Assessing Carbon Storage in Kamalganj of Bangladesh:

A Quantitative Approach with InVEST Model

by

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DISSERTATION

Submitted in partial fulfilment of the

Requirement of the degree of

MASTER OF SCIENCE IN

ECOLOGY AND ENVIRONMENT STUDIES

Nālandā
UNIVERSITY

SCHOOL OF ECOLOGY AND ENVIRONMENT STUDIES

NALANDA UNIVERSITY

RAJGIR, NALANDA – 803116

BIHAR, INDIA

May 2024

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DECLARATION

I hereby declare that this dissertation entitled " **Assessing Carbon Storage in Kamalganj of Bangladesh: A Quantitative Approach with InVEST Model**" is a bonafide record of research done by me during the course of study and that the dissertation has not previously formed the basis for the award of any degree, diploma, fellowship, or other similar titles, of any other University or Society.

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CERTIFICATE

Certified that this dissertation entitled "**Assessing Carbon Storage in Kamalganj of Bangladesh: A Quantitative Approach with InVEST Model**" is a record of research work done independently by **Bedadyuti Dash** (Student ID: 020222010) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship, or associateship to him/her.

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ACKNOWLEDGEMENT

I want to thank my supervisor Dr. Kishore K. Dhavala, Associate Professor at the School of Ecology and Environment Studies at Nalanda University, who has supervised me to complete this dissertation work. I would like to thank Dr. Jaishanker R Nair, Professor and Dean of the school for his constant support throughout the process. I would also like to thank all the other professors of the department for their support. They have built my knowledge to understand environmental issues clearly. The professors have also increased my confidence in my career through encouragement and giving hope. Indeed, I have settled on a specific area of research through the knowledge I have acquired from them. I would also like to thank all my friends, classmates, and non-teaching staff who have ensured my welfare at the University.

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ABSTRACT

As the twentieth century has progressed, climate change has emerged as one of the most significant environmental dangers that the world is currently facing. Natural forests are considered to be one of the most important ecosystem services because of their ability to sequester and store carbon. Forests limit the amount of carbon dioxide in the atmosphere, which speeds up climate change. For this reason, calculating the spatial distribution of carbon storage is essential for mitigating climate change. In spite of the fact that the Kamalganj subdistrict in Bangladesh is home to more than fifty percent of these types of national parks and reserve forests, the spatial distribution and quantification of carbon storage are rarely investigated. Utilizing the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST 3.14.1) carbon storage and sequestration modeling program, the primary purpose of the current study was to model and estimate the carbon storage of the Kamalganj subdistrict in Bangladesh. The model generated a raster output of the spatial distribution of carbon storage, which summarized the results of the model. According to the findings, the research region has a land area of 51,238 hectares and now stores 6350252.62 million tons of carbon. However, the amount of carbon that is stored varies depending on the type of land use land cover (LULC) that is there. The LULC types with a greater amount of vegetation had a greater amount of carbon stored per hectare basis, and the opposite was also true. The amount of carbon stored in forests was the highest, with a total of 3322028.65 million tons. This represents approximately 52% of the total carbon stock now present in the region. On the other hand, the results of this study could be effectively utilized in formulating environmental management plans and environmental policies, and establishing country development plans carried out by the government and other organizations. This study emphasizes the significance of natural forests for the storage of carbon.

Keywords: Carbon storage and sequestration, GIS, InVEST, Kamalganj subdistrict, Bangladesh.

Chapter 1

Introduction

1.1. Background

The idea of the provision of ecosystem services evolved as a method for enhancing communication and promoting the conservation of the environment. (G. et al., 1997; Mononen et al., 2016). The intricate equilibrium of Earth's ecosystems is crucial in sustaining life on our planet, offering many vital services that promote human well-being. Carbon sequestration and storage by natural forests and other vegetative land-use types are vital ecosystem services in the global fight against climate change (Lahiji et al., 2020; Liu, 2018; Thom et al., 2017; Ziter, 2016). Carbon storage plays a crucial role in reducing the effects of greenhouse gas emissions. Also, it helps regulate climatic trends, conserve biodiversity, and enhance the ability of ecosystems to withstand environmental stressors. Traditional methods for monitoring carbon sequestration involve sampling over time to estimate changes in relevant carbon pools. In recent years, there has been a rise in the usage of Land use Land cover (LULC) and a change in the global carbon cycle. Land cover change is responsible for approximately one-third of anthropogenic CO2 emissions over the past 150 years (R. A. Houghton, 2003). As a result, it has become crucial to employ new methods that involve quantifying the dynamics of land use and land cover (LULC) in order to examine the decrease and disparities in the global carbon budget (R. A. Houghton, 1999; Prentice et al., 2001; Tian et al., 1998; S. Wang et al., 2002).

