cyperaceae	93.80
2	*Axonopus compressus* (Sw.) P. Beaub.	Carpet ghas	Gramineae	91.18
3	*Curcuma zeoderia* Rosc.	Shathi	Zingiberaceae	25.33
4	*Pteris* sp.	Pteris	Pteridaceae	21.95
5	*Kyllinga brevifolia* Rottb.	Shabujnirbisa	Cyperaceae	24.90
6	*Musa acuminata*	Bonkola	Musaceae	20.34
7	*DiosCorea bulbifera* L.	Banalu	DiosCoreaceae	12.06
8	*Trifolium repens* L.	Ampin	Fabaceae	10.40

Phyto-sociological association among the plant species in the Winter season of the Buffer zone of the Madhupur Sal forest is shown in Table 4.10. A total of 12 plant species were recorded in this season. Among the species observed, 9 were trees and 3 were shrubs. Among the tree species, *S. robusta* showed the highest IVI value (71.90) followed by *Syzygium grande* (49.51), *Ziziphus oenoplia* (L.) Mill. (34.62) and *Mallotus philippensis* (34.62). These data indicated that *S. robusta* was the dominating tree species over other species in the Buffer zone of Madhupur Sal forest during the Winter season. Among the shrubs, *Clerodendrum infortunatum* L. showed the highest IVI value (153.04), followed by *Calamus viminalis* Willd. (124.55) and *Glycosmis pentaphylla* (22.16).

Table 4.10 Importance Value Index (IVI) of plants in the Buffer zone of the Madhupur Sal forest during the Winter season (2019).

Sl.no.	Scientific name	Local name	Family	IVI
Trees				
1	*Shorea robusta* Roxb. *ex* Gaertn.	Sal	Dipterocarpaceae	71.90
2	*Syzygium grande* (Wight.) Walp.	Jam	Myrtaceae	49.51
3	*Ziziphus oenoplia* (L.) Mill.	Bonboroi	Rhamnaceae	34.62
4	*Mallotus philippensis*	Shinduri	Euphorbiaceae	34.62
5	*Grewia nervosa* (Lour.) G. Panigrahi	Datoi	Malvaceae	31.00
6	*Randia dumetorum* (Retz.) Lam.	Mon kata	Rubiaceae	28.61
7	*Albizia procera* (Roxb.) Benth.	Koroi	Mimosaceae	22.08
8	*Dillenia indica*	Bon chalta	Dilleniaceae	13.81
9	*Tectona grandis*	Segun	Lamiaceae	13.81
Shrubs				
1	*Clerodendrum infortunatum* L.	Vaat	Lamiaceae	153.04
2	*Calamus viminalis* Willd.	Bet	Palmae	124.55
3	*Glycosmis pentaphylla (*Retz.*)* A. DC	Motkila	Rutaceae	22.16

4.1.2 Study of regeneration of Sal plants through field experiment

4.1.2.1 Effects of forest management on the growth of Sal plants.

Results on the forest management effects on Sal seed germination rate in the Core zone and Buffer zone are shown in Figure 4.9. The management effect was significant in the Sal seed germination. The seed germination rate was much higher in the Buffer zone (77.33%) than in the Core zone (51%).

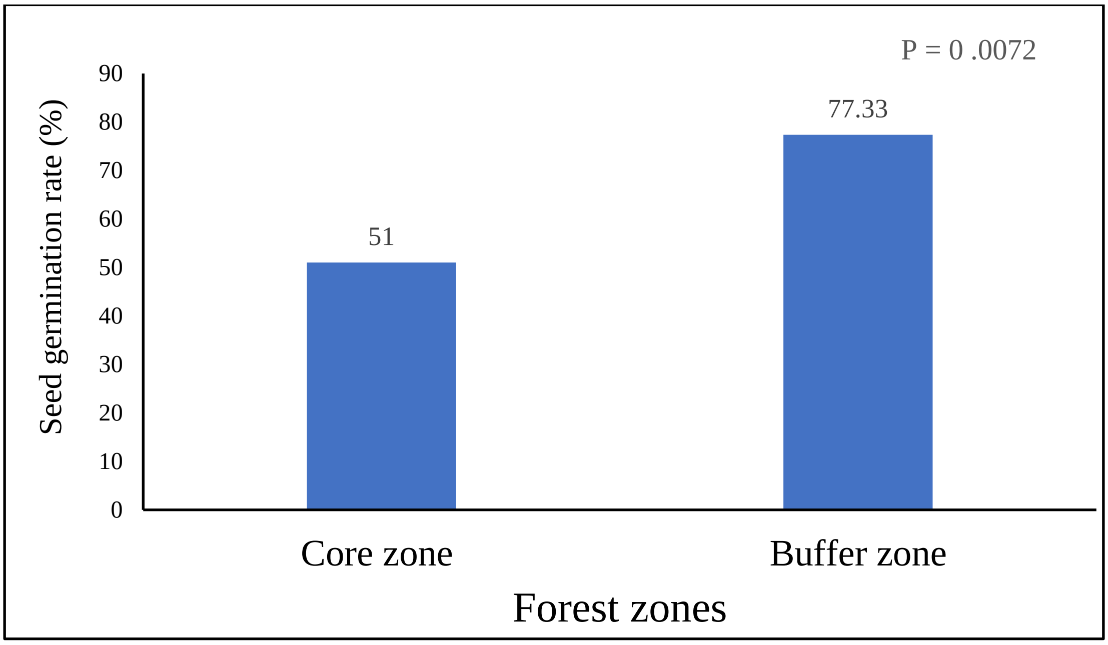

Figure 4.9: Mean values (± SEM) of the effects of forest management on the seed germination rate of Sal plants of Madhupur Sal forest.

The effects of forest management, time and their interaction on seedlings' survival rate, height and soil moisture in the Core zone and Buffer zone of the Madhupur Sal forest are shown in Table 4.11. The effects of forest management (P = <0.0001), month (P = <.0001) and their interaction (P = <0.0001) were highly significant on the number of seedlings. The effects of forest management (P = 0.0098) and month (P = 0.0009) on the seedling height were also significant. The effects of month (P = <0.0001) on the soil moisture content was highly significant in the Core zone and Buffer zone of the Madhupur Sal forest.

Table 4.11 Two-way ANOVA statistics on the effects of management (Core zone and Buffer zone) and time (month) on the survival rate and height of seedling and soil moisture in the Core zone and Buffer zone of the Madhupur Sal forest.

Parameters	Source of variation	df	F ratio	P value
Number of seedlings	Management	1	350.1293	<.0001
	Month	7	53.7200	<.0001
	Management x Month	7	13.5857	<.0001
Height of seedlings (cm)	Management	1	8.5979	0.0098
	Month	3	9.2137	0.0009
	Management x Month	3	0.2940	0.8292
Soil moisture (%)	Management	1	1.0417	0.3151
	Month	7	904.3750	<.0001
	Management x Month	7	1.3274	0.2698

The mean values of the effects of forest management (Core zone and Buffer zone), time (month) and their interaction on the number of seedlings during eight different studied months in the Core zone and the Buffer zone of Madhupur Sal forest are shown in Figure 4.10. The number of seedlings grown after sowing seeds in the field was much higher in the Buffer zone than in the Core zone during eight different studied months. The number of seedlings gradually decreased from October to February in both zones.

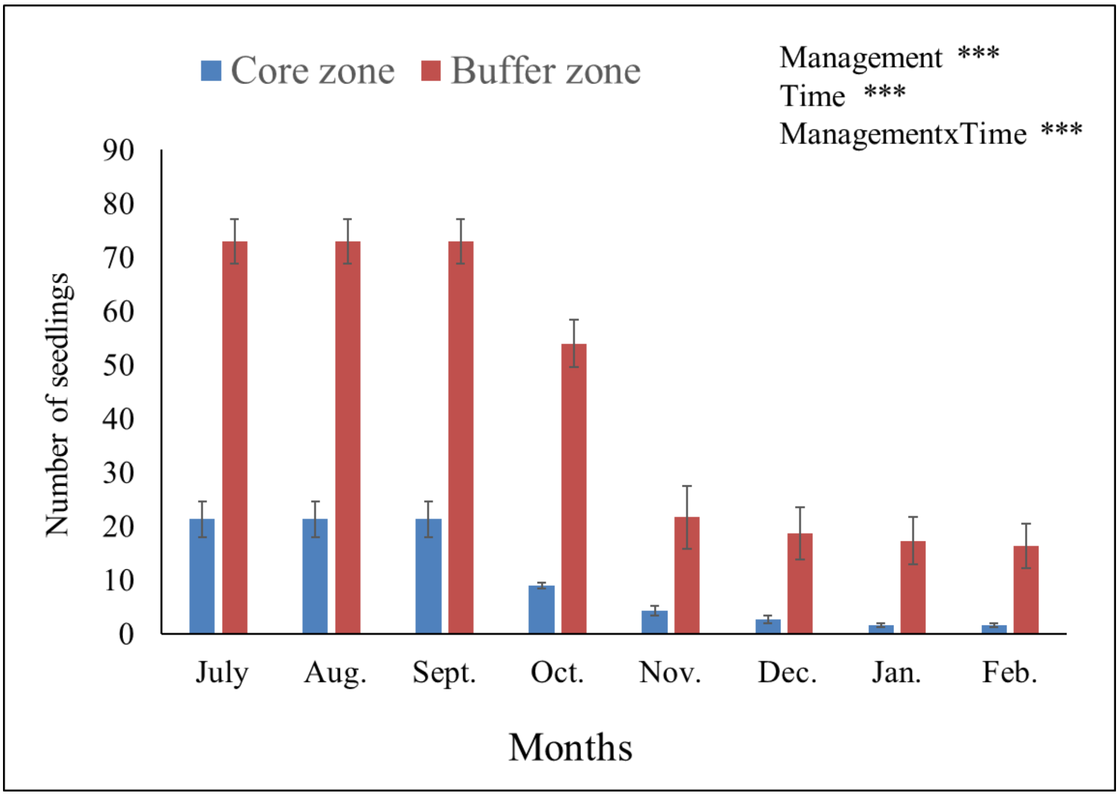

Figure 4.10: Mean values (± SEM) of the effects of forest management (Core zone and Buffer zone) and time (month) on the number of seedlings during eight different studied months in the Core zone and Buffer zone of the Madhupur Sal forest.

The mean values of the effects of forest management (Core zone and Buffer zone) and time (month) on the height of seedlings in four different studied months in the Core zone and Buffer zone of the Madhupur Sal forest are shown in Figure 4.11. The height of seedlings was higher in the Core zone than in the Buffer zone in four different studied months. The height of seedlings gradually increased from November to February in both zones of Madhupur Sal forest.

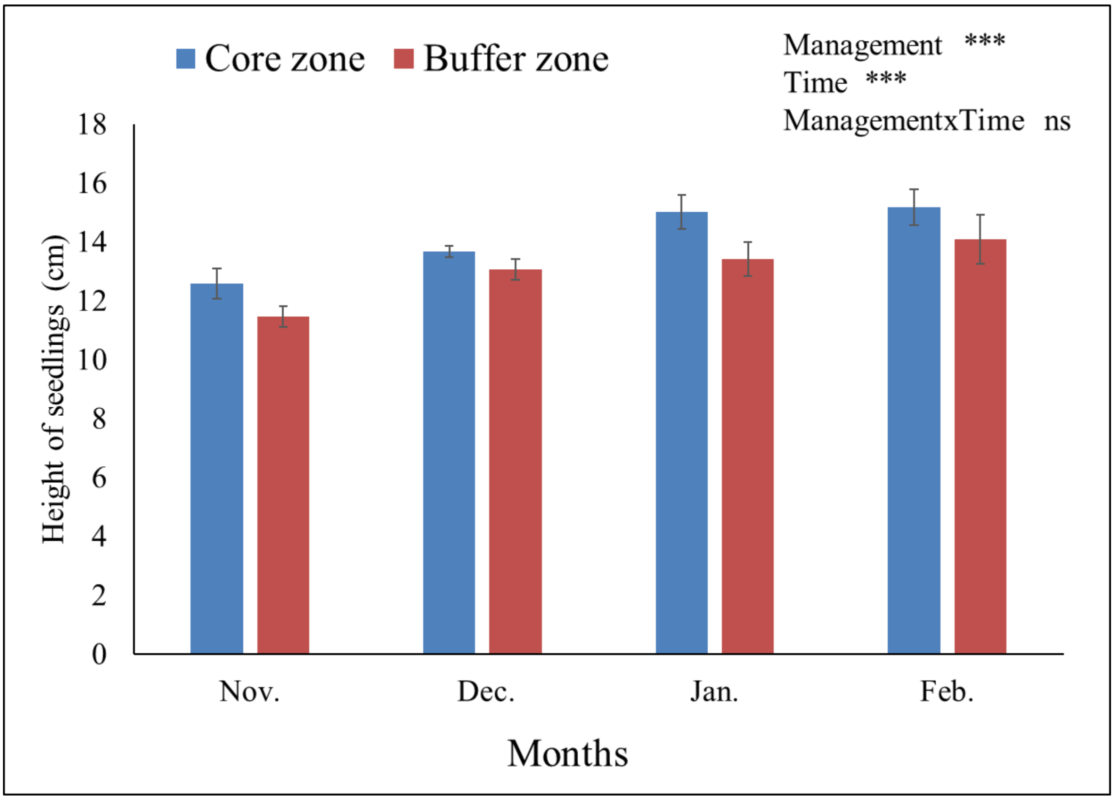

Figure 4.11: Mean values (± SEM) of the effects of forest management (Core zone and Buffer zone) and time (month) on the height of seedlings in the Core zone and Buffer zone of the Madhupur Sal forest.

The mean values of the effects of forest management (Core zone and Buffer zone) and time (month) on the percentage of soil moisture content during eight different months in the Core zone and Buffer zone of Madhupur Sal forest are shown in Figure 4.12. The percentage of the soil moisture content was almost the same in both zones of Madhupur Sal forest in the eight different studied months.

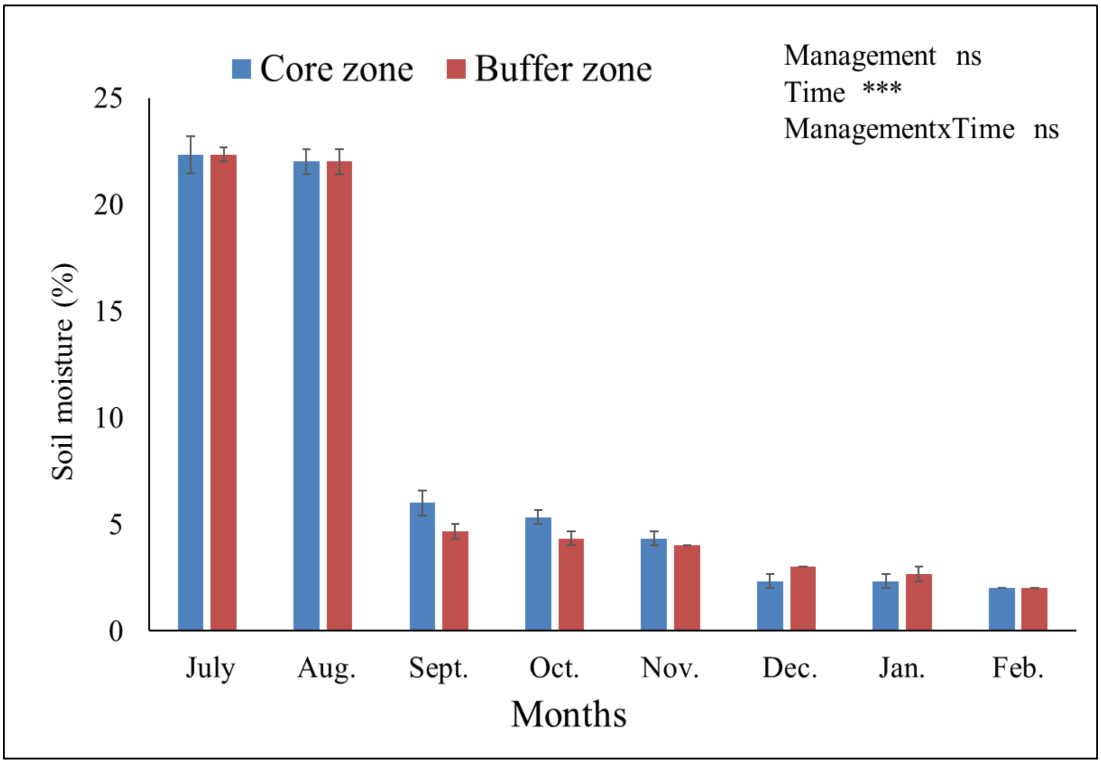

Figure 4.12: Mean values (± SEM) of the effects of forest management (Core zone and Buffer zone) and time (month) on the soil moisture content in the Core zone and Buffer zone of Madhupur Sal forest.

The mean values of the effects of forest management and seasons on the soil pH in the Core area and Buffer area of the Madhupur Sal forest are shown in Figure 4.13. There was no significant effect of management, seasons and their interaction on the soil pH of the study areas. The soil pH was almost the same in the Core zone and Buffer zone of Madhupur Sal forest. The mean value of soil pH ranged between 5.5 to 6.0.

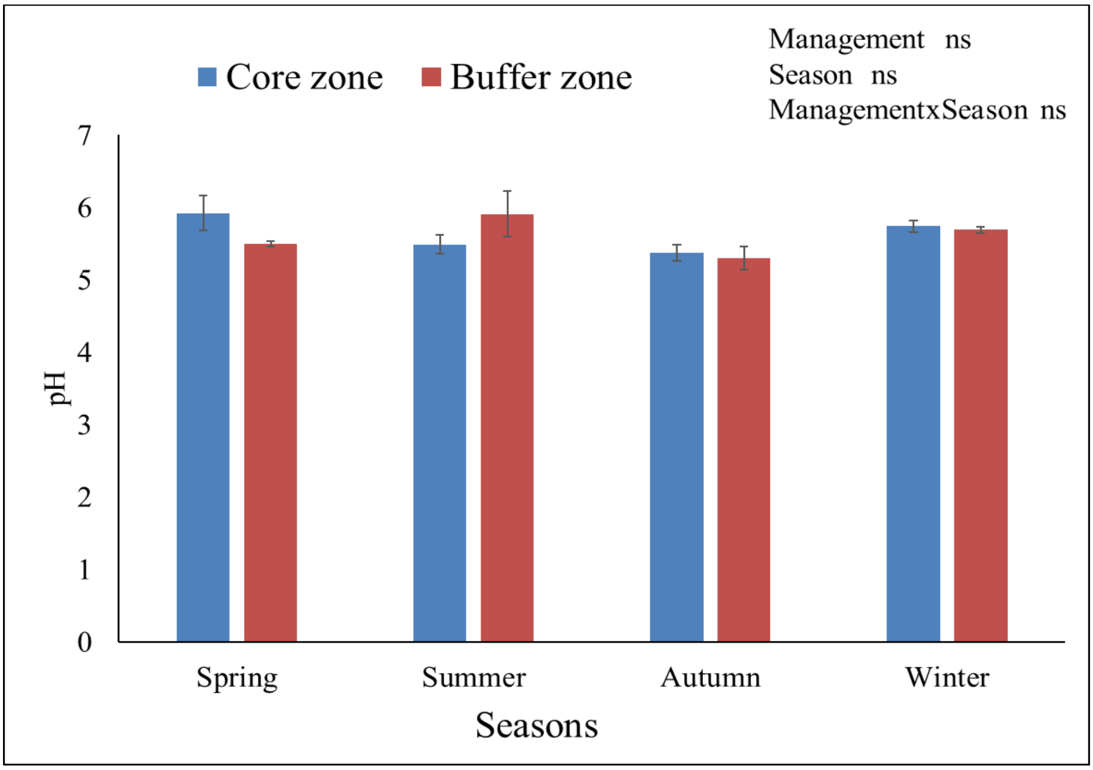

Figure 4.13: Mean values (± SEM) of the effects of forest management (Core zone and Buffer zone) and time (season) on the soil pH in the Core zone and Buffer zone of Madhupur Sal forest.

The mean values of the effects of forest management and seasons on the soil electrical conductivity in the Core zone and Buffer zone of the Madhupur Sal forest are shown in Figure 4.14. There was no significant effect of management, seasons and their interaction on the soil electrical conductivity. The soil electrical conductivity was relatively higher in the Buffer zone than in the Core zone of the Madhupur Sal forest.

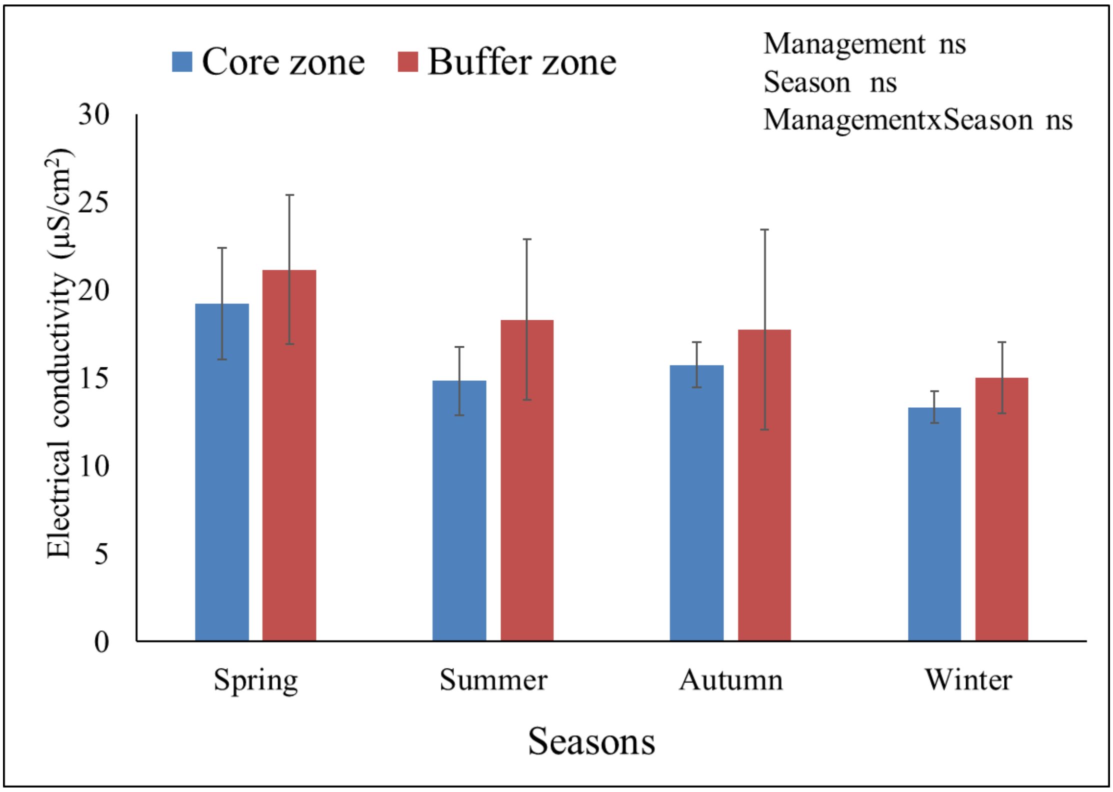

Figure 4.14: Mean values (± SEM) of the effects of forest management (Core zone and Buffer zone) and time (season) on the soil electrical conductivity in the Core zone and Buffer zone of Madhupur Sal forest.

Figure 4.15: Photos showing the plots selected for the germination test of the seeds of Sal plants in the Core zone and Buffer zone of the Madhupur Sal forest.

4.2 Study of leaf phenology of Sal plants

4.2.1 Study of leaf phenology of Sal plants by leaf counting

Morphometric properties of the selected plants

A comparison in shoot height of the selected Sal plants of Madhupur Sal forest and Charkai Sal forest is shown in Figure 4.16a. There was no significant difference in shoot height of the selected Sal plants between the Madhupur Sal forest and Charkai Sal forest. A comparison in DBH (diameter at breast height) of the selected Sal plants of Madhupur Sal forest and Charkai Sal forest is shown in Figure 4.16b. There was no significant difference in DBH between the two Sal forests.

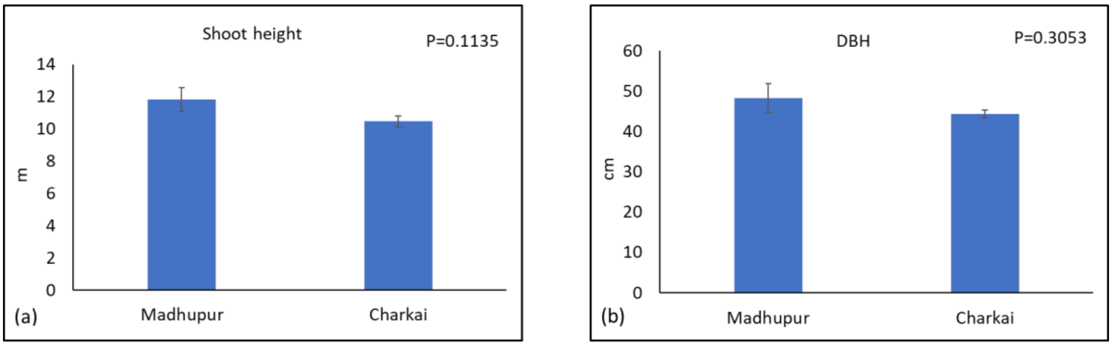

Figure 4.16: Mean values (± SEM) of shoot height (a) and DBH (b) of the selected Sal plants of Madhupur Sal forest Tangail and Charkai Sal forest Dinajpur (n=10 plants).

Functional properties of leaves of Sal plants

Figure 4.17 shows the leaf morphological traits of the selected Sal plants of Madhupur Sal forest and Charkai Sal forest. There was no significant difference in leaf length (Figure 4.17a), leaf breadth (Figure 4.17b), leaf perimeter (Figure 4.17c), leaf area (Figure 4.17d), specific leaf area (Figure 4.17e), leaf turgid weight (Figure 4.17g) and leaf dry weight (Figure 4.17h), but a significant difference was present in the leaf fresh weight (Figure 4.17f) between the two Sal forest sites.The higher fresh weight of the leaves of Sal plants in the Charkai Sal forest might be due to the reason that the leaves of this plant contained a higher amount of leaf water content.

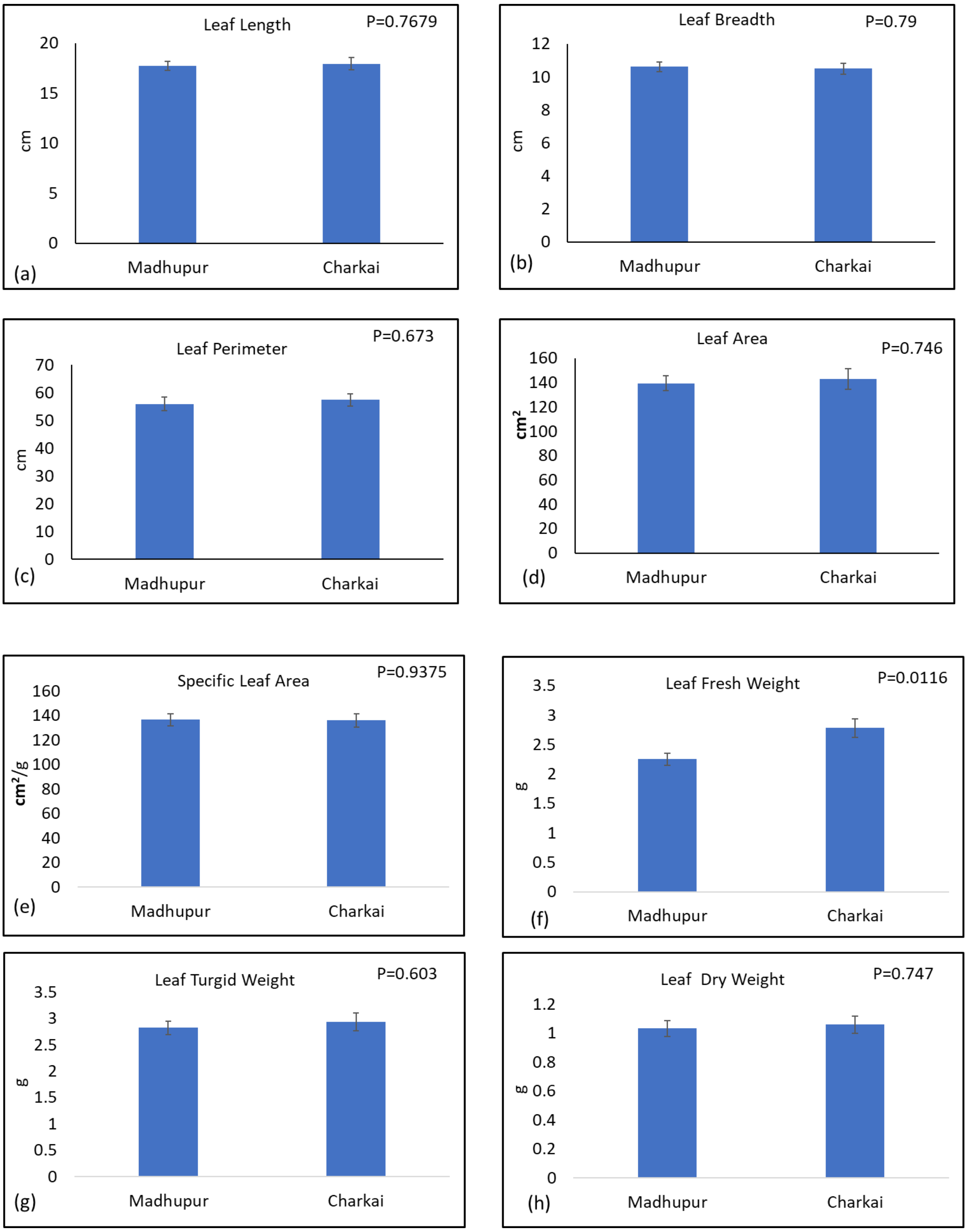

Figure 4.17: Mean values (± SEM) of the leaf morphological traits of the selected Sal plants of Madhupur Sal forest and Charkai Sal forest: Leaf length (a), Leaf breadth (b), Leaf perimeter (c), Leaf area (d), Specific leaf area (e), Leaf fresh weight (f), Leaf turgid weight (g) and Leaf dry weight (h); (n = 60).

Leaf physiological traits of the selected Sal plants of Madhupur Sal forest and Charkai Sal forest are shown in Figure 4.18. Significant difference was present in leaf water content (Figure 4.18a), leaf dry matter content (Figure 4.18b) and relative water content (Figure 4.18c), but there was no significant difference in chlorophyll content (Figure 4.18d) between the Madhupur Sal forest and Charkai Sal forests.

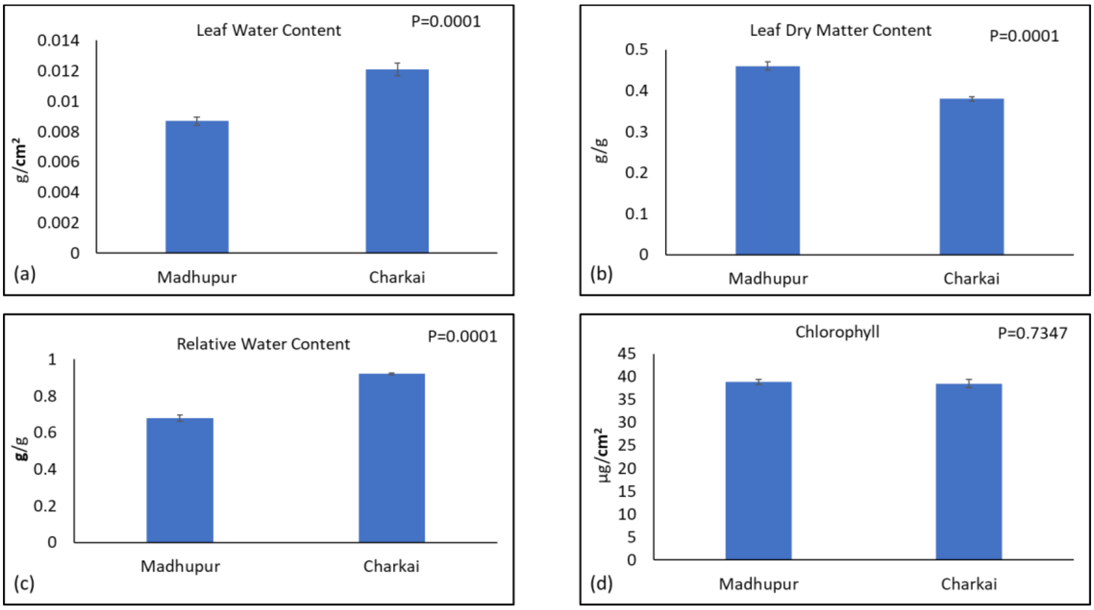

Figure 4.18: Mean values (± SEM) of the difference in leaf physiological traits of the selected Sal plants between Madhupur Sal forest and the Charkai Sal forest: Leaf water content (a), Leaf dry matter content (b), Relative water content (c) and Chlorophyll content (d); (n = 60).

Leaf anatomical traits of the selected Sal plants of the Madhupur Sal forest and Charkai Sal forest are shown in Figure 4.19. Significant differences were present in all the parameters of leaf anatomical traits such as stomatal length (Figure 4.19a), stomatal breadth (Figure 4.19b), stomatal density (Figure 4.19c), stomatal pore index (Figure 4.19d), percent of open stomata (Figure 4.19e) and percent of close stomata (Figure 4.19f).