Given the circumstances in Bangladesh, a nation dealing with both the fast growth of cities and the deterioration of the environment, it is crucial to comprehend and measure the changes in carbon storage at the community level. The significant impacts of climate change in hilly regions result from deforestation and forest degradation, which adversely impact the accumulation of carbon in forests and soils locally and the regulation of climate on a larger scale (Upadhyay et al., 2005).

To enhance its nationally determined contributions and implement more vigorous policies and measures aimed to peak carbon dioxide emissions by 2030 (Y. Zhang et al., 2024). Bangladesh submitted its revised NDC (nationally determined contribution) in August 2021, where it stated that compared to BAU (business as usual), Bangladesh's conditional emissions reduction target was raised from 36 MtCO2e to 89.47 MtCO2e (*Bangladesh*, n.d.). An in-depth examination of the spatial distribution, features, and mechanisms of land-use carbon storage is essential to understanding the impact of human activities on regional or local carbon storage. Bangladesh contributes a minuscule portion of the greenhouse gas emissions responsible for climate change. Moreover, the per capita emission of Bangladesh is 0.5 metric tons of CO2 annually, which is way below in comparison to the per capita emission of the United States (15.2 metric tons per person). Although Bangladesh contributes only 0.56% of the total global emissions causing climate change, it is ranked seventh on the Global Climate Risk Index (CRI) by Germanwatch on vulnerability to climate-related disasters (Rojas, 2021). The increasing sea levels pose an escalating danger to individuals throughout Bangladesh., as 66% of the country is less than 15 feet above sea level. According to estimates, climate change will lead to the displacement of around one in every seven individuals in Bangladesh by the year 2050 (Khan, 2019). With a projected increase of 19.6 inches (50 cm) in sea level. Due to the rising sea level, Bangladesh may lose approximately 11% of its land, potentially displacing up to 18 million people (Rojas, 2021). According to a World Bank analysis from March 2018, the number of Bangladeshis forced to leave their homes due to climate change's many effects could reach 13.3 million by the year 2050. This would make climate change the primary cause of internal migration in the country (Rigaud et al., 2018).

Carbon sequestration is crucial for addressing climate change as it involves capturing and storing carbon dioxide (CO2) from the atmosphere, decreasing greenhouse gas emissions. The atmospheric CO2 concentration is steadily increasing, mainly as a result of human activities, including the combustion of fossil fuels and the clearing of forests. These highlight the pressing need to decrease carbon emissions and improve carbon sinks. Carbon sequestration involves various natural and artificial techniques that seek to extract CO_2 from the atmosphere and store it in different reservoirs such as forests, soils, oceans, and geological formations (McLaughlin et al., 2023). Extracting carbon dioxide (CO_2) from the atmosphere diminishes the levels of greenhouse gases, alleviates the warming impact, and promotes climate stabilization. Carbon sequestration has other advantages, including enhancing air quality, preserving biodiversity, improving soil health, and promoting sustainable land management techniques (Nguyen et al., 2023). Nevertheless, implementing efficient carbon sequestration efforts is challenging. Key issues include guaranteeing the durability and soundness of carbon storage, mitigating the possibility of leakage, limiting adverse environmental effects, and assuring cost efficiency. To have a substantial worldwide impact, it is necessary to expand carbon sequestration initiatives. This expansion requires policy backing, international cooperation, and the establishment of suitable regulatory frameworks (Prajapati et al., 2023).

1.2. Research gaps

Although there is global and national research on carbon storage, there is a lack of precise, localized assessments specifically for subdistricts such as Kamalganj. This gap hinders the capacity to provide accurate and situation-specific suggestions for carbon management and conservation endeavors. The research focused on only some significant forest areas, and there is a widespread absence of carbon estimating models relevant to species and ecosystems (Majumder et al., 2019). The use of complex modeling methods, such as the Integrated Valuation Ecosystem Services and Tradeoffs (InVEST) model, to evaluate carbon storage in Bangladesh is currently limited. This discrepancy emphasizes the necessity of employing such technologies to improve the precision and dependability of carbon storage estimations at the regional level.

Current research frequently fails to thoroughly examine the spatial distribution of carbon stocks among various land use and land cover categories. Identifying this gap is crucial for determining regions with significant carbon storage capacity and providing valuable information for focused conservation measures. There is a lack of comprehensive knowledge regarding the effects of alterations in land use and land cover on carbon storage in specific areas such as Kamalganj. It is crucial to solve this gap to formulate land management policies capable of improving carbon sequestration and reducing the impact of climate change.

The integration of research on carbon storage in Kamalganj with local climate action plans and policies has been insufficient. This discrepancy provides a chance to synchronize scientific discoveries with policy frameworks in order to optimize the efficiency of climate mitigation initiatives. Local communities lack involvement in the assessment and maintenance of carbon storage. Community engagement and knowledge are crucial for effectively implementing sustainable land use practices and conservation programs.