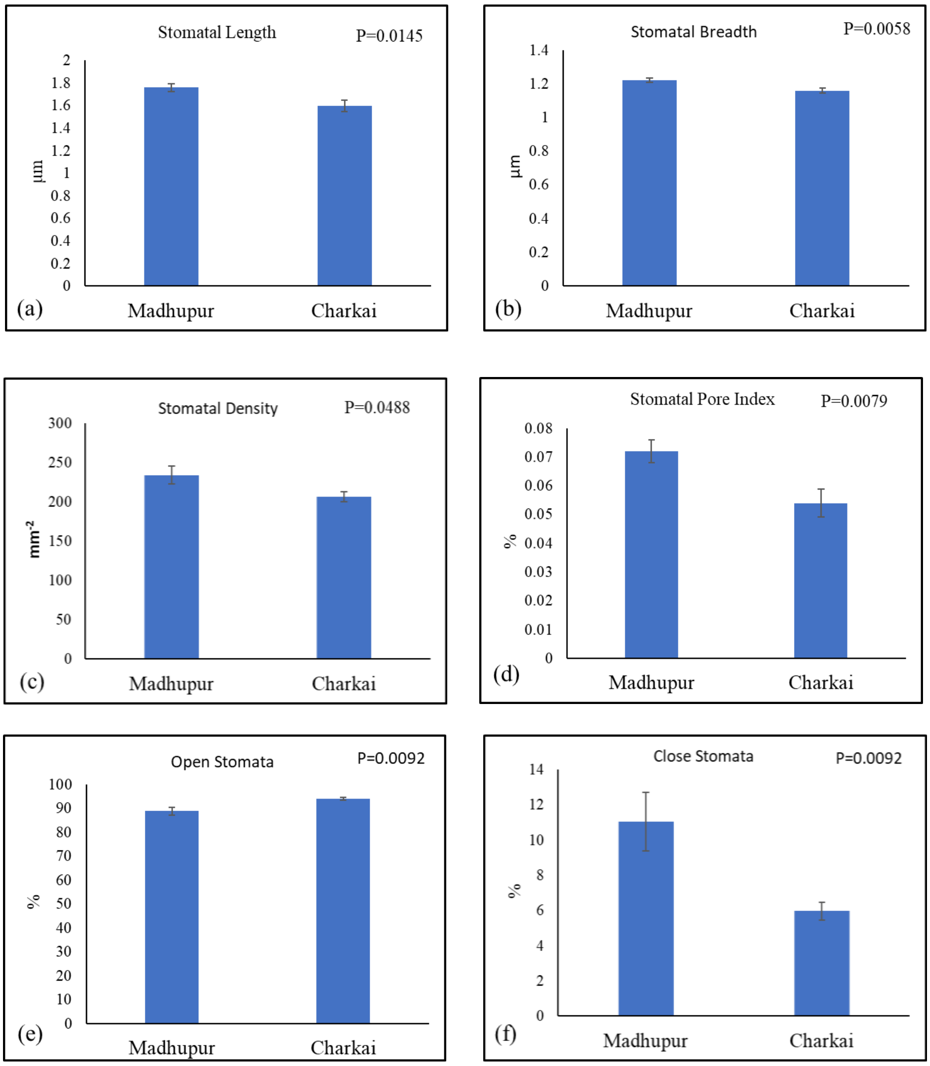

Figure 4.19**:** Mean values (± SEM) of the **l**eaf anatomical traits of selected Sal plants of Madhupur Sal forest and the Charkai Sal forest: Stomatal length (a), Stomatal breadth (b), Stomatal density (c), Stomatal pore index (d), Open stomata (e) and Close stomata (f), (n = 60).

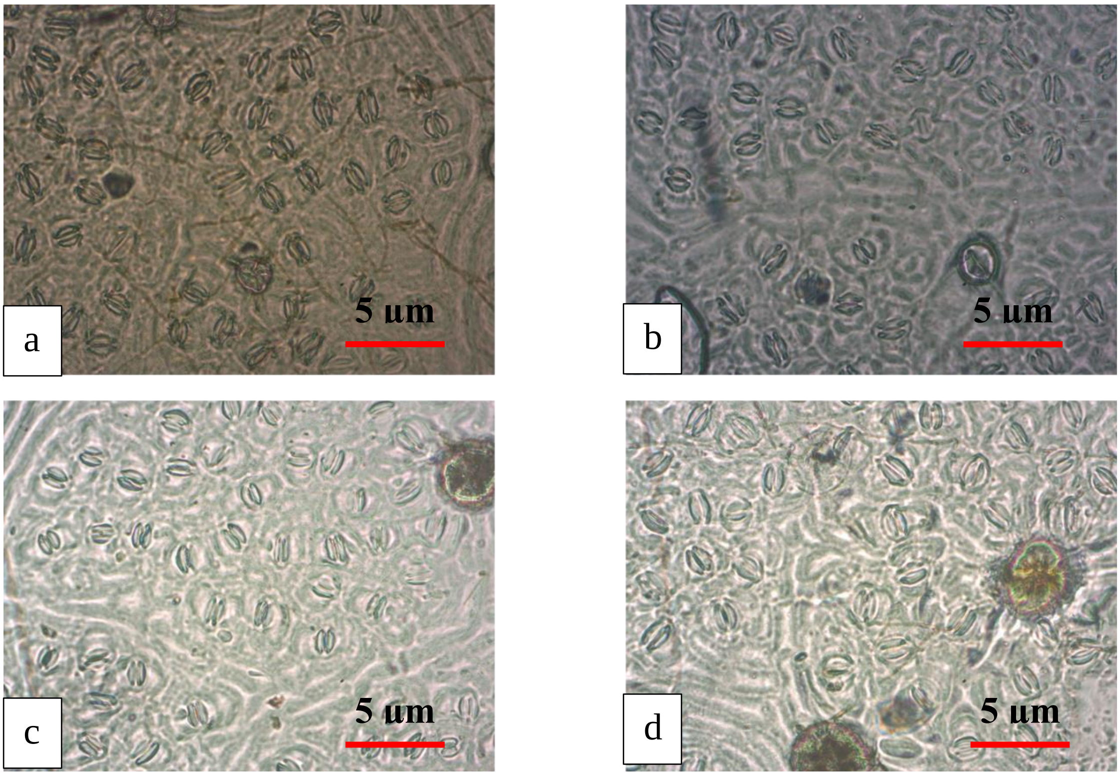

Figure 4.20: Photos showing the images of leaf stomata of the selected Sal plants of Madhupur Sal forest (a-b) and Charkai Sal forest (c-d) taken under microscope (Axio Lab, A1 Microscope, Carl Zeiss Microscopy GmbH, Germany) with (10x40) magnification.

Counts of leaf per twig:

The monthly average number of leaves per twig of the selected Sal plants of Madhupur Sal forest and Charkai Sal forest during the study period is shown in Figure 4.21. The maximum leaf fall was found in the month of February in all three years (2019, 2020 and 2021) in Madhupur Sal forest (Synchronous). On the other hand, the maximum leaf fall was noted in the month of March of the year 2019 and 2020 as well as in the month of February of the year 2021 in Charkai Sal forest (Asynchronous). The maximum number of leaf-out was seen in the month of March of the year 2019, 2020 and 2021 in Madhupur Sal forest (Synchronous). On the other hand, the maximum number of leaves out was seen in the month of May of the year 2019 and in the month of April of the year 2020 as well as in the month of March of the year 2021 in Charkai Sal forest Asynchronous).

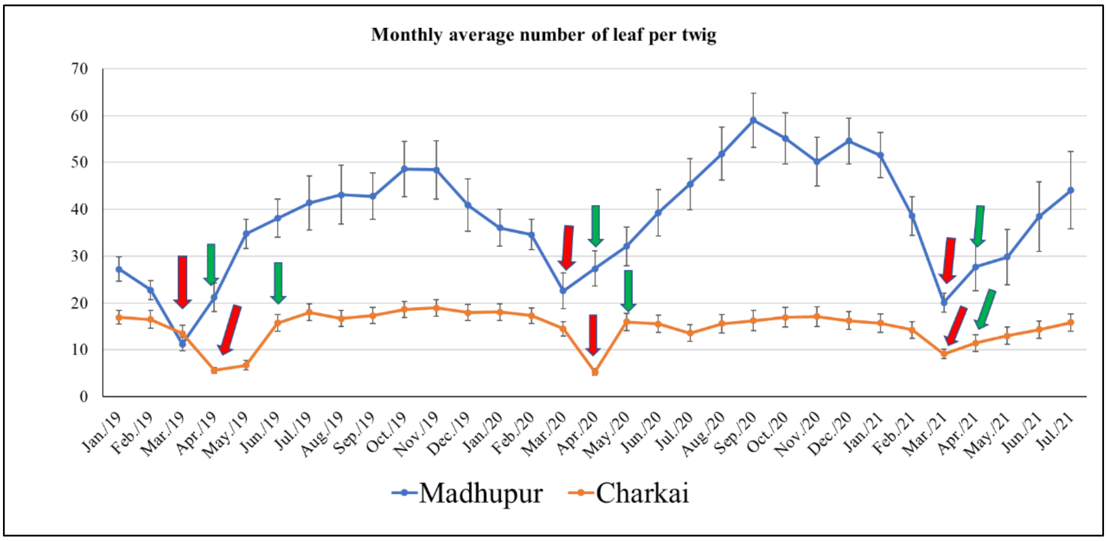

Figure 4.21: Monthly average number of leaves per twig of the selected Sal plants in the Madhupur Sal forest and Charkai Sal forest during the study period (January 2019 to July 2021).

The percentage of twigs with leaves of the selected Sal plants of Madhupur Sal forest and Charkai Sal forest during the study period (January 2019–July 2021) is shown in Figure 4.22. In 2019, only 20% and 22.5% of leafless twigs were seen in March and April, respectively, in Madhupur Sal forest, as well as 12.5% of leafless twigs were seen in May in Charkai Sal forest. In 2020, only 12.5% of leafless twigs were seen in March in Madhupur Sal forest and only 15% of leafless twigs were seen in April in Charkai Sal forest. In 2021, only 2.5% of leafless twigs were seen in May in Madhupur Sal forest and only 7.5% of leafless twigs were seen in April in Charkai Sal forest.

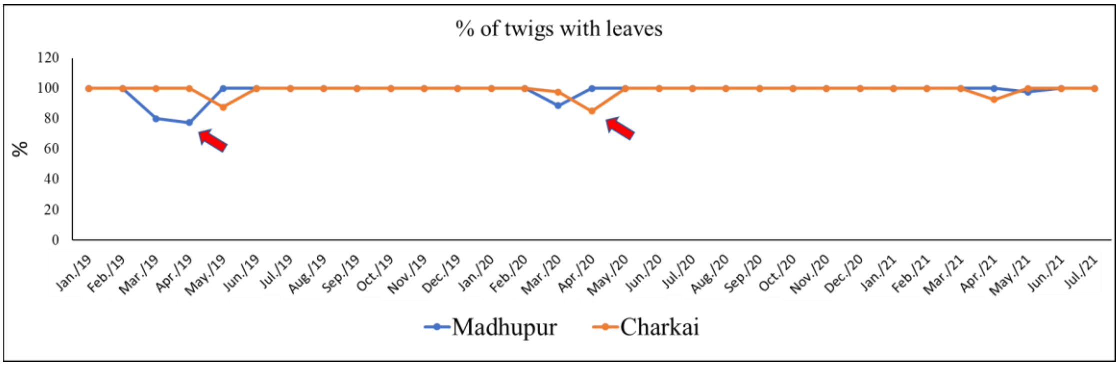

Figure 4.22: Percentage of twigs with leaves of the selected Sal plants of Madhupur Sal forests and Charkai Sal forests during the study period (January 2019 to July 2021).

Soil properties of Sal plants selected for leaf counts

Figure 4.23 shows the monthly average values of soil moisture, pH and electrical conductivity and yearly values of soil moisture, pH and electrical conductivity of Madhupur Sal forest and Charkai Sal forest. The monthly values of soil moisture (Figure 4.23a), pH (Figure 4.23b) and electrical conductivity (Figure 4.23c) were almost the same in both forests. Monthly soil moisture content was higher in the wet seasons than in the dry season in both forests. There was no significant difference in yearly average soil moisture (Figure 4.23d), pH (Figure 4.23e) and electrical conductivity (Figure 4.23f) between Madhupur Sal forest and Charkai Sal forest, though the yearly soil moisture, pH and electrical conductivity in Madhupur Sal forest were slightly higher than in Charkai Sal forest. The Madhupur Sal forest and Charkai

Sal forest showed variation in the yearly average values of soil moisture (17.33 vs 16.47), pH (5.87 vs 5.79) and electrical conductivity (39.22 vs 33.53. The yearly average values were almost the same in both forests.

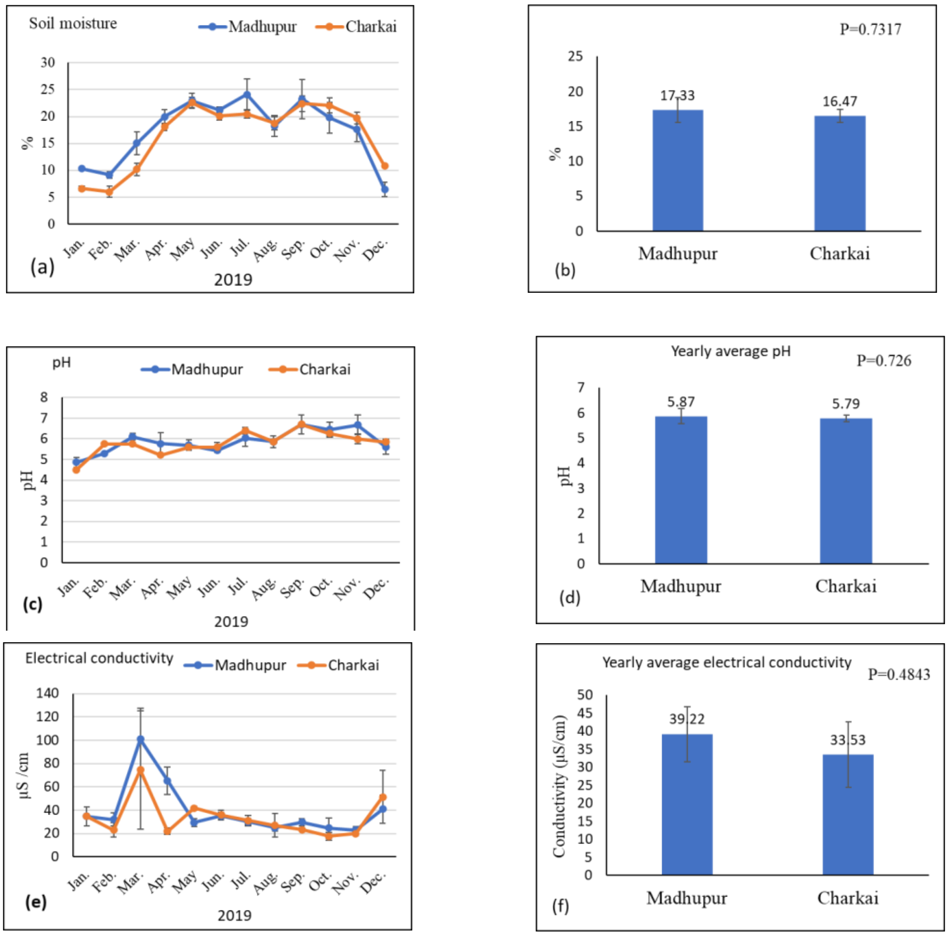

Figure 4.23: Monthly and yearly average soil moisture (a, b), pH (c, d) and electrical conductivity (e, f) of Madhupur Sal forest and the Charkai Sal forest.

4.2.2 Effects of soil moisture on the growth of Sal plants

The effects of water treatments at 3 days, 5 days and 7 days intervals on the plant height and the number of branches per plant of Sal plants grown under experimental conditions in the garden are shown in Figure 4.24. The maximum plant height was found at the treatment of 5 days interval compared to the other two treatments and the plant height was higher at 3 days of interval than that at 7 days of interval of water treatment. The maximum number of branches per plant was found at the water treatments of 3 days of interval and the minimum number of that was seen at 5 days of interval of water treatment.

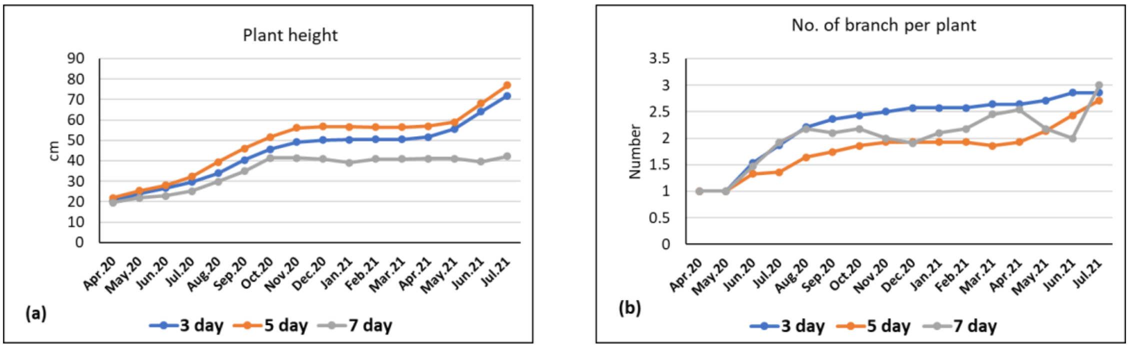

Figure 4.24: Effects of water treatments of 3 days, 5 days and 7 days interval on plant height (a) and number of branches per plant (b) of Sal plants grown under experimental conditions in the garden.

Effects of water treatments at 3 days, 5 days and 7 days intervals on the leaf morphological traits are shown in Figure 4.25. Significant effects of water treatments at 3 days, 5 days and 7 days interval were present on the leaf length (Figure 4.25a), leaf breadth (Figure 4.25b), leaf perimeter (Figure 4.25c), leaf area (Figure 4.25d), leaf fresh weight (Figure 4.25f), leaf turgid weight (Figure 4.25g) and leaf dry weight (Figure 4.25h) of Sal plants grown under experimental conditions in the garden.

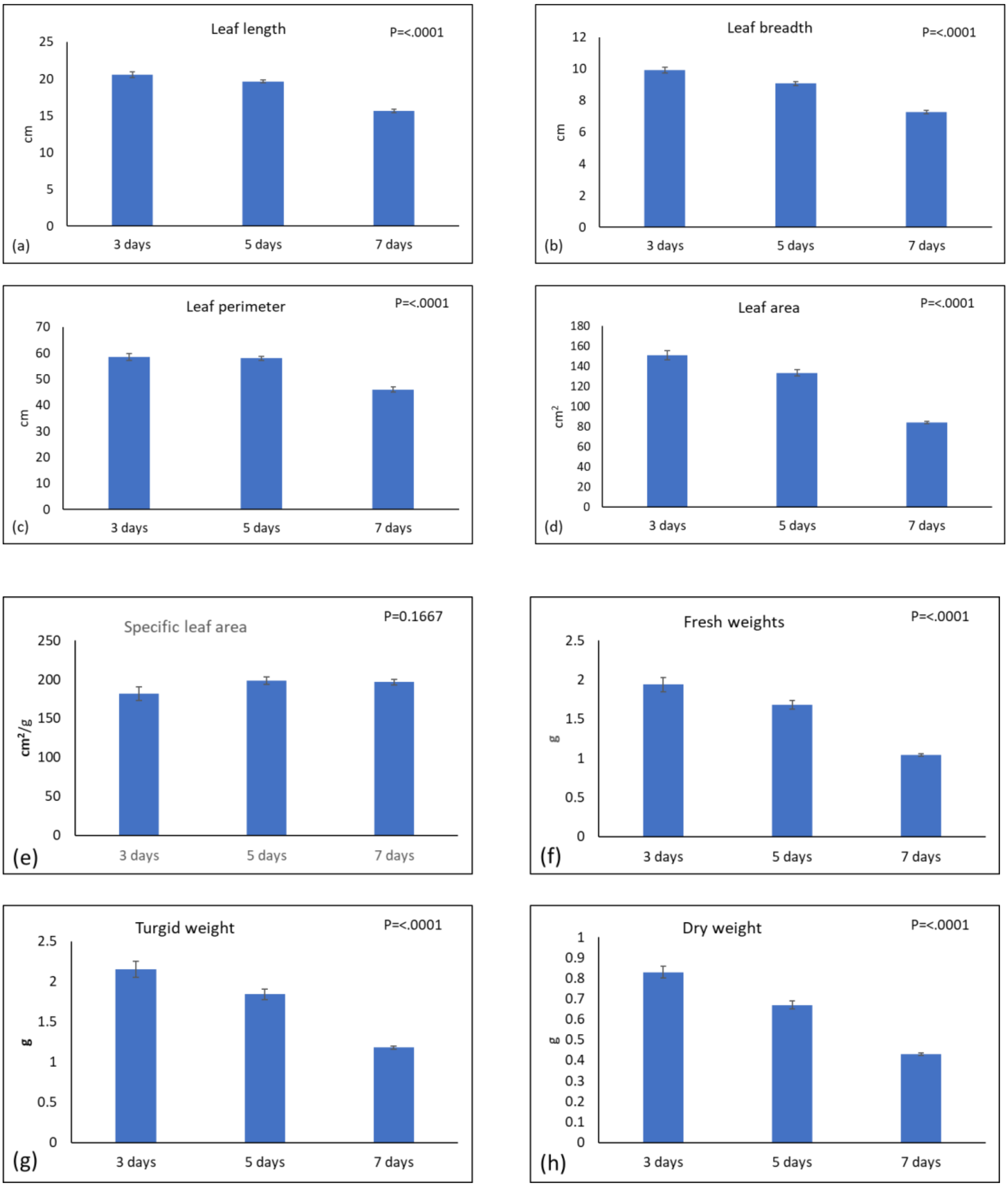

Figure 4.25: Mean values (± SEM) of the effects of water treatments at 3 days, 5 days and 7 days interval on leaf morphological traits: leaf length (a), leaf breadth (b), leaf perimeter (c), leaf area (d), specific leaf area (e), fresh weight (f), turgid weight (g) and dry weight (h) of Sal plants grown in the garden.

Effects of water treatments at 3 days, 5 days and 7 days intervals on the leaf physiological traits are shown in Figure 4.26. Significant effects of water treatments at 3 days, 5 days and 7 days intervals were found on the leaf dry matter content (Figure 4.26b) and relative water content (Figure 4.26c) of Sal plants grown under experimental conditions in the garden. Leaf dry matter content was higher (0.43) in 3 days intervals treatment plants than in the 5 days (0.4) and 7 days (0.41) intervals treatment plants. Relative water content was higher in 5 days intervals (0.86) treatment plants than in the 3 days (0.84) and 7 days (0.81) intervals treatment plants.

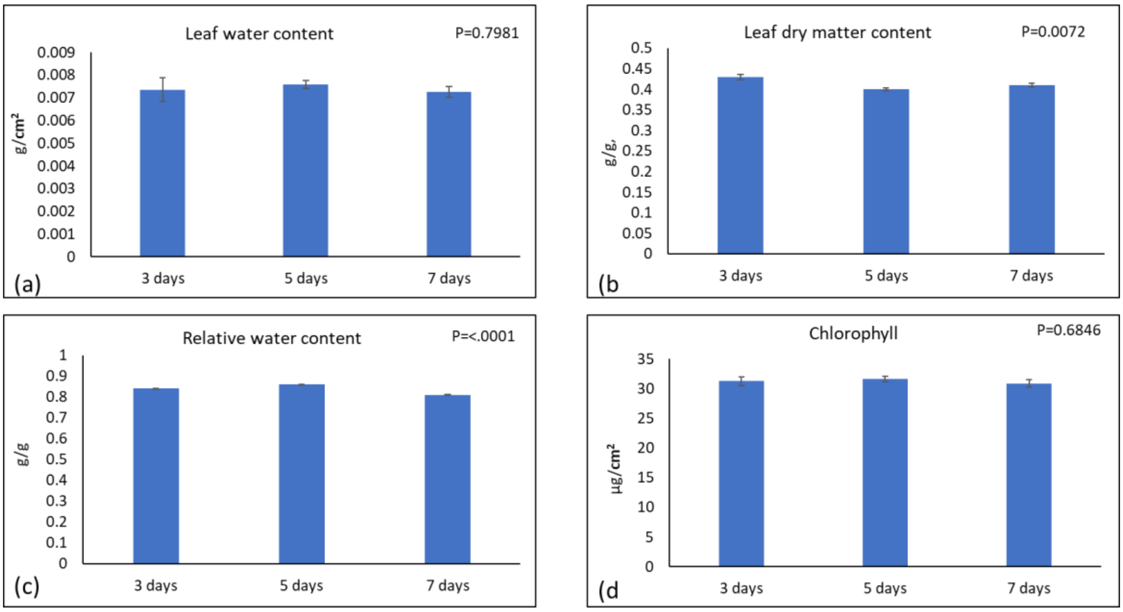

Figure 4.26: Mean values (± SEM) of the effects of water treatments at 3 days, 5 days and 7 days interval on leaf physiological traits: leaf water content (a), leaf dry matter content (b), relative water content (c) and chlorophyll content (d) of Sal plants grown under experimental condition in the garden.

The effects of water treatments of 3 days, 5 days and 7 days intervals on the leaf anatomical traits are shown in Figure 4.27. Significant effects of water treatment at 3 days, 5 days and 7 days intervals of water treatments were found in the stomatal density (Figure 4.27c) and stomatal pore index (Figure 4.27d) of Sal plants grown under experimental conditions in the garden. Stomatal density was higher in 5 days (177.9) intervals treatment plants than in the 3 days (163.24) and 7 days (144.27) intervals treatment plants. Stomatal pore index was also higher in 5 days (0.05107) intervals treatment plants than in the 3 days (0.04257) and 7 days (0.03741) intervals treatment plants.

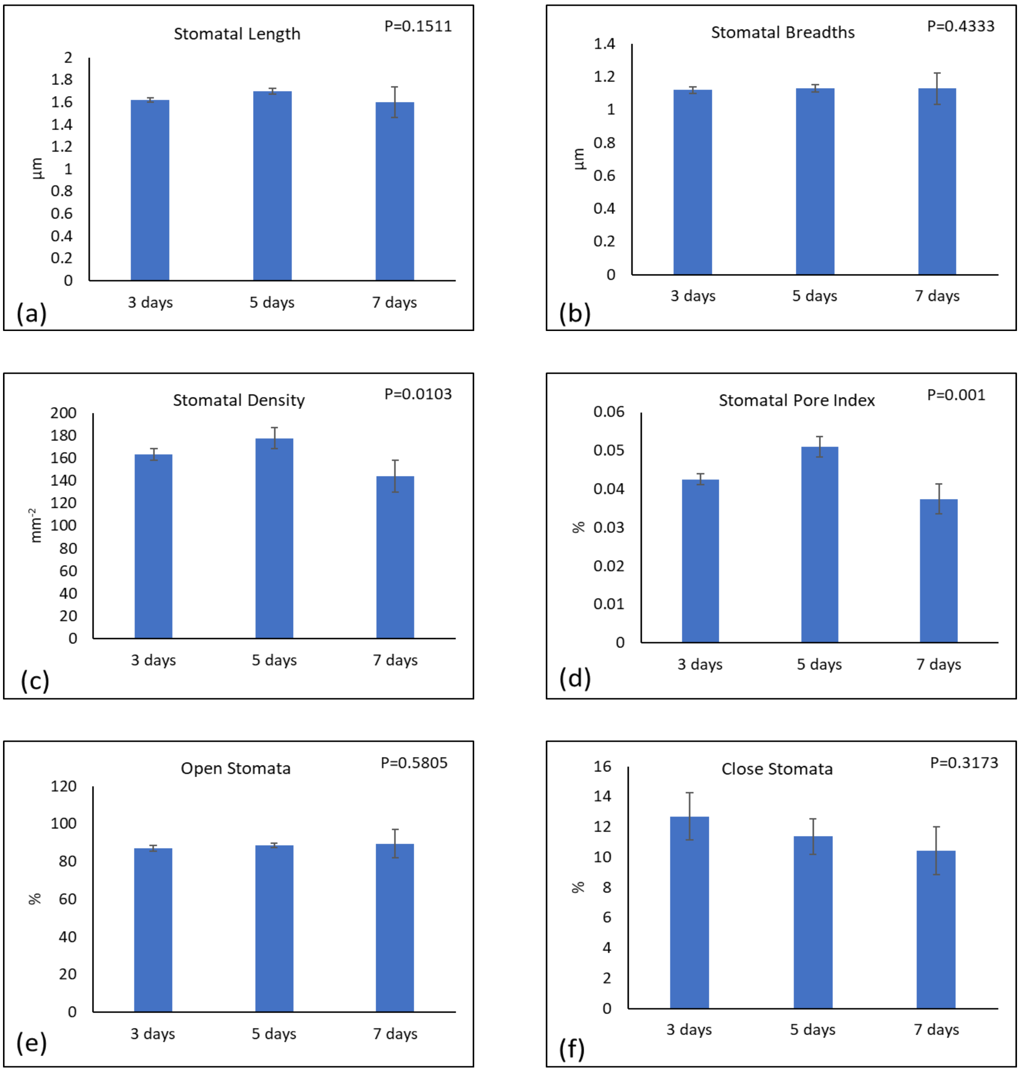

Figure 4.27: Mean values (± SEM) of the effects of water treatments at 3 days, 5 days and 7 days interval on leaf anatomical traits: stomatal length (a), stomatal breadth (b), stomatal density (c), stomatal pore index (d), % of open stomata (e) and % of closed stomata (f) of Sal plants grown under experimental condition in the garden.

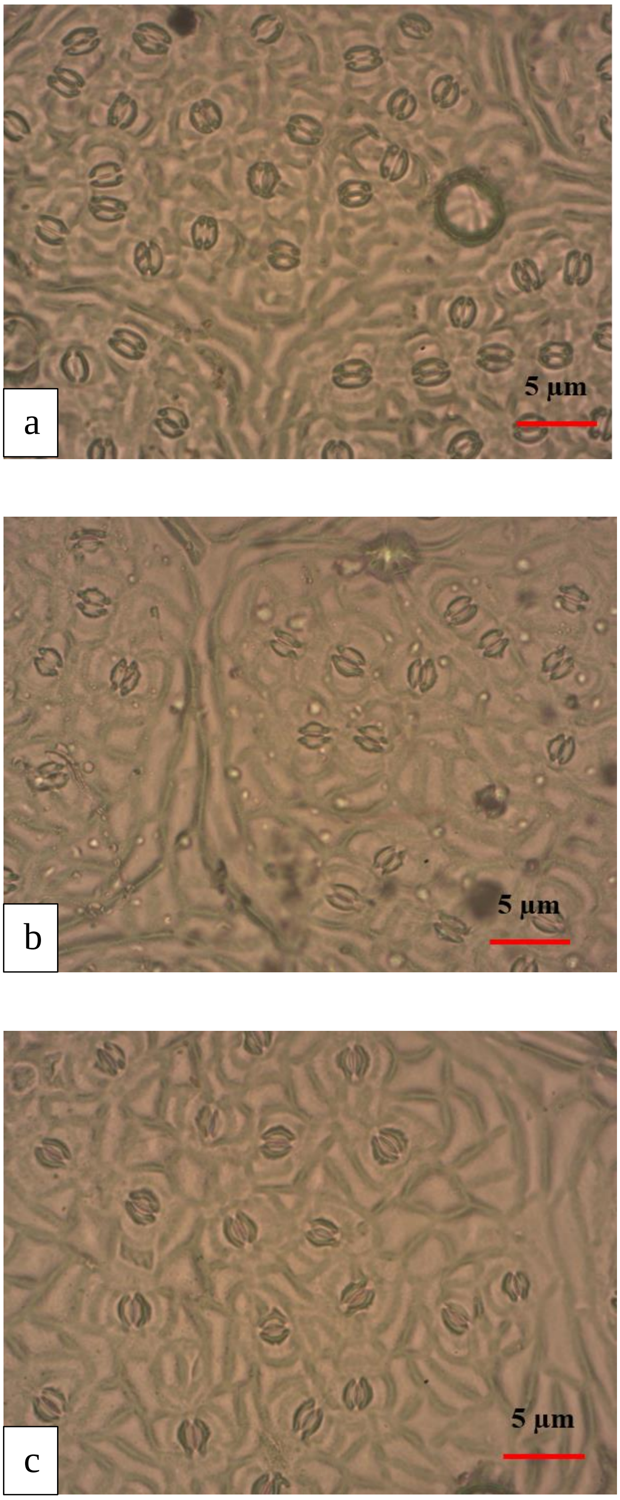

Figure 4.28: Images of stomata of leaf of Sal plants grown under experimental condition in the garden at 3 days (a), 5 days (b) and 7 days (c) intervals of water treatment.

Figure 4.29: Photos showing Sal plants grown under experimental condition in the garden at 3 days interval of water treatment during March 2020 to July 2021.

Figure 4.30: Photos showing Sal plants grown under experimental condition in the garden at 5 days interval of water treatment during March 2020 to July 2021.

Figure 4.31: Photos showing Sal plants grown under experimental condition in the garden at 7 days interval of water treatment during March 2020 to July 2021.

The effects of water treatments at 3 days, 5 days and 7 days intervals of water treatment on the number of total leaves of Sal plants grown under experimental conditions in the garden are shown in Figure 4.32a. During the leaf exchange period (January-June), the maximum number of total leaves per plant was seen in the month of February at 3 days, 5 days and 7 days intervals of water treatments and the minimum number of total leaves was seen in the month of April at 3 days and 5 days and 7 days intervals of water treatment plants. New leaf formation was seen in April at 3 days and 5 days as well as in May at 7 days interval of water treatment.

The effects of water treatments at 3 days, 5 days and 7 days intervals on the number of old leaves of Sal plants grown under experimental conditions in the garden are shown in Figure 4.32b. During the leaf exchange period (January-June), the maximum number of old leaves per plant was seen in the month of February at 3 days, 5 days and 7 days intervals of water treatments; the minimum number of old leaves was seen in the month of May at 3 days and 5 days intervals of water treatments and the minimum number of old leaves at 7 days intervals of water treatment was seen in the month of June.

The effects of water treatments at 3 days, 5 days and 7 days intervals on the number of new leaves of Sal plants grown under experimental conditions in the garden are shown in Figure 4.32c. New leaf formation per plant was not found from January to the beginning of April at 3 days, 5 days and 7 days intervals of water treatment during the leaf exchange period (January–June). Leaf-out started in April at 3 days, 5 days and 7 days intervals of water treatment and the maximum number of new leaves was seen in June at 3 days, 5 days and 7 days intervals of water treatment.