1.3. Research questions

1. Mapping Carbon Storage: Where does Kamalganj store its carbon, and how does this change with different types of land use?
2. Hotspots for Carbon: Which areas of Kamalganj are the best at storing carbon, and what are the influencing factors?
3. How have land use and management practices changed carbon storage and ecosystem services provision in Kamalganj over time?
4. What are the potential future scenarios for carbon storage and ecosystem services provision in Kamalganj under different land management strategies?
5. What policy interventions and management approaches can be recommended to enhance carbon storage and ecosystem services in Kamalganj while promoting sustainable development goals?

1.4. Research Objectives

1. To estimate and map carbon storage across different land use and land cover types in the Kamalganj subdistrict using the InVEST model.
2. To assess the spatial distribution of carbon storage hotspots and identify areas of high carbon sequestration potential in Kamalganj.
3. To evaluate the impact of land use changes and land management practices on carbon storage dynamics in Kamalganj.
4. To explore potential scenarios for enhancing the provision of carbon storage and ecosystem services in Kamalganj through targeted land management strategies.
5. To provide recommendations for policy-makers and local stakeholders for sustainable land use planning and management aimed at enhancing carbon storage and ecosystem services in Kamalganj.

1.5. Significance of the study

Knowledge of the local dynamics of carbon storage in the Kamalganj Subdistrict of Bangladesh is supported by the findings of this study, which is the reason for its significance. Utilizing the Integrated Valuation Ecosystem Services and Tradeoffs (InVEST) model, your research findings offer significant insights into the spatial distribution of carbon stocks. It contributes to the formation of management and policy decisions to improve carbon sequestration, reduce the effects of climate change, and advance sustainable development in the region.

Chapter 2

Literature Review

2.1. Carbon in Natural Ecosystems

Carbon is an essential component of the Earth's system. It is a fundamental constituent of all organic matter on Earth and a crucial factor in determining Earth's temperature. The carbon cycle involves the transfer of carbon from the atmosphere to the land, ocean, and living organisms through various biological, chemical, geological, and physical processes. Because certain carbon gases act as greenhouse gases, any alterations in the carbon cycle that increase carbon in the atmosphere also contribute to the warming of Earth's climate.

From 2010 to 2019, human activities released 10.9 ± 0.9PgC yr–1 of CO_2. This CO_2 was distributed among three components of the Earth system: 46% remained in the atmosphere, accumulating at a rate of 5.1 ± 0.02PgC yr–1, the ocean absorbed 23% at a rate of 2.5 ± 0.6PgC yr–1, and 31% was stored by vegetation in terrestrial ecosystems at a rate of 3.4 ± 0.9PgC yr–1 (Intergovernmental Panel On Climate Change (IPCC), 2023). These findings are highly reliable. The combustion of fossil fuels accounted for 81-91% of all human-caused CO_2 emissions. At the same time, the remaining portion was attributed to the net CO_2 flow resulting from land-use change and land management activities such as deforestation, degradation, regrowth after agricultural abandonment, and peat drainage. Throughout the last sixty decades, the proportion of human-caused CO_2 emissions that have built up in the atmosphere, known as the airborne fraction, has stayed relatively stable at around 44%. Both the amount of CO_2 absorbed by the ocean and the amount absorbed by land have consistently increased during the last sixty years due to the rise in human-caused CO_2 emissions (with a high level of certainty). The interannual and decadal fluctuations of the regional and global ocean and terrestrial sinks demonstrate their susceptibility to climate conditions and, consequently, to climate change (Intergovernmental Panel On Climate Change (IPCC), 2023). Carbon in natural ecosystems shown in (Table. 1).

Table 1. Carbon in Natural Ecosystems (Reposted from (Trumper & Trumper, 2009))

	Vegetation growth	Vegetation decomposition	C Source or Sink	Current C storage (t C/ha)	Where the majority of C is stored	Main threat(s) for potential C emissions
Tundra	Slow	Slow	Sink	Approx 258	Permafrost	Rising temperature
Boreal Forest	Slow	Slow	Sink	Soil: 116-343; Vegetation: 61-93	Soil	Fires, logging, mining
Temperate Forest	Fast	Fast	Sink	156-320	Biomass above- and below-ground	Historic losses high but largely ceased
Temperate grassland	Intermediate	Slow	Likely sink	Soil: 133; Vegetation: 8	Soil	Land degradation
Desert and dry shrublands	Slow	Slow	Sink (but uncertain)	Desert soil: 14-102; Dryland soil: <266; Vegetation: 2-30	Soil	Fire with subsequent conversion to pasture or grazing land
Savannas and tropical grasslands	Fast	Fast	Sink	Soil:<174; Vegetation: <88	Soil	Deforestation and forest degradation
Tropical forests	Fast	Fast	Sink	Soil: 94-191; Vegetation: 170-250	Aboveground vegetation	Drainage, conversion, fire
Peatlands	Slow	Slow	Sink	1450	Soil	Not emission but decreasing uptake capacity

Ocean and coasts	In terms of plankton: Fast	Fast	Sink	(Total) Surface: 1020 Gt C; DOC: 700 Gt C; Deep ocean: 38100; Sediments: 150	Deep ocean

Human activities, specifically the combustion of fossil fuels and changes in land use, have added 651 gigatons of carbon (GtC) to the atmosphere. This has caused the average world surface temperature to increase by 1.07°C. It is worth noting that even though more than half (56%) of this carbon has been reabsorbed by lands and oceans (Intergovernmental Panel On Climate Change (IPCC), 2023).

Tropical deforestation in the 1990s resulted in the annual release of around 1.5 billion metric tons of carbon (GtC) into the atmosphere. This accounted for nearly 20% of all human-caused greenhouse gas emissions (Gullison et al., 2007). If effective regulations and measures to slow down deforestation are not implemented, the clearance of tropical forests is projected to release an additional 87 to 130 gigatons of carbon (GtC) by 2100. This is equivalent to the carbon emissions produced by worldwide fossil fuel consumption for more than ten years at current rates (Gullison et al., 2007; R. Houghton, 2005). Stopping deforestation would effectively prevent these emissions. However, by making more cautious estimates on the decrease in deforestation (assuming that deforestation rates observed in the 1990s decline linearly from 2010-2050 by 50% and that deforestation completely stops when 50% of the originally forested area in each country remains by 2000), it is possible to achieve a total reduction of 50 Gt C in emissions by 2100 (Gullison et al., 2007).

2.2. Concepts of Carbon Storage and Sequestration

Approximately 50 percent of the world's tropical forests are gone, and this destruction accounts for 20% of the carbon emissions caused by humans annually (2 gigatonnes) (Lehmann, 2007). The carbon storage capacity of ecosystems is influenced by alterations in the natural environment, such as climate change and human activity, specifically land use (Li et al., 2021; Sleeter et al., 2019; Xu et al., 2016). Evaluating terrestrial ecosystems' ability to store carbon is essential for developing land management policies and reducing carbon (Liu et al., 2023). The amount of carbon stored in forests is influenced by various factors, including the kind and structure of the forest, environmental conditions, disturbances, and management techniques (Arasa-Gisbert et al., 2018; Gogoi & Sahoo, 2018; Sahoo et al., 2019). Soil is also a significant terrestrial C sink, which consists of about 2/3 of the total terrestrial C pool (Scharlemann et al., 2014).

2.3. Importance of Carbon Storage in Ecosystem Services

Global warming substantially influences Earth's ecosystems and is a pressing issue that requires attention (Ali et al., 2022). To combat climate change, it is necessary to make substantial cuts in greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), which is the leading cause of global warming (Pachauri et al., 2014). The greenhouse gas (GHG) emissions resulting from oil production consist mainly of carbon dioxide (CO2), with lesser amounts of methane (CH_4) and nitrous oxide (N_2O). The combustion of fossil fuels, such as coal, oil, and natural gas, for electricity generation results in the emission of these gases (Le Quéré et al., 2018; Matsumoto & Tabata, 2022).

Terrestrial ecosystem carbon storage(CS) refers to the substantial quantity of carbon stored in plant leaves, woody components, and soil as part of the continuous flow of carbon between plants, soil, and the atmosphere (Z. Wang, 2019), shown in (Figure. 1). Carbon storage is an essential factor in studying the movement of carbon between land ecosystems and the atmosphere. It is crucial to determine the amount of carbon gases absorbed and emitted by these ecosystems (Hu et al., 2022). Land use and cover change (LUCC) has a substantial impact on the carbon cycling process in terrestrial ecosystems, which in turn affects the carbon balances at a regional level (Chang et al., 2022). The specific land use and cover type heavily influence the carbon-storing capacity of terrestrial ecosystems. Changes in land use categories often result in considerable carbon exchanges, making it a crucial factor to consider (Hu et al., et al., 2022; Zhang et al., 2015). Ecosystems are undergoing rapid transformations due to climate change and other global factors. Shifts in temperature do not solely drive these changes but also by alterations in precipitation patterns, atmospheric carbon dioxide levels, water distribution, ocean chemistry, and the occurrence and intensity of extreme events.