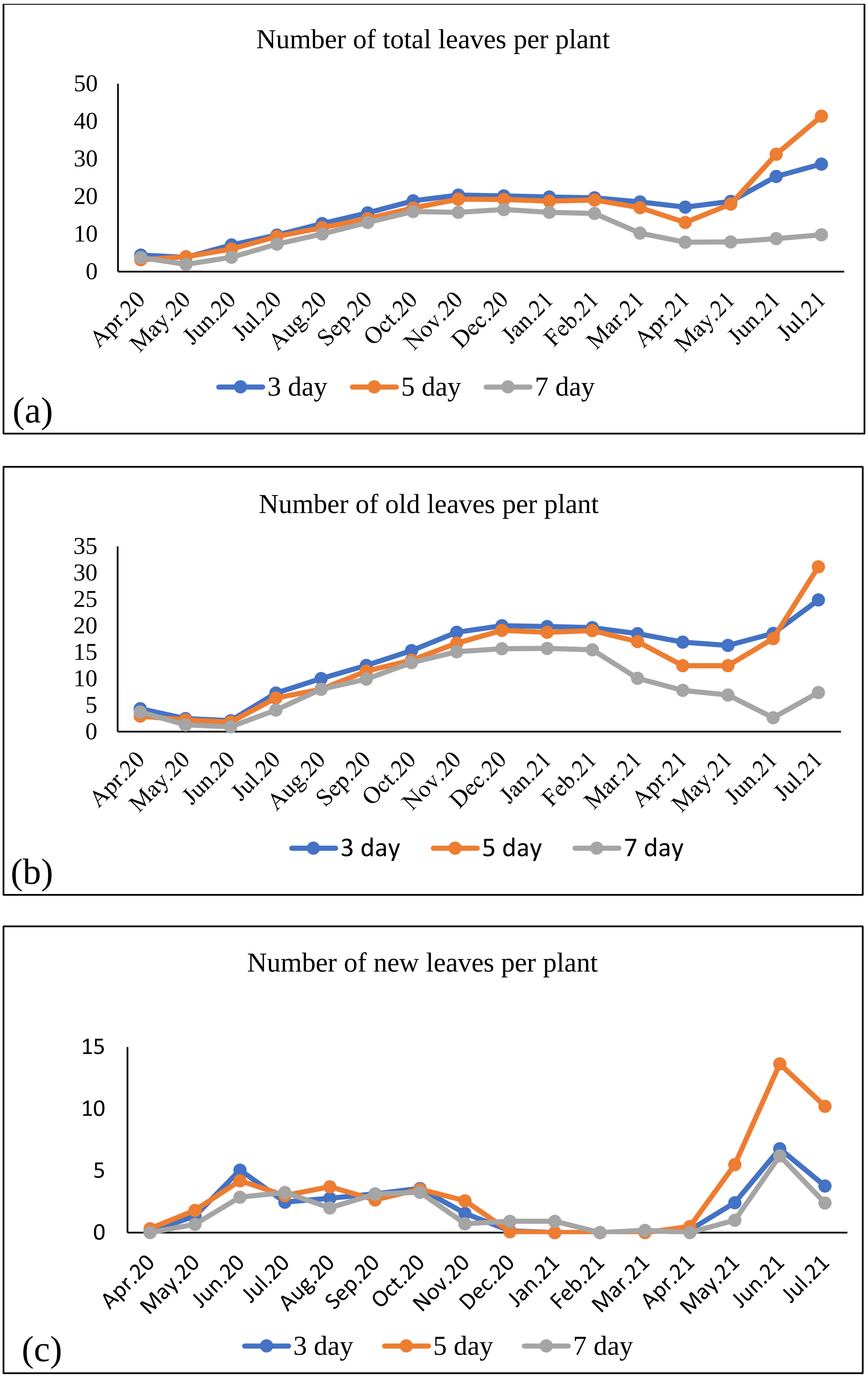

Figure 4.32: Effects of water treatments at 3 days, 5 days and 7 days intervals of water treatments on the number of total leaves (a), old leaves (b) and new leaves (c) of Sal plants grown under experimental condition in the garden.

Figure 4.33a depicts the composition (%) of old and new leaves of Sal plants grown under water treatment of 3 days intervals. The maximum number of old leaves (100%) was seen in the months of January and February and the maximum number of new leaves was seen in the months of June at 3 days interval of water treatment.

Figure 4.33b shows the composition (%) of old and new leaves of Sal plants grown under water treatment of 5 days intervals. The maximum number of old leaves (100%) was seen in the months of January to March and the maximum number of new leaves was seen in the month of June at 5 days interval of water treatment.

Figure 4.33c shows the composition (%) of old and new leaves of Sal plants grown under water treatment of 7 days intervals. The maximum number of old leaves (100%) was seen in the months of February to April and the maximum number of new leaves was seen in the month of June at 7 days interval of water treatment.

Figure 4.33: Composition (%) of new and old leaves of Sal plants grown under water treatments of 3 days interval (a), 5 days interval (b) and 7 days (c) interval.

The overall average soil moisture of the water treatments at 3 days, 5 days and 7 days intervals of water treatment applied to the Sal plants grown under experimental conditions in the garden are shown in Figure 4.34a. A significant difference was present in soil moisture content among 3 days, 5 days and 7 days intervals of water treatment. The soil moisture content at 3 days interval treatment was much higher than that at 7 days interval of water treatment and the soil moisture content at 5 days interval treatment was higher than that at 7 days interval of water treatment.

The monthly average soil moisture of the water treatments at 3 days, 5 days and 7 days intervals applied to the Sal plants grown under experimental conditions in the garden is shown in Figure 4.34b. The soil moisture content at 3 days interval of water treatment was higher than 5 days interval of water treatment and the soil moisture content at 5 days interval of water treatment was higher than at 7 days interval of water treatment. The monthly soil moisture content was higher in the wet season than in the dry season across the three types of intervals of water treatment.

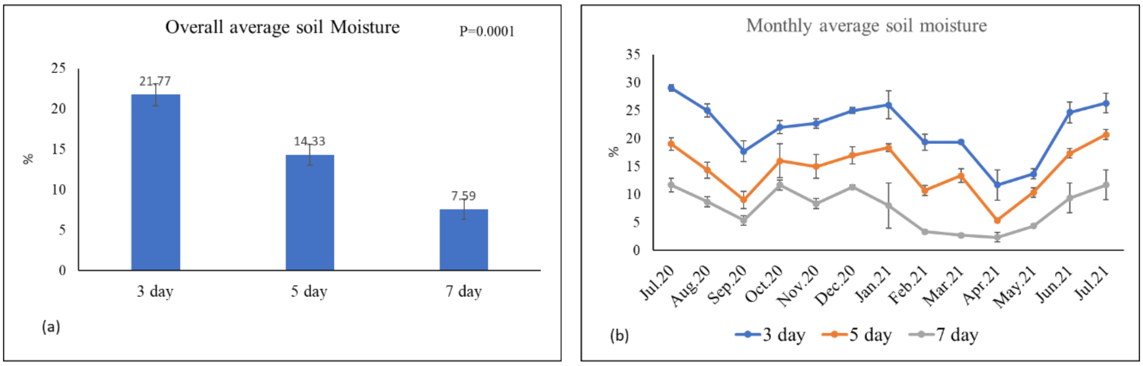

Figure 4.34: Overall average (a) and monthly average (b) soil moisture of the water treatments at 3 days, 5 days and 7 days intervals applied to the pots grown with Sal plants under experimental conditions in the garden.

Figure 4.35 shows the monthly soil pH and electrical conductivity (a-b) and the overall average soil pH and electrical conductivity (c-d) of the water treatments at 3 days, 5 days and 7 days intervals of water supplied to the Sal plants grown under experimental conditions in the garden. There was no significant difference in soil pH and electrical conductivity at 3 days, 5 days and 7 days intervals of water treatment.

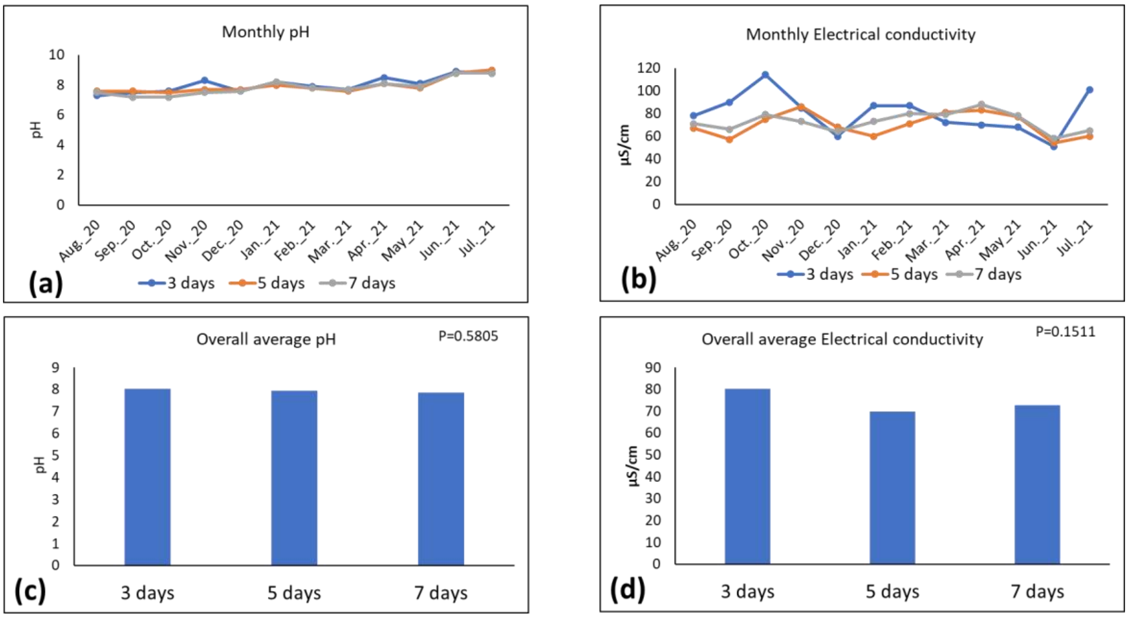

Figure 4.35: Monthly soil pH (a) and electrical conductivity (b) and overall average soil pH (c) and electrical conductivity (d) of the water treatments of 3 days, 5 days and 7 days intervals of water supplied to the Sal plants grown under experimental condition in the garden.

4.3 Nutritional adaptation of Sal plants

The effects of forests (Madhupur Sal forest versus Charkai Sal forest) and age of leaves (Green leaf versus yellow leaf) on the concentrations of leaf Nitrogen (N), Phosphorus (P), Potassium (K) and chlorophyll are shown in Table 4.12. Forest effect was significant on the leaf N (P = <0.0001), K (P = 0.0019) and Chlorophyll content (P = 0.0003). Effects of age of leaf on the leaf N (P = <0.0001), P (P = 0.0011), K (P = <0.0001) and Chlorophyll content (P= <0.0001). The interactions between forests and age of leaves were significant for leaf N (P = <0.0001), P (P = 0.0379), K (P = <0.0001) and Chlorophyll content (P= 0.0111).

Table 4.12 Two-way ANOVA statistics on the effects of forests (Madhupur Sal forest vs Charkai Sal forest) and the age of leaf (Green leaf vs yellow leaf) in the deciduous forest of Bangladesh.

Property	Source of variation	f	p
N	Forest type	139.7544	<.0001
	Age of leaf	894.6179	<.0001
	F x A	89.0009	<.0001
P	Forest type	1.3715	0.2753
	Age of leaf	24.4568	0.0011
	FxA	6.1639	0.0379
K	Forest type	20.6298	0.0019
	Age of leaf	326.8480	<.0001
	FxA	164.0105	<.0001
Chlorophyll	Forest type	36.6573	0.0003
	Age of leaf	2321.086	<.0001
	FxA	10.7904	0.0111

Figure 4.36 shows the (%) of leaf N in mature green leaves and old yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest. The percentage of N in matured green leaves (2.8) was higher than in the old yellow leaves (2.1) of Madhupur Sal forest and it was also higher in the matured green leaves (3.52) than in the old yellow leaves (2.18) of Charkai Sal forest. The percentage of N in both green leaves and in yellow leaves was higher in Charkai Sal forest than in Madhupur Sal forest.

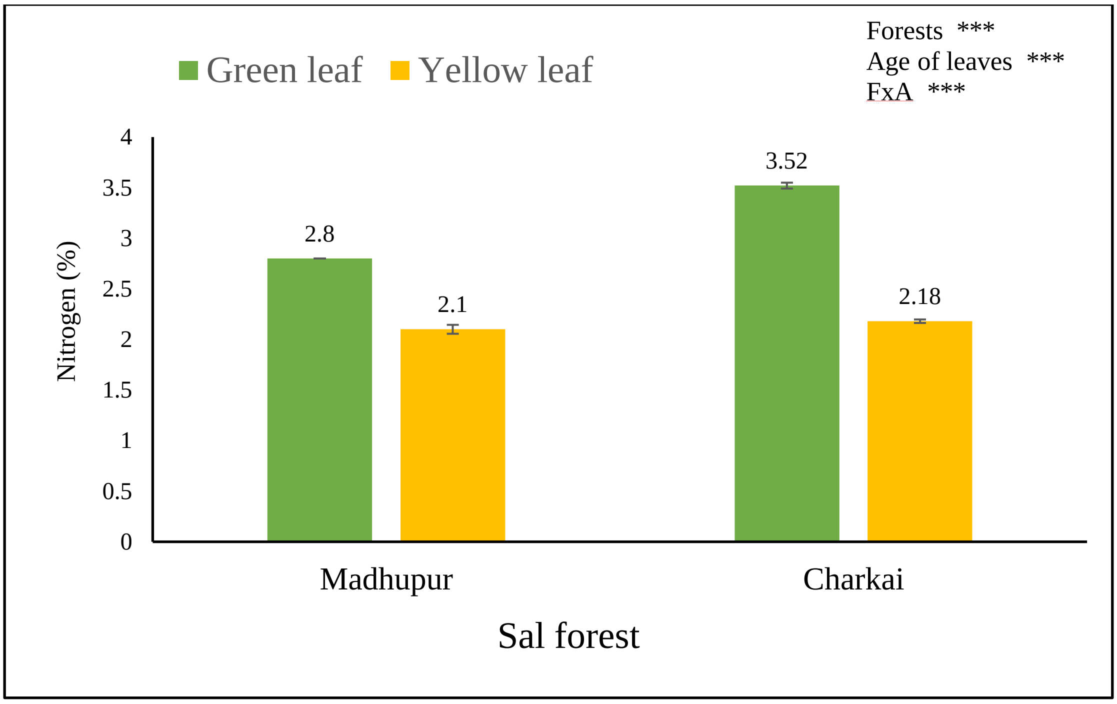

Figure 4.36: Nitrogen content (%) of green leaves and yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest.

Figure 4.37 shows the (%) of leaf P in green leaves and yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest. The percentage of P in matured green leaves (0.255) was higher than in the old yellow leaves (0.194) of Madhupur Sal forest and it was also higher in the matured green leaves (0.346) than in the old yellow leaves (0.161) of Charkai Sal forest.

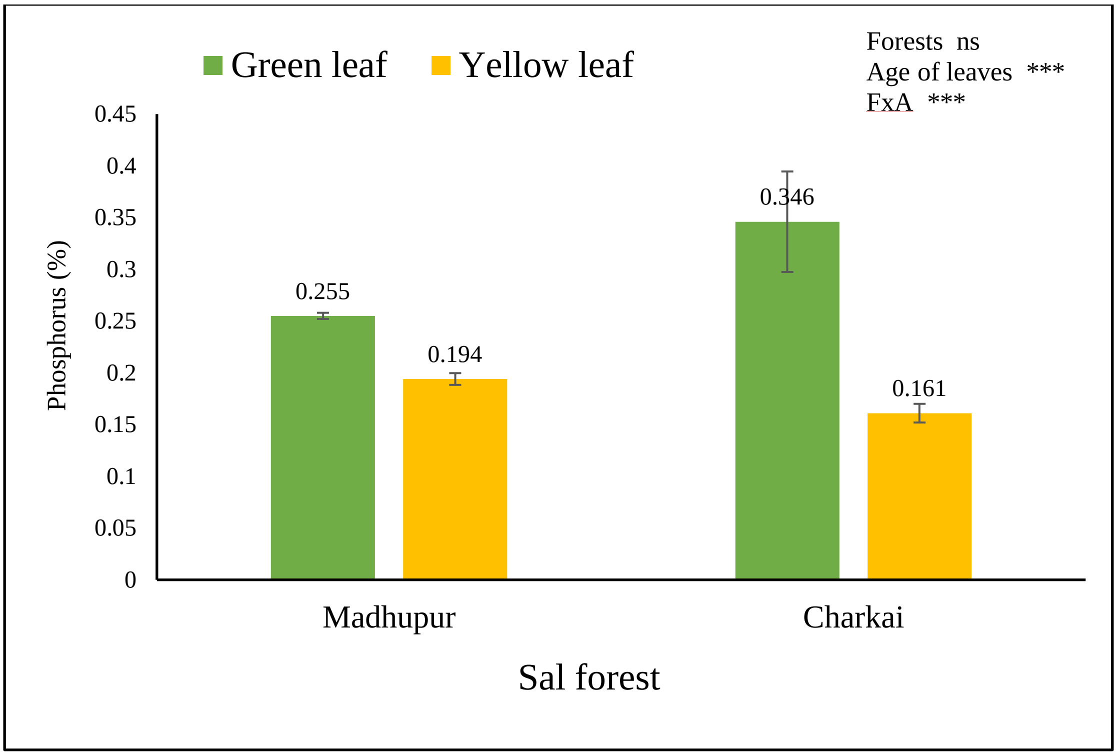

Figure 4.37: Phosphorus content (%) of green leaves and yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest.