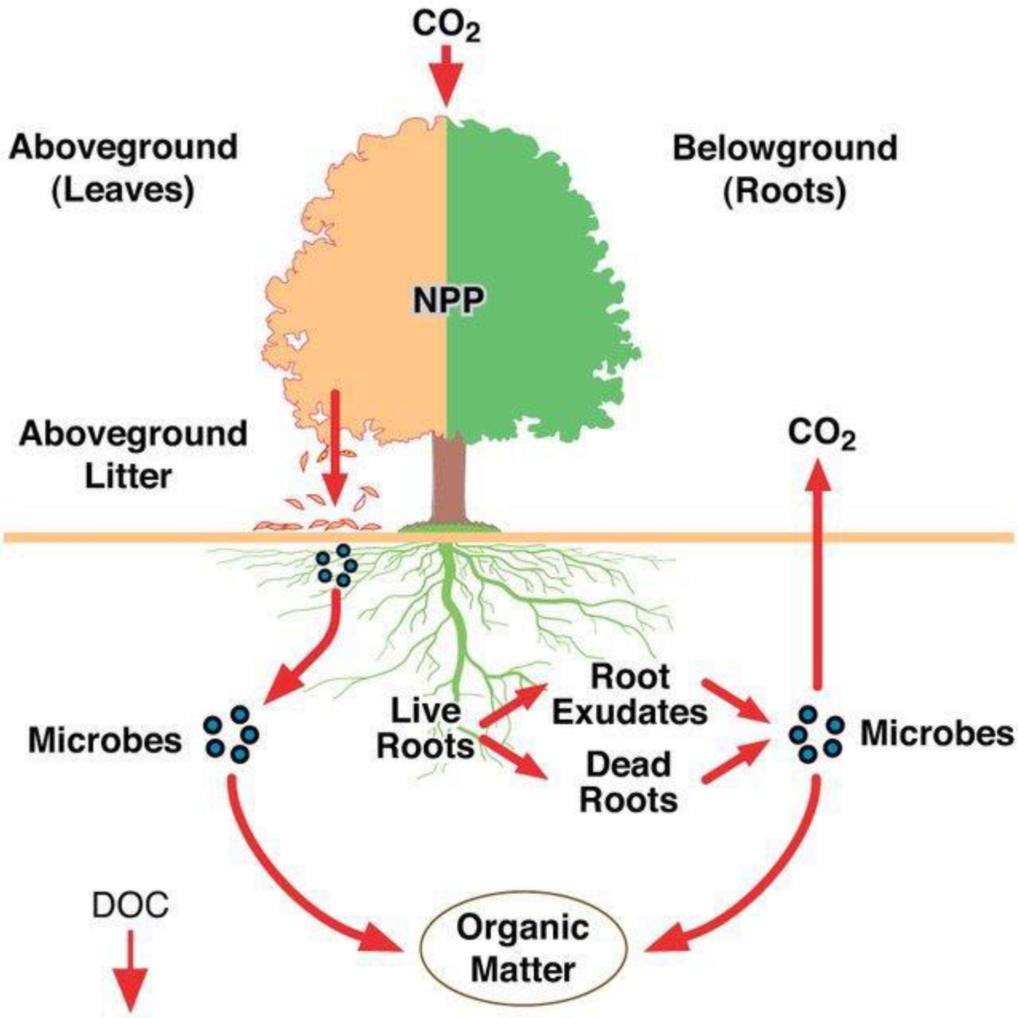

Figure 1. Schematic diagram of terrestrial C sequestration (Oldenburg et al., 2008)

Ecosystems exhibit varying degrees of sensitivity and responsiveness to climate change due to intricate interactions among organisms, disturbances, and other stressors. Global food production is affected by changes in natural ecosystems, which also endanger biodiversity (Malhi et al., 2020). Land use change, such as increased agriculture due to climate change, impacts ecosystem carbon storage indirectly and ultimately leads to the loss of terrestrial biodiversity. Molotoks et al. (2020) employ a modeling approach to investigate the unknown surrounding biodiversity and carbon loss predictions. Despite the substantial unknowns surrounding land use projections, future agricultural expansion is anticipated to negatively affect biodiversity and carbon storage in numerous biodiversity hotspots, such as the Congo Basin, Amazonia, and Mexico. When calculating the overall consequences of climate change on biodiversity and carbon emissions, it is crucial to account for indirect effects caused by changes in land use, as shown in this study.

2.4. Studies on Carbon Storage in Bangladesh

The total terrestrial carbon stock (aboveground, belowground, 0-30cm soil, dead wood, and litter) is estimated to be 1275.55 million tons. The majority of the country's carbon stock is located in soils up to a depth of 30 cm, accounting for 80.5% of the total, followed by aboveground (15%), belowground (4%), deadwood (0.5%), and litter (0.1%) biomass (Henry et al., 2021). Forest areas hold 21.5% of the total carbon stock in the country, and Hill Forest and Mangrove Forest alone hold 9.7% and 5.2% of the total, respectively (Tree and Forest Resources of Bangladesh, Report on the Bangladesh Forest Inventory. Pdf, n.d.).