Figure 4.38 shows the mean values of K (%) content in green leaves and yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest. The K content in matured green leaves was higher (0.418%) than in the old yellow leaves (0.368%) of Madhupur Sal forest and it was also higher in the matured green leaves (0.58%) than in the old yellow leaves (0.291%) of Charkai Sal forest.

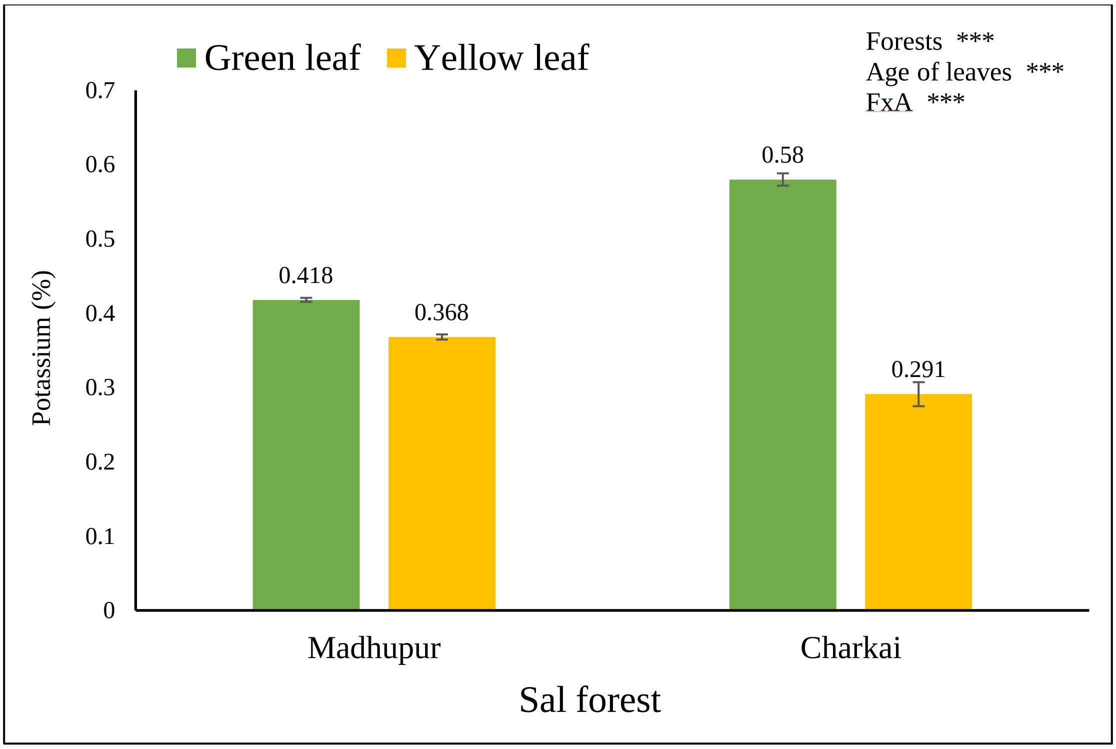

Figure 4.38: Potassium content (%) of green leaves and yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest.

Figure 4.39 shows the chlorophyll content in green leaves and yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest. The chlorophyll content was higher in matured green leaves (40.16 µg/cm^2) than in yellow leaves (17.23 µg/cm^2) of Madhupur Sal forest. Similar trend was found in Charkai Sal forest where chlorophyll content was much higher in the green leaves (36 µg/cm^2) than in the old yellow leaves (16 µg/cm^2).

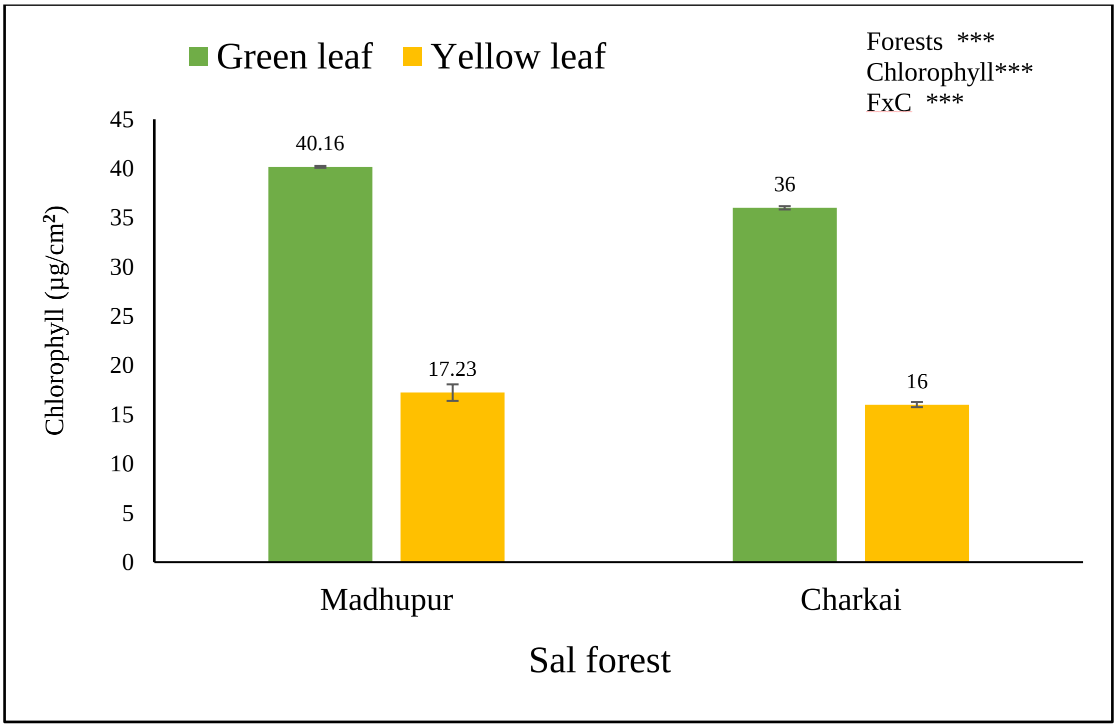

Figure 4.39: Mean value (± SEM) of the chlorophyll (µg/cm^2) of green leaves and yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest.

Figure 4.40 shows the percent of resorption of N, P and K from old yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest. The percent of resorption of nitrogen was 25% in the Madhupur Sal forest and it was 38.07% in the Charkai Sal forest. The percent of resorption of phosphorus was 23.92% in the Madhupur Sal forest and it was 45.66% in the Charkai Sal forest. The percent of resorption of potassium was 11.96% in the Madhupur Sal forest and it was 49.82% in the Charkai Sal forest. The percent of resorption of N, P and K was higher in the Charkai Sal forest than in the Madhupur Sal forest.

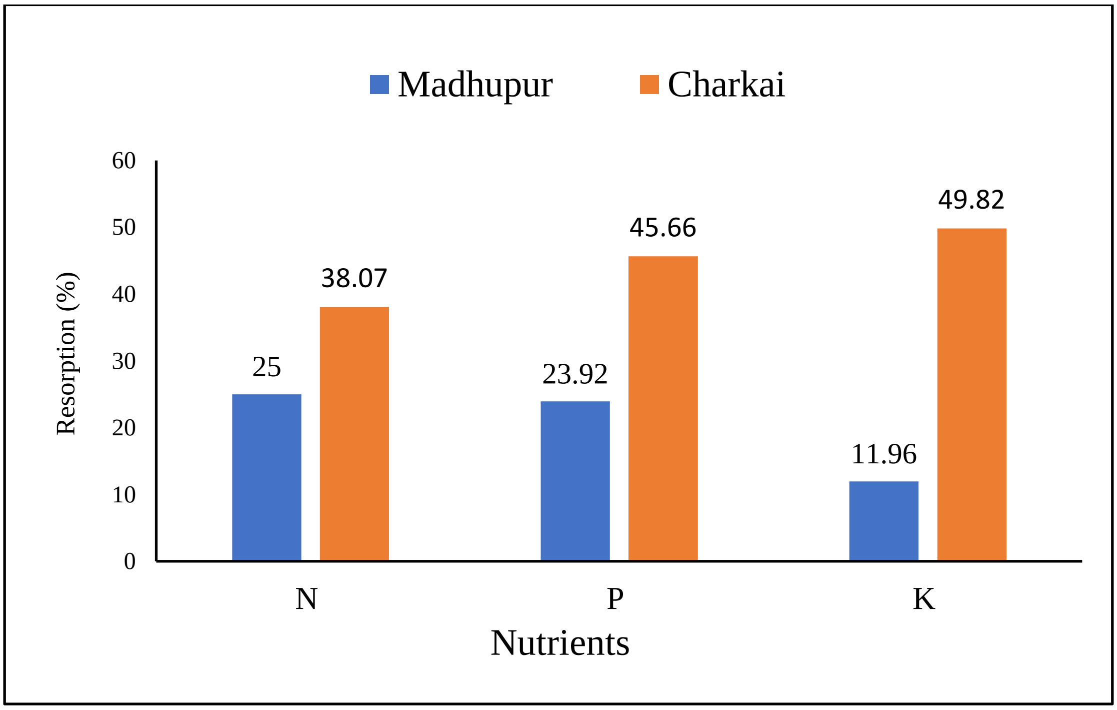

Figure 4.40: Resorption of nutrients (%) from old yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest.

CHAPTER 5

DISCUSSION

5.1 Effects of forest management on regeneration of Sal plants

The natural regeneration of Sal plants has been constrained by a number of factors including borer attack, lower viability of seed, less tolerance to drought condition, edapho-climatic changes and anthropogenic disturbances (Chazdon and Guariguata 2016). Some studies were done on ecological aspects of the Sal forests: land use effects (Kashem *et al.* 2015), soil nutrients (Sultana *et al.* 2009), microbial community (Hossain *et al.* 2010), seasonal variation of edaphic features (Hoque *et al.* 2009), anthropogenic disturbance and plant diversity (Rahman *et al.* 2009) and floristic composition (Malaker *et al.* 2010). However, several research questions on the factors affecting regeneration of *S. robusta* have not yet been addressed in the context of the environment of Bangladesh. Management interventions may cause changes in vegetation structure and abiotic environmental conditions which may influence seed germination and hence regeneration of the Sal plants. In order to ensure biodiversity conservation in the Protected Areas, the Forest Department has initiated a program on the management of Madhupur Sal forest. They declared Core area and Buffer area which differ in disturbance intensity, although its impact has not yet been studied. Therefore, an attempt was made to understand the regeneration status of Sal plants in the Core zone and Buffer zone of Madhupur Sal forest to clarify the effects of management interventions.

5.1.1 Study of forest management on the regeneration of Sal plants by using quadrat methods

Vegetation survey using quadrat method revealed that the maximum number of species, as well as the maximum density of tree species, shrub species and herb species, were found in the Summer season compared to the Winter season in both Core zone and Buffer zone of the Madhupur Sal forest. The number of species and the density of trees and shrubs were higher in the Buffer zone than in the Core zone. The density of Sal plants was also higher in the Buffer zone than in the Core zone in the Spring, Summer and Autumn seasons, but the density of Sal plants was higher in the Core zone than in the Buffer zone in the Winter season.

The present study of Sal plants on the basis of girth class revealed that the density of Sal plants of 0-10 cm girth class was higher in the Buffer zone than in the Core zone in the Spring, Summer and Autumn seasons, but it was higher in the Core zone than in the Buffer zone in Winter. Data also showed that the density of Sal plants of 10–20 cm, 20–40 cm and 60–80 cm girth classes were higher in the Core zone than in the Buffer zone in all four seasons.

In the present study, the regeneration of Sal plants was studied in four different seasons and this type of study has never been done before in the Madhupur Sal forest. Some other studies on the regeneration of Sal plants, are available elsewhere. Bhatta and Devkota (2020) reported that there were 15,905 seedlings per hectare 1,876 saplings per hectare and 1,287 trees per hectare indicating that each life form has enough individuals to replenish the number lost in previous life forms even after their deaths. A population with a sufficient number of seedlings, saplings and young trees demonstrates successful regeneration (Khumbongmayun *et al.* 2006, Tripathi and Khan

2007, Pokhriyal *et al*. 2010, Sarkar and Devi 2014, Manna and Mishra 2017). The regeneration status of the forest is regarded to be good if the forest has seedlings >5000 and saplings >2000 per hectare, according to the Community forest resource inventory guideline (Pandey *et al.* 2012). Since the regeneration of the currently examined woods meets the criteria listed above, it can be concluded that Sal plants have a good and satisfying regeneration pattern in this forest. When the current regeneration pattern of the study area was compared to that of other studies on Sal forests of Nepal (Timilsina *et al.* 2007, Pandey *et al.* 2012, Paudyal 2013, DFRS 2014, Awasthi *et al.* 2015, Napit and Paudel 2015) and India (Adhikari *et al.* 2017, Raj 2018), the current regeneration status of the present study area was within the range of these studies.

A regeneration study by using girth class stated that the population structures of various tree species showed four types of growth patterns (Knight 1975). One pattern of population structure is represented by a greater proportion of individuals in the lower and middle girth classes, indicating frequent regeneration. Another pattern showed most of the individuals in middle girth classes with the absence of seedlings and saplings (Knight 1975). Benton and Werner (1976) stated that if such a trend continues, the population of these species is on the way to extinction. The population structure of certain species is characterized by gap-phase regeneration (interrupted). Interrupted regeneration of species may indicate that one or more climatic and/or bio-edaphic factors inhibited the regeneration completely for certain periods of time and with the return of favorable conditions, the species was able to regenerate again. Chaubey and Sharma (2013) stated that there is another pattern that consists of individuals in lower and middle girth classes but an absence of seedlings. The last pattern consists of seedlings with the absence of some intermediate classes. This requires a detailed study of reproductive biology and eco-silvicultural requirements at different growth stages. The Sal showed adequate regeneration with an uninterrupted growth pattern in most of the stands studied, indicating healthy signs of establishment and growth of the Sal plants in the past.

The present study found that the maximum number of species, as well as the maximum density of tree species, shrub species and herb species, were found in the Summer season and that of the minimum was found in the Winter season in both the Core zone and Buffer zone of the Madhupur Sal forest, which indicated that the regeneration in different types of plants happened in the Summer season. On the other hand, herb species and seedlings of some plant species died in the Winter season in both the Core zone and Buffer zone. The present study also found that the density of Sal plants of 0-10 cm girth class was higher in the Buffer zone than in the Core zone in the Spring, Summer and Autumn seasons, but it was higher in the Core zone than in the Buffer zone in Winter, which indicated that the regeneration rate was higher in the Buffer zone than in the Core zone. Results of the present study also showed that the density of Sal plants of 10–20 cm, 20–40 cm and 60–80 cm girth classes were higher in the Core zone than in the Buffer zone in all four seasons. From this data, it was very evident that the density of mature Sal plants was higher in the Core zone than in the Buffer zone. The regeneration rate was lower in the Core zone, which might be due to the higher density of Sal plants. Emborg (1998) examined that the relative light intensity had influenced on the regeneration in plant species. The present study found that the density of Sal plants of 0-10 cm girth class was increased in the Spring season compared to that in the Winter season and that happened due to the regeneration through coppices. Rahman *et al.* (2020) stated that the native tree species were regenerating naturally through seeds, coppice and root suckers in the Madhupur Sal forest. Rahman *et al.* (2020) also revealed that 47 tree species belonging to 24 families and 42 genera were regenerating naturally.

The physical observation of that study also indicated that most of the regeneration occurred from seed where a few were found to grow from coppices. However, the regeneration species composition is less than that of Dudhpukuria-Dhopachari Wildlife Sanctuary (120 species), Chunati Wildlife Sanctuary (105 species), Khadimnagor National Park and Tilagor Eco-Park of 55 species (Rahman *et al.* 2011, Hossain *et al.* 2013, Hossain and Hossain 2014). But, the number of regenerating tree species is higher than that of Tankawati Natural Forest of Chittagong South Forest Division (29 tree species) (Motaleb and Hossain 2011) and Durgapur hill forest of Netrokona (27 tree species) (Rahman *et al*. 2011). In addition, Deb *et al.* (2015) recorded the total regenerated understory species was 61 belonging to 27 families, but it was not easy to compare with their findings because they considered not only seedlings but also saplings. Disturbance in natural forests can change the habitat suitability of plant species (Wilcox *et al.* 2006), which affects plant species composition and ecosystem functions (Berhane *et al.* 2013). Human-induced disturbances and various influences, such as logging, browsing and grazing, can significantly modify species diversity and composition. As the intensity and frequency of disturbance increase, the availability and abundance decrease. The number of many species could decline with an increased risk of local extinction. More abundant and generalized species are less vulnerable to disturbance than rare and specialized species. Disturbance can also change the size of the gaps in the forest and alter species composition by encouraging pioneer plant species. Madhupur Sal forest is tremendously disturbed by the local people, but the existing control measures are very inadequate to address the issues. As per the findings of that study, the number of species showed the suitability of the forest for regrowth if kept undisturbed.