There have been several studies on carbon storage in Bangladesh, focusing on different aspects such as the impact of tree species diversity, stand structure, and agroforestry practices. In 2021, a study investigated the connections between biodiversity, environmental variables, and carbon storage in home-garden agroforestry plantings in southern Bangladesh. The study revealed that the number of different species, the functional composition, and the variety of structures substantially impacted the amount of carbon stored above the ground. Among these factors, structural diversity has the most pronounced influence (Jaman et al., 2020). A separate study was carried out on homestead forests at Maheshkhali Island, located in Southern Bangladesh, to determine the amount of carbon stored above and below the ground. The study found that the carbon stocks are highly influenced by the diversity of tree species and the variation in stand structure. Specifically, a rise in the richness of tree species and the diversity index is associated with a higher amount of carbon stored in tree biomass (Baul et al., 2021).

A study by Ullah & Al-Amin (2012) on total carbon stock in the Tankawati forest of Bangladesh was estimated to be 283.80 t/ha, with trees contributing 38 t/ha, undergrowth 3 t/ha, and soil and litter fall 59 t/ha. The study identified forests as a significant carbon sink, storing a substantial amount of carbon in the atmosphere. Aboveground biomass of trees was determined using the model by Brown et al. (1989), a suitable method for biomass carbon stock estimation in tropical forests. Belowground biomass was calculated as 15% of the aboveground biomass. Prajapati et al. (2023) explored various carbon sequestration strategies, including natural carbon sinks like forests, wetlands, and agricultural lands, as well as technological carbon capture and storage (CCS) methods that involve capturing CO2 emissions from industrial sources and storing them underground. This paper highlighted the importance of carbon sequestration in mitigating climate change by capturing and storing carbon dioxide (CO2) from the atmosphere, emphasizing the urgent need to address rising CO2 levels and the detrimental impacts of climate change on ecosystems, human health, and the economy. However, it also addresses challenges related to carbon sequestration, emphasizing the need for sustainable land management practices, policy support, international cooperation, and considerations regarding technological solutions' permanence, monitoring, costs, and scalability.

A study by Majumder et al. (2019) (Figure 2) observed that most (55.10%) of lead authors of published carbon studies in Bangladesh are affiliated with academic institutions. Interestingly, 28.57%, is occupied by lead authors from overseas institutions. This is followed by other government organizations, NGOs, and the Bangladesh Forest Department (BFD), which occupy 10.20%, 4.08%, and 2.04% of the pie, respectively. The number of lead authors in published studies from BFD could be much higher despite BFD being the government-accredited agency responsible for handling such things (Majumder et al., 2019).

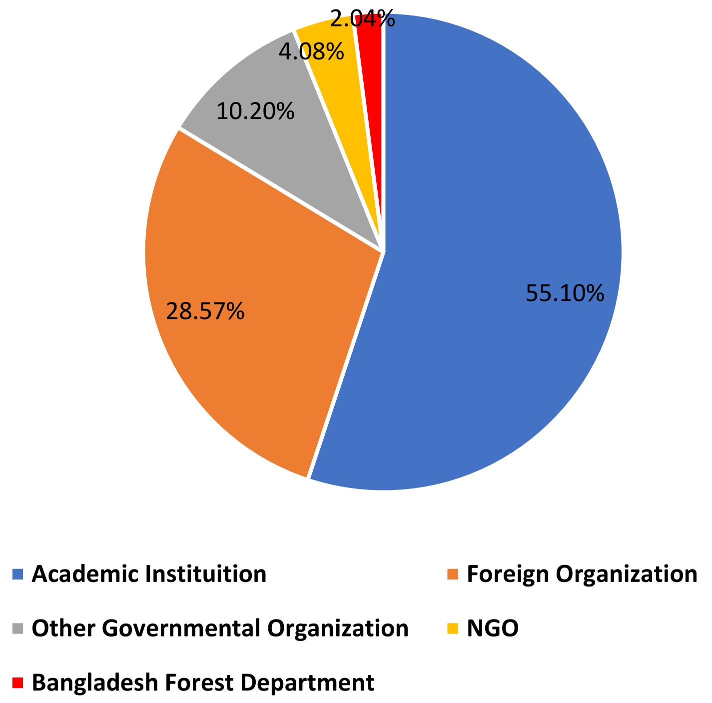

Figure 2. Institutional attachments of lead researchers of carbon studies of Bangladesh.

An area now being investigated is the Kamalganj subdistrict, located within the beautiful surroundings of the hilly area of Sylhet Division. Kamalganj, known for its varied habitats encompassing marshes and forests, possesses untapped potential as a crucial carbon reservoir essential for regional and global climate resilience. The spatial boundaries of the land must be precisely delineated to enable precise measurement, monitoring, accounting, and verification

(Pearson et al., 2007). Satellite images offer a comprehensive overview of a landscape at different levels of detail and over different periods. They allow us to accurately identify the spatial distribution of land use and land cover units and track how they change over time. GIS-based models facilitate the production and analysis of different aspects of these changes and their influence on ecosystem services (Gupta et al., n.d.). The introduction of sophisticated modeling approaches has dramatically transformed our capacity to understand the complex mechanisms of ecosystems and their impact on human welfare. The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model is a robust instrument that can effectively measure and map the diverse advantages obtained from nature. InVEST is a spatially explicit model that predicts ecosystem services using "ecological production functions" and then integrates these estimates with economic valuation methodologies to determine their complete economic value for a given landscape.

Utilizing the InVEST model enables researchers to understand the geographical arrangement of ecosystem services, facilitating well-informed decision-making and sustainable management of resources. This study aims to explore the complex dynamics of carbon storage in Kamalganj. This study aims to use the InVEST model to conduct a thorough quantitative analysis to reveal the valuable resources of carbon stocks. It will provide insights into the spatial distribution, factors influencing it, and opportunities for improvement. In light of this context, this introduction establishes the framework for a comprehensive investigation of carbon storage in Kamalganj. The following sections of this thesis will explore the research goals, methods, results, and consequences, leading to practical suggestions for policymakers, local communities, and stakeholders. This study aims to contribute to the broader discussion on sustainable development, climate resilience, and preserving the natural legacy of Kamalganj's ecosystems by uncovering its carbon resources.

2.5. Methodologies for Assessing Carbon Storage

Assessing carbon storage is a critical aspect of understanding and mitigating climate change. The academic community has shown significant interest in studying carbon storage in recent years, particularly in evaluation methodologies, research subjects, and temporal scopes. Scholars have developed many approaches to evaluating carbon storage (Bachu et al., 2007). Conventional methods encompass biomass techniques and accumulation methods (Lu et al., 2016). Nevertheless, the limitations of traditional methods in reliably capturing changes in carbon storage across different spatial and temporal scales have prompted numerous researchers to utilize modeling techniques to evaluate these dynamic modifications (J. Wang et al., 2020). The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model is notable among other models for its minimal data needs and effective performance (Cong et al., 2020).

The allometric models illustrate the correlation between various tree-related variables such as diameter at breast height (DBH), height of the tree trunk, total height of the tree, crown diameter, height-diameter ratio (H/D), and tree species richness (Hossain et al., 2016; Islam et al., 2017). The selection of these variables differed throughout various research. Furthermore, certain studies have considered the impact of hill slopes on the biomass yield (Haque & Karmakar, 2009; Shin et al., 2007). Several studies have considered the age factor to accurately estimate the carbon stock of plantation species in terms of trunk, litter, and soil (Shin et al., 2007). In their total carbon estimation reports, Ullah and Al-Amin (2012) included herb, shrub, tree, and grass species. Several researchers have approximated the carbon stock by relying just on the diameter at breast height (DBH) (Dey et al., 2014; Hossain et al., 2016), while a few others have taken into account 10-12 factors (Rahman, 2004). In their study, Mizanur et al. (2015) discovered that the dominant species of mangroves serve as a crucial signal for the amount of carbon stored in an ecosystem. The content of organic carbon in soil is affected by microbial activity (Rasid et al., 2016), pH levels (Bangladesh Rice Research Institute, 2014; Hossain, 2016), the depth of the soil (Saha et al., 2014), and the type of fertilizer used (Rahman, 2015; Rahman et al., 2016). Whether fragmented or continuous, the kind of forest substantially impacts the carbon content (Islam et al., 2017). Therefore, holistic models must be used to consider all relevant variables when estimating carbon. (Table. 2) provides a summary of the frequently utilized equations in Bangladesh. While the quantity of allometric equations tailored specifically for Bangladesh has risen, around 50% of these models lack statistical validity. In their study, Mahmood et al. (2016) determined that a mere 5% of tree species and shrubs in Bangladesh possess an allometric equation that may be used to estimate biomass.

Table 2. Commonly used equations in carbon studies in Bangladesh (Majumder et al., 2019)