Rahman *et al.* (2020) found that among the regenerating tree species, *S. robusta* showed the highest density of 18,046 seedlings and saplings per hectare, followed by *Aporosa* sp. of 3142 seedlings and saplings per hectare, *Mallotus philippensis* of 3084 seedlings per hectare and *Terminalia bellirica* of 2490 seedlings per hectare. They also stated that the density of seedlings and saplings of Sal plants was quite adequate for the natural regeneration, but there is lack of published information through seasonal basis seedlings and saplings number. Data of the present study showed that in the Core zone, the number of Sal plants of 0-10 cm girth class was 8000, 9500, 11,833 and 533 per hectare, respectively in Spring, Summer, Autumn and Winter seasons, whereas in the Buffer zone, the number of Sal plants of 0-10 cm girth class was 10,000, 13,433, 15,500 and 766 per hectare, respectively in Spring, Summer, Autumn and Winter seasons. In the Core zone, the number of Sal plants of 10-20 cm girth class was 1,400, 1,466, 1,466 and 1,400 per hectare, respectively in Spring, Summer, Autumn and Winter seasons, whereas in the Buffer zone, that was 533, 666, 700 and 266 per hectare, respectively in Spring, Summer, Autumn and Winter seasons. Compared to the other studies, it was very clear that the number of seedlings and saplings were quite good enough for the natural regeneration of Sal plants in the Core zone and Buffer zone of the Madhupur Sal forest.

The IVI values indicate the overall dominance of a species in an area (Das *et al.* 2018), where the maximum IVI value for *S. robusta* was 66.25 out of 300, followed by *M. philippensis* was 27.33, *Aporosa* sp. was 17.82, *T bellirica* was 14.75, *G. nervosa* and *B. tomentosa* were 14.10. In contrast, *G. asiatica, D. robusta and L. glutinosa* showed the lowest regeneration IVI (0.93) of the regenerating tree species. However, Chowdhury *et al.* (2018) studied the regeneration diversity of Rampahar Natural Forest Reserve in Rangamati South Forest Division, where they recorded that the IVI values of regenerating tree species was the highest in *P. serratum* 50.09 followed by *B. ceiba* 39.37. There is a lack of published information about the phytosociological attributes of regenerating tree species on the basis of seasonal variation in the Madhupur Sal forest. From the present study, it is very much clear that, to understand the regeneration pattern of Sal plants well, a seasonal variation in the regeneration of Sal species is needed to be understood. Sal species especially newly born Sal seedlings die in the dry season and start to grow through copies in the wet season when rain starts. There are some studies on the regeneration of Sal species, but the seasonal effects on the regeneration of Sal plants is not studied yet in the deciduous Sal forest.

The present study found that the maximum IVI value was 154.18 in the Autumn season and the minimum was 84.40 in the Winter season, whereas the maximum IVI value was 154.33 in the Autumn season and the minimum IVI value was 71.90 in the Winter season for the *S. robusta* plants, respectively in the Core zone and Buffer zone of the Madhupur Sal forest. The result showed that in both studied zones, IVI values were almost the same in both seasons. Compared to the other studies of IVI value, the present study indicated that the regeneration condition was quite adequate in both the Core zone and Buffer zone of the Madhupur Sal forest.

5.1.2 Study on the effects of forest management on regeneration of Sal plants by investigating seed germination

The effects of management on Sal seed germination rate in the Core area and Buffer area were studied through field experiment by sowing seeds. It is very important to know well about seed germination in order to know well about the reproduction of any species. Although natural regeneration of Sal seeds has been studied, but no research has been done through field experiment on regeneration of Sal seeds in any deciduous Sal forest.

Rahman *et al.* (2020) stated that the native tree species were naturally regenerating through seeds, coppice and root suckers and their observations revealed that the majority of the regeneration happened from seed, with only a few coppices growing. Natural regeneration is a direct indicator of the health of a forest ecosystem since it is the ability of a tree species to reproduce itself. Although many known and unknown causative factors influence natural regeneration, the following are the most important: climate e.g., humidity, temperature, light intensity, span of light receiving hours, precipitation and wind; soil e.g., depth, aeration, moisture level, nutrients and erosion; seed e.g., sensitivity, output and dispersal; and biotic conditions e.g., wildlife, forest fire and overgrazing, among others (Singh *et al.* 2016). The bulk of these characteristics, on the other hand, are more or less uniform over a limited area, however spontaneous regeneration in Sal has been found to fluctuate with varied overhead canopy densities. Because, micro-environmental factors such as soil moisture and light intensity differ depending on canopy density (Dam 2001, Hutchinson *et al.* 2005, Vandenberghe *et al*. 2006, Tyagi *et al.* 2011) studied in a small Sal forest watershed with the primary goal of determining the impact of soil moisture fluctuation and light intensity on natural Sal regeneration.

Management effects on Sal seed germination rate in the Core zone and Buffer zone was studied through seed germination rate. From this data, it was very much evident that, the management effect was significant in the Sal seed germination rate in the Core zone and Buffer zone of Madhupur Sal forest. The seed germination rate was much higher in the Buffer zone than in the Core zone. It was higher in the Buffer zone than in the Core zone because, the density of large-sized Sal plants was higher in the Core zone than in the Buffer zone. Due to the high density of large Sal trees in the Core zone, sunlight could not reach up to the ground level of soil due to which Sal seed germination was lower in the Core zone than in the Buffer zone.

The effects of management, time (month) and their interaction on the number of seedlings during eight sampling times (one month) in different months in the Core zone and the Buffer zone of Madhupur Sal forest were studied. From this data, it was very evident that the effects of management and time were significant in the number of seedlings. The number of seedlings was much higher in the Buffer zone than in the Core zone during the eight different sampling months of the studied period. The number of seedlings was lower in the Core zone than in the Buffer zone because of the high density of large-sized Sal plants in the Core zone. In dense forests, the seed germination rate becomes lower because of inadequate sunlight. The number of seedlings gradually decreased from October to February because of the decreased soil moisture content in both zones. The soil moisture content became gradually lower from wet season to dry season and that was the reason for which the number of Sal seedlings gradually decreased from October to February in both zones.

The effects of management and time (month) on the height of seedlings in four different months in the Core zone and Buffer zone of the Madhupur Sal forest were studied. From this data, it was evident that the effects of management were significant in the height of seedlings. The height of seedlings was higher in the Core zone than in the Buffer zone in four different studied months. The height of seedlings was higher in the Core zone than in the Buffer zone because of the high density of large-sized Sal plants in the Core zone. In dense forests, plants grow faster because of the competition for sunlight. The effects of management and time (month) were significant in the height of seedlings because the height of seedlings gradually increased from November to February in both zones of Madhupur Sal forest.

The effects of management and time (month) on the percentage of soil moisture content during eight different months in the Core zone and Buffer zone of Madhupur Sal forest were studied. From this data, it was found that the effect of time on the soil moisture content was highly significant. The effects of time (month) on soil moisture content were highly significant in both zones because the soil moisture content became gradually lower from wet season to dry season and for that reason the soil moisture content was gradually lower from September to February in both zones and the percentage of the soil moisture content was almost the same in both zones in eight different studied months.

Natural regeneration studies in response to parameters like soil moisture and light intensity are uncommon (Dabral *et al.* 1980). Poor soil aeration and insufficient moisture, according to Hole (1914, 1921) and Boyce and Bakshi (1959), are the main causes of poor Sal regeneration. Seth and Bhatnagar (1960) discovered that soil moisture content and excellent regeneration are linked. According to Gautam *et al.* (2007), the relationship between Sal and soil moisture was positive in seedlings, positive but not significant in saplings and negative in mature trees. Chauhan *et al.* (2008) conducted a multiple regression between Sal seedling density and six soil parameters (e.g., soil moisture, soil organic carbon, pH, nitrogen, phosphorous and potassium) and found that the coefficient of determination in natural and planted forests was 0.042 and 0.222 respectively.

5.2 Study of leaf phenology of Sal plants

S. robusta is found in both dry and moist deciduous forests in other parts of the world (Singh and Kushwaha 2005). In Bangladesh, the Sal forest is distributed in different geographical and climatic conditions. The districts where the major stands of Sal forests are found in Bangladesh include Gazipur, Mymensing, Tangail, Sherpur, Naogaon, Dinajpur and Cumilla. However, several research questions on the ecology of *S. robusta* have not yet been addressed well in the context of the environmental condition of the deciduous forests of Bangladesh. Some studies on various aspects of Sal forests are available in Bangladesh which are already described. However, leaf phenology of *S. robusta* species is not well understood in different geographical and climatic conditions of Bangladesh although it is important because it reflects the influence of evolution and environment on plant characteristics and plant functioning. However, *S. robusta* has been paradoxically described as deciduous, semi-deciduous or evergreen species (Singh and Kushwaha 2005 and Reich *et al.* 2004). To assess this contradiction, study of leaf phenology is important because it reflects the influence of evolution and environment on plant characteristics and plant functioning (Shankar 2001). The present study, therefore, focused to determining the leaf phenological nature of the species in two different geographical and climatic conditions of Sal forests in Bangladesh by monthly counting of quantitative documentation of leaf dynamics, flowering and fruiting.

5.2.1 Study of leaf phenology of Sal plants by leaf counting

The study of leaf phenology of Sal plants was conducted by leaf counting in the Madhupur Sal forest under Tangail district and the Charkai Sal forest under Dinajpur district of Bangladesh. It is very important to know well about the leaf phenology of Sal plants because Sal forests are very important for the ecological and economic perspective of Bangladesh. In order to know more about the leaf phenology of Sal plants, the number of leaves was counted systematically in both the forests and leaves were collected for the study of physiological, morphological and anatomical traits of leaves.

Forest structure and function are linked with leaves, which are the most basic structure and feature of terrestrial plants (Sterner and Elser 2002). Plant leaf attributes are influenced by environmental elements such as temperature (Li and Bao 2014), light intensity (Lusk and Warton 2007, Bajpai *et al.* 2012) and water status (Bajpai *et al.* 2012, Bajpai *et al.* 2017). As a result, leaf features help to explain how plants respond to resource constraints, such as a lack of water. The results of this study revealed that the plants of Madhupur Sal forest and Charkai Sal forest differed in some leaf morphological, physiological and anatomical traits.

Leaf length, leaf breadth, leaf perimeter, leaf area, fresh weight, turgid weight, dry weight and specific leaf area; leaf chlorophyll content, relative water content, leaf water content, leaf dry matter content; and stomatal length, breadth, stomatal density, percentage of open and close stomata and stomatal pore index have been linked to the adaptability of plants of various functional categories in a number of studies (Westoby *et al.* 2002, Tomlinson *et al.* 2013, Rodriguez *et al.* 2016, Tian *et al*. 2016, Qin *et al.* 2019, Yan *et al.* 2019). From the leaf features of these two forests, it has yet to be determined whether the leaves of the Sal plants of Madhupur Sal forest and Charkai Sal forest are functionally distinct.

The physiological status of a leaf of a plant grown under various edaphic and climatic circumstances can be determined by its fresh weight (Rodriguez *et al.* 2016). Variation in fresh weight, turgid weight and dry weight of leaves among species has been linked to water use efficiency in several studies. The leaf moisture condition is reflected in the variation in morphological features among the leaves and the leaf area, which regulates the process of transpiration. Furthermore, the leaf moisture content may be linked to the productivity of root system in absorbing more water from the soil, which could indicate the greater turgidity of leaves (Salisbury and Ross 1994).

Leaf morphological, physiological and anatomical traits of the selected Sal plants of Madhupur Sal forest and Charkai Sal forest were studied. A significant difference was present in the leaf fresh weight of the two Sal forests. Leaf fresh weight was little higher in the Charkai Sal forest than in the Madhupur Sal forest. Significant difference was present in leaf water content, leaf dry matter content and relative water content between the two Sal forests. Leaf water content and relative water content were higher in the leaves of the Charkai Sal forest than in the Madhupur Sal forest, whereas the leaf dry matter content was lower in the leaves of the Charkai Sal forest than in the Madhupur Sal forest. Significant difference was present in all the parameters of leaf anatomical traits such as stomatal length, breadth, density, stomatal pore index, open stomata and close stomata between the two Sal forests. All the parameters of the leaf anatomical traits were higher in the leaves of the Madhupur Sal forest than in the Charkai Sal forest.

Singh and Kushwaha (2005) studied the leaf phenology of Sal plants. From their biannual study, they described how diverse phenological patterns of leafing, blooming and fruiting were observed in conspecific *Shorea* trees growing in the same habitat. The duration of leaf fall (January-March) was substantially less than the extended duration of leaf flush (March-November). As a result, during the mid-dry season, a concentrated fall of leaves of different lifespan occurred, resulting in an annual turnover of the overall foliage. Around the Spring equinox (March-April), the shedding of old leaves was accompanied or followed by leaf flush. According to their findings, 70% of individuals started leaf flushing in March and 30% in April. During both annual cycles, leaf fall began in January in all versions. Leaf fall was completed in 60 percent of cases by the end of February and in 40 percent of cases by the end of March. In October, only a small percentage of the leaves were shed. Blooming began with the commencement of leaf fall in Winter in all phenological varieties and the duration of flowering coincided with the leaf transitional stage (leaf fall and leaf flush initiation). During the leafless period, some individual plants proceeded to blossom and begin fruiting. As a result, both the reproductive (flowering and fruit development) and leaf initiation phases were supported simultaneously. Individual asynchrony for many phenological events differed between years. Leaf flushing was more synchronized in conspecific trees during both annual cycles (as shown by a lower asynchrony index) than other phenological occurrences. Fruit fall was the least synchronized of the phenological phenomena in conspecific trees. Flowering, fruit commencement and fruit fall were highly synchronized during annual cycle one compared to annual cycle two.

The duration and intensity of seasonal drought determine the phenology of trees in the dry tropics. The extent to which trees are exposed to drought varies greatly, depending on temperature and soil water availability, as well as tree attributes such as root length (Van *et al.*1993). *Shorea* changes foliage around the Spring equinox in the middle of the dry season, in contrast to the co-existing deciduous tree species, which produce new leaves after varied leafless intervals during the dry-hot Summer (May-June), just before the rainy season begins (Kushwaha and Singh 2005). Deciduous species leaf out just before or with the beginning of the rainy season, whereas evergreen species leaf out in the middle of the dry season (Medina 1995). Sal cannot be classified as a deciduous plant because of its Spring leaf flushing, significant leaf exchange and substantial re-establishment of the canopy during the hottest and driest months of the year (March–June). Ability of Sal plants, like many evergreen species, to swiftly rehydrate the stem during the dry season is reflected in its leaf flushing and flowering during the mid-dry portion of the annual cycle. Leaf falls and twigs with a high-water potential are required for subsequent leafing (Borchert *et al*.2002). Leaf-exchanging plants (such as *Shorea*) are restricted to damp environments and have a high-water potential even during the dry season (Rivera *et al*. 2002). Sal has a deep root system that allows it to access subsurface water (Joshi *et al.* 1980). The discovery of four leaf phenological variants in *Shorea*, reported by Singh and Kushwaha (2005) demonstrating that conspecific trees have a lot of functional variety. Individuals of *Shorea* adapt to microsite conditions in a variety of ways (from leaf exchange or ever greenness to leaflessness or deciduousness, but with a one-year leaf life cycle), making it essentially a semi-evergreen species. Short leaflessness imposed on a few individuals at drier microsites could be due to longer stem rehydration times and thus delayed leaf flushing. Semi-evergreen species rarely go without green leaves and if they do, it is only for a brief time (De Bie 1998, Gerhardt and Hytteborn 1992).

Annual leaf exchange of *Shorea* appears to be a survival mechanism during the dry season. To prevent water loss due to transpiration, it replaces all old leaves of various ages with new leaves. Flowering and leaf flushing in deep-rooted *Shorea* are likely dependent on previous leaf fall and the availability of sub-soil water stores, both of which increase the water status of trees. *Shorea* has an opportunistic leaf phenological nature, with individuals able to withstand (evergreenness) or avoid (deciduousness) drought depending on microsite conditions; most individuals tolerate drought, but only a small percentage (approximately one-fifth) avoid dryness for a short time. In the study of Singh and Kushwaha (2005), the presence of four phenological variants suggests that semi-evergreen *Shorea* can leaf out whenever trees or branches are fully hydrated, indicating that their opportunistic phenology is mostly governed by seasonal fluctuation in tree hydration status at a specific microsite. Singh and Singh (1992) found that in the dry tropics, *Shorea* does not go leafless on the moist site, but on the dry site, most individuals become leafless for a week or more in March, based on qualitative visual observations. *Shorea*, on the other hand, is a dominating evergreen species in the subtropical Central Himalaya, with concentrated early Summer leaf fall and simultaneous leafing (Singh and Singh 1992). The vast distribution of *Shorea* in the tropics, from moist parts (e.g., Central Himalaya) to dry regions, may be attributable to its wide leaf phenological response, as a result of its semi-evergreen nature. *S. robusta* is the only semi-evergreen tree species in the dry deciduous forest now being investigated and its semi-evergreenness may be an indicator of its high adaptability.

Individual phenological asynchrony allows plants to increase their flexibility (Devineau 1999). Conspecific asynchrony for key phenological phenomena varied between the two annual cycles in this study. Variations in the beginning date of monsoon, as well as the volume and distribution of rainfall over the course of the year, may have an impact on the components that regulate the soil–plant–atmosphere water continuum. In dry situations, water supply heterogeneity and periodicity have been shown to be important variables in tree phenological cycles of plant populations (Konate *et al.* 1999). Borchert (1994) suggested that differences in water availability guide within-species asynchrony in tree phenology in dry forests and so tree water status is likely to generate the observed variation in the phenology of *Shorea*. Conspecific phenological asynchrony is another functional trait that contributes to species dominance in a variety of microenvironmental settings.

Shorea flowering begins in late February while the trees are leafless, according to Atluri *et al.* (2004), with little asynchrony among individual trees. Conspecific *Shorea* trees in the Vindhyan region, on the other hand, begin flowering significantly asynchronously with the onset of leaf fall during the Winter season and flowering coincides with the leaf transitional stage (leaf fall and leaf initiation). As a result, drought-induced leaf loss appears to be a flowering signal. Rehydration of twigs produced by leaf loss triggers flower bud growth and anthesis in several species throughout the dry season (Borchert 2000). In semi-evergreen plants, soil water condition appears to have a significant impact on the reproductive period as well as leaf shedding (Konate *et al.* 1999, Seghieri and Simier 2002). Drought-induced leaf shedding causes intra-species asynchrony at flowering time, which varies in a landscape depending on soil water storage (Borchert *et al*. 2002). Winter flowering semi-evergreens are present. *Shorea* in tropical dry forests suggests the presence of microsites with extensive subsurface water reserves from which deep-rooted trees can collect water throughout the dry season.

The present study investigated the monthly average number of leaves per twig of Sal plants in the Madhupur Sal forest and Charkai Sal forests. From this data, it was found that the maximum number of leaf-fall was seen in the months of February 2019, 2020 and 2021 in the Madhupur Sal forest. But, the maximum number of leaf-fall was seen in the months of March 2019 and 2020 as well as in February 2021 in the Charkai Sal forest. From this result, it was found that the leaf-fall started earlier in the Madhupur Sal forest than in the Charkai Sal forest. The maximum number of leaf-out was seen in the months of March 2019, 2020 and 2021 in Madhupur Sal forest. But, the maximum number of leaf-out was seen in the months of May 2019 and April 2020, as well as in the month of March 2021 in Charkai Sal forest. This result indicated that the leaf-out started earlier in the Madhupur Sal forest than in the Charkai Sal forest. The leaf falling and the leaf flushing happened earlier and was relatively more synchronous in the Madhupur Sal forest, whereas the leaf falling and the leaf flushing of the Charkai Sal forest happened later and it was asynchronous.

The present study also investigated the percentage of twigs with leaves of Sal plants of the Madhupur Sal forest and Charkai Sal forest. Data of the study suggested that in 2019, only 20% and 22.5% of completely leafless twigs were seen in March and April, respectively, in the Madhupur Sal forest, whereas 12.5% of completely leafless twigs were found in May in the Charkai Sal forest. In 2020, only 12.5% of completely leafless twigs were found in March in the Madhupur Sal forest and only 15% of completely leafless twigs were found in April in the Charkai Sal forest. In 2021, only 2.5% of leafless twigs were found in May in the Madhupur Sal forest and only 7.5% of completely leafless twigs were found in April in the Charkai Sal forest. From this result, it was found that the leaf-fall in the Madhupur Sal forest happened earlier than in the Charkai Sal forest. Data also showed that maximum 22.50% completely leafless twigs were found in both forests during the studied period, which indicated that both forests were semi-deciduous in nature.

Some studies revealed that the global climate change is influencing species physiology, distribution and phenology (Borchert 1998). The phenology displayed in tropical forest trees at the moment will shift towards forests with a lower or higher moisture balance, roughly proportional to how any global change element modifies moisture balance (Reich 1995). Wintertime rainfall in India might drop by 5 to 25% (Pandey 2002), wreaking havoc on tree species like *Shorea*, which undergo important phenological events such as leaf exchange and flowering towards the conclusion of the season. Even a slight decrease in annual rainfall, along with increased evapotranspiration due to expected temperature increases, might deplete soil water stores, further marginalizing the distribution of semi-evergreen *Shorea* in the tropical dry deciduous forest zone.

5.2.2 Effects of soil moisture on the growth of Sal plants

Soil moisture is a key element that interacts with soil pH and soil nutrients to determine growth and vegetative structure of plants. It can affect plant growth and variations in leaf functional traits (Niu *et al.* 2021). In some studies, the effects of dryness on the deciduousness of plants have been studied in field condition but not in the experimental conditions. The present study reported a significant difference present in soil moisture content among the three types of intervals of water treatment that was applied under experimental conditions to understand the effects of soil moisture on the growth of Sal plants grown in the garden.

In contrast to the co-existing deciduous tree species, which develop new leaves after varying leafless intervals during the dry-hot Summer (May-June), right before the rainy season begins, *Shorea* changes foliage around the Spring equinox in the middle of the dry season (Kushwaha and Singh 2005). Evergreen plants leaf out in the middle of the dry season and deciduous species leaf out immediately before or at the start of the rainy season (Medina 1995). Because of its Spring leaf flushing, major leaf exchange and substantial re-establishment of the canopy throughout the hottest and driest months of the year (March–June), *Shorea* cannot be described as a deciduous plant. Ability to quickly rehydrate the stem during the dry season, like many evergreen plants, is mirrored in its leaf flushing and flowering during the mid-day period of the yearly cycle of Sal plants. For further leafing, leaf falls and twigs with a high-water potential are required (Borchert *et al.* 2002). *Shorea* and other leaf-exchanging plants are constrained to damp settings and have a high-water potential even during the dry season (Rivera *et* *al*. 2002). *Shorea* has a deep root system that permits it to reach water beneath the surface (Joshi 1980). Singh and Kushwaha (2005) revealed, four leaf phenological variants in *Shorea*, demonstrating that conspecific trees exhibit a lot of functional variety. *Shorea* is essentially a semi-evergreen species because it adapts to microsite circumstances in a variety of ways (from leaf exchange or evergreenness to leaflessness or deciduousness, but with a one-year leaf life cycle). Short leaflessness imposed on a few individuals at drier microsites could be attributed to delayed leaf flushing due to longer stem rehydration durations. Semi-evergreen plants seldom lose their leaves and if they do, it is just for a short time (De Bie 1998, Gerhardt and Hytteborn 1992).

Sterner and Elser (2002) stated that the most basic structure and feature of terrestrial plants, leaves, are linked to forest structure and function. Environmental factors such as temperature (Li and Bao 2014), light intensity (Lusk and Warton 2007, Bajpai *et al*. 2012) and water status all influence plant leaf attributes (Bajpai *et al.* 2012, Bajpai *et al.* 2017). As a result, leaf characteristics contribute to understanding how plants respond to resource constraints such as a lack of water. Leaf characteristics such as leaf morphological, physiological and anatomical traits have been linked to the adaptability of plants of various functional categories in a number of studies (Westoby *et al.* 2002, Tomlinson *et al.* 2013, Rodriguez *et al.* 2016, Tian *et al*. 2016, Qin *et al.* 2019, Yan *et al*. 2019).

The present study investigated that the significant effects at 3 days, 5 days and 7 days intervals of water treatments was found in all the parameters of leaf morphological traits except specific leaf area. Significant effects of water treatments were found on the leaf length, leaf breadth, leaf perimeter, leaf area, leaf fresh weight, leaf turgid weight and leaf dry weight of Sal plants grown under experimental conditions in the garden. It indicated that soil moisture played an important role in these leaf morphological parameters. Result also showed significant effects on the leaf dry matter content, relative water content, stomatal density and stomatal pore index of Sal plants grown under experimental conditions and that it might be due to the difference in soil moisture content of these three types of water treatments.

The present study investigated the effects of three types of water treatments on the number of total leaves of Sal plants grown under experimental condition. Result showed that during the leaf exchange period (January-June), the maximum number of total leaves per plant was seen in the month of February at 3 days, 5 days and 7 days intervals of water treatments and the minimum number of total leaves was seen in the month of April at 3 days, 5 days and 7 days intervals of water treatments. The maximum number of total leaves per plant was seen in the month of February in all these three treatments, which indicated that the leaf fall had not started up to that point. The minimum number of total leaves per plant was found in the month of April at all three types of intervals of water treatment. This experiment revealed that the maximum number of leaf fall happened in April. The new leaf formation was found in April at 3 days and 5 days treatment plants and in May at 7 days treatment plants. The present study showed that the leaf fall happened at the same time in all these three water treatments, as well as the new leaf formation happened earlier in the plants of 3 days and 5 days intervals of water treatments than in the plants of 7 days intervals of water treatments.

The present study also counted the number of old leaves per plant and it was found that during the leaf exchange period (January-June), the maximum number of old leaves per plant was seen in the month of February at all these three treatments. From the previous data, it was found that the maximum number of total leaves per plant was seen in the month of February in all these three treatments. Thus, from both data (Number of total leaves and number of old leaves), it was very clear that the leaf fall had not started up to that point. The minimum number of old leaves was found in the month of May at 3 days and 5 days intervals of water treatment, whereas the minimum number of old leaves at 7 days intervals of water treatment was seen in the month of June. From the previous data, it was found that the minimum number of total leaves was seen in the month of April at 3 days and 5 days intervals of water treatment and it was in May at 7 days intervals of water treatment. Thus, from both data, it was found that the leaf fall continued up to May at 3 days and 5 days intervals of water treatments and it continued up to June at 7 days intervals of water treatments.

This study also counted the number of new leaves per plant of Sal plants and it was found that during the leaf exchange period (January–June), there was no new leaf formation from January to the beginning of April at all three types of water treatment conditions. Leaf-out started in April and the maximum number of new leaves was seen in June at all three types of water treatments. From the experimental data, it was found that the leaf fall continued up to June at 7 days intervals of water treatments, whereas it continued up to May at other two intervals of water treatments. From this investigation it was found that the leaf fall period was longer at 7 days interval of water treatments than at the other two intervals of water treatments and it was also found that the new leaf formation was higher at the 7 days interval of water treatments than at the other two intervals of water treatments in the month of June.

The present experiment investigated the composition (%) of the old and new leaves and it was found that the maximum number of old leaves (100%) was seen in the months of January and February and the maximum number of new leaves was seen in the month of June at 3 days interval of water treatment. The same results were found from the study of the total number of old leaves and the total number of new leaves at 3 days intervals of water treatments. The maximum number of old leaves (100%) was seen in the months of January to March and the maximum number of new leaves was seen in the month of June at 5 days interval of water treatment. The same results were also found in case when the total number of old leaves and new leaves at 5 days intervals of water treatment. The maximum number of old leaves (100%) was found in the months of February to April and the maximum number of new leaves was found in the month of June at 7 days interval of water treatment. The number of new leaf formations was higher at the 7 days interval of water treatments than at the other two intervals of water treatment plants in the month of June. The same result was found from the study of the total number of old leaves and the total number of new leaves.

From the present investigation it was found that the maximum number of the new leaf-out was found in the month of March 2019, 2020 and 2021 in Madhupur Sal forest which was synchronous. On the other hand, the maximum number of new leaves out was found in the month of May 2019 and in the month of April 2020 as well as in the month of March 2021 in the Charkai Sal forest which was asynchronous. From the present investigation it was found that leaf fall started in February among the three types of intervals of water treatments and the maximum number of leaf falling was found in the month of March among 3 days and 5 days intervals of water treatments and it was found in February at 7 days interval of water treatment.

The studied results also revealed that in both field study and experimental study, leaf fall began at about the same time a month before or after in the studied Sal plants. It was also found that the maximum number of leaf falling occurred at about the same time a month before or after in the studied Sal plants of both field study and experimental study. From this investigation, it was found that the new leaf formation in the experimental plants occurred later than in the field study plants. Through the physical observation and the leaf counting methods, in both the field and experimental studies, it was found that maximum 20% completely (100%) leafless twigs and completely (100%) leafless seedling occurred. Thus, from both the field and experimental studies, it was evident that the Sal plant was semi-deciduous in nature in both the Madhupur Sal forest and Charkai Sal forest.

From both the field study and the experimental study, it was evident that the leaf fall began in the dry season when the soil moisture content started to decrease. It was also found that soil moisture content has a great influence on the deciduousness of Sal plants.

5.3 Study of Nutritional adaptation of Sal plants

Plant nutrients are classified as macronutrients and micronutrients and among the macronutrients, N, P and K are very important. Plants use different mechanisms to adapt with different environmental conditions. Many factors including water and plant nutrients influence plant adaptation, distribution and net primary productivity (Wright *et al*. 2001, Ordonez *et al.* 2009). Plant functional traits reflect how plants adapt to physical environmental variation and biotic interactions. Leaves play critical roles in plant function and long-term environmental adaptation (Royer *et al.* 2008). However, deciduous species shed their leaves in the dry season and it is an important feature of nutritional adaptation. Some studies were done on different adaptation strategies of leaves in plants: tree species adapt to changing microhabitat conditions by using a variety of leaf strategies that control a tree species' ability to utilize resources (water, CO_2, nutrients) in relation to its ability to conserve the same (Singh and Kushwaha 2005). Plant species that grow in seasonal systems frequently have mechanisms to deal with prolonged periods of water scarcity. Multiple traits at the leaf and whole plant levels reduce carbon assimilation due to a strong control of stomatal conductance (Meinzer *et al.* 1999, Prior *et al*. 2004, Franco *et al*. 2005). Some studies also revealed that the old leaves return their essential nutrients back to the plant before their shedding, which is a very important adaptation mechanism of the leaves of some plants. Such research questions on nutritional adaptation of Sal plants have not yet been addressed in the context of deciduous forests of Bangladesh. Therefore, an attempt was made to understand the nutrient availability in the green leaves and yellow leaves of Sal plants of Madhupur Sal forest and Charkai Sal forest of Bangladesh.

Resorption of nutrients from senescing leaves has been reported by some studies. The resorption of nutrients from senescing leaves is an important component of plants' nutrient conservation strategy (Milla *et al.* 2005). Nutrient absorption is greater in senescing leaves than in stems or roots. Woody plants have lower nutrient absorption from their stems and roots than non-woody plants. Deciduous plants are more efficient than evergreen plants at reabsorbing leaf nutrients prior to senescence. Furthermore, reproductive efforts have been shown to increase nutrient resorption (Brant and Chen 2015). One of the conservation mechanisms in plants that can increase nutrient use efficiency is nutrient withdrawal from senescing leaves towards developing tissues or internal stores for future use (Vitousek 1982, Yuan and Chen 2015, Aerts 1996). Nutrient absorption occurs throughout the life cycle of leaf (Leopold 1961, Ackerly and Bazzaz 1995). A significant proportion of nutrient resorption usually occurs shortly before abscission (Ares and Gleason 2007, May and Killingbeck 1992, Karlsson 1997). It was reported that nutrient resorption from old leaves significantly contributed to plant fitness in terms of growth and reproduction in the deciduous tree *Quercus ilicifolia*. This can be expressed quantitatively as the plant's nutrient resorption efficiency or proficiency (Killingbeck 1996, Yuan *et al.* 2005). Killingbeck (1996) stated that there is a minimum level of nutrient reduction that species can achieve in their senescing leaves.

The present study revealed a significant difference in the effects of forests and age of leaves in leaf N, P and K concentrations. The present study found that the resorption (%) of N, P and K was 25%, 23.92% and 11.96%, respectively, in the Madhupur Sal forest and 38%, 45.66% and 49.82%, respectively, in the Charkai Sal forest. This result thus indicated that the resorption (%) of N, P and K was higher in the Charkai Sal forest than in the Madhupur Sal forest. From this study, it was revealed that the deciduous Sal plants shed their leaves in the dry season as well as resorption of N, P and K occurred during the senescing period which was an important feature of nutritional adaptation.

Conclusion

This study revealed that Sal was the dominant tree species across the four seasons in both Core zone and Buffer zone of the Madhupur Sal forest. The seasonal variation in the number of seedlings, saplings and juvenile Sal plants showed that the regeneration status was quite enough in both the management zones, though the density of seedlings and saplings of Sal plants was higher in the Buffer zone than in the Core zone. On the other hand, the density of old and tall Sal plants was higher in the Core zone than in the Buffer zone indicating a positive effect of the long term forest management.

The leaf phenological data revealed that Sal was semi-deciduous in nature in both the Madhupur and Charkai Sal forests. Experimental data also revealed that Sal plants started to shed their leaves in dry conditions when the soil moisture content started to decrease indicating the effect of soil moisture on the deciduousness of Sal plants.

Resorption of nutrients (N, P and K) occurred significantly in the Sal plants of both the two different forests. The resorption of N, P and K was higher in the Charkai Sal forest than in the Madhupur Sal forest. Resorption efficiency by Sal plants also varied among the different nutrients.

CHAPTER 6

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