Name	Expression	Specification	Reference
Above-ground biomass	$\log Y = \log\beta_0+\beta_1\log X$	X = physical parameter of trees (e.g., height, DBH)	(Hossain et al., 2016b)
	$Y = \exp(-\beta_0+\beta_1\ln(D^2HS))$	H = height D = diameter S = oven dry density	(Akter et al., 2013; Alamgir & Al-Amin, 2007; Islam et al., 2017; Shin et al., 2007; Ullah & Al-Amin, 2012; Ullah et al., 2014)
	$Y = \beta_0+\beta_1X_1+\beta_2X_2$	Y = total carbon stock X = physical parameter of trees (e.g., height, DBH)	(Dey et al., 2014; Hossain, Saha, Abdullah, Saha, & Siddique, 2016a; Hossain & Banik, 2005; Ullah et al., 2014)
	$Y = \rho.\exp(-\beta_0+\beta_1\ln X+\beta_2\ \ln X^2 -\beta_3\ln X^3)$	ρ = wood density X = physical parameter of trees (e.g., height, DBH)	(Islam, 2013; Jaman et al., 2016; Kamruzzaman et al., 2018; Mizanur et al., 2015)
Below-ground biomass	$BGB = \beta_0\rho^{\beta 1}\ D^{\beta 2}$	BGB = below-ground biomass ρ = wood density D = DBH	(Kamruzzaman et al., 2018; Mizanur et al., 2015)
	$BGB = \exp(-\beta_0+\beta_1\ln AGB)$	AGB = above-ground biomass	(Islam, 2013; Jaman et al., 2016)
	BGB = 15% of the total above-ground biomass		(Islam et al., 2017; Miah et al., 2009; Ullah & Al-Amin, 2012; Ullah et al., 2014)
	BGB = 20% of the total above-ground biomass		(Hanif, Bari, & Rahman, 2015)
Moisture content	Moisture content (%) = $(W2 -W3/W3-W1)\times100$	W1 = weight of Petri dish W2 = weight of Petri dish with moist soil W3 = weight of Petri dish with dry soil	(Akter et al., 2013; Alamgir & Al-Amin, 2007; Rahman et al., 2013; Sohel et al., 2015; Ullah & Al-Amin, 2012)
Loss on ignition (LOI)	LOI (%) = $(W1/W2)\times100$	W1 = loss in weight W2 = weight of oven dry soil	(Rahman et al., 2013; Sohel et al., 2015)
Carbon (%) from LOI	Carbon (%) = 0.476×(%LOI−1.87)		(Rahman et al., 2013)
	Carbon (%) = 0.476×(%LOI−1.47)		(Sohel et al., 2015)
Carbon in the stand by using GIS and remote sensing	Carbon, $C = f(D,A,L,R,H, O,S,F,P, Cr,B,W)$	D = average tree diameter at breast height A = stand age L = leaf area index H = canopy height O = canopy cover R = total area of the stand S = stems per unit area F = forest type P = species Cr = crown height B = bole height W = crown width Cl = leaf cluster index	(Al-Amin, 2016; Rahman, 2004)

In 2005, a National Forest Assessment was conducted in Bangladesh. In 2007, allometric equations published for other nations were utilized in the Sundarbans carbon inventory. This was further supported by a study conducted in 2009-2010 by Chanda et al. (2016). While the diversity of species restricts the applicability of species-specific allometric equations (Mizanur et al., 2015), using equations from other countries would result in unreliable estimates, raising concerns about the accuracy of national estimation (Ahiduzzaman & Islam, 2016; Mizanur et al., 2015). The carbon storage rate in the same environment is determined completely by the species present. This highlights the importance of developing localized allometric equations that are specific to each species. In most studies, the calculation of below-ground carbon stock was determined to be 15% of the above-ground carbon stock (Miah et al., 2009; Ullah & Al-Amin, 2012). However, a separate study found that it was actually 14% in a real field setting (Rahman et al., 2015), which introduced additional inaccuracies into the estimates.

2.6. Case studies and comparative analysis

Most research on natural strategies for coping with climate change has concentrated on either terrestrial-coastal systems (such as mangroves and salt marshes) or ecosystems entirely located on land, such as forests and peatlands (Malhi et al., 2020). The ability of ecosystems to aid human adaptation (i.e., supply so-called "adaptation services") decreases due to climate change. Humans and ecosystems 'co-produce' these services; this was the goal of the article by Lavorel et al. (2020). They go beyond the box by studying the interplay between ecosystem management, mobilization, appropriation, social access, and appreciation and the synergies, co-benefits, and trade-offs of various adaptation services along an ecosystem cascade. Five case studies from different socio-ecological systems show how broad mechanisms might improve co-benefits and reduce trade-offs amongst adaptation services. Finally, they state that collective adaptation to changing ecosystems can be facilitated through proactive management and governance, made possible by being aware of such co-production mechanisms.

Over the last decade, researchers have better understood how ecosystems produce services and how those services translate into economic value (Daily et al., 1997; Reid et al., 2005; *Valuing* *et al.: Toward Better Environmental Decision-Making*, n.d.). (Polasky et al., 2011) Used InVEST to analyze the trade-offs between ecosystem services and their values in Minnesota, considering real land-use change and several scenarios. A study conducted in the Willamette Basin, Oregon, USA, also used InVEST to examine ecosystem service outcomes from carbon sequestration under three different land-use trajectories (Nelson et al., 2009). The primary objective of the study conducted by Malhi et al. (2020) is to examine the potential benefits and difficulties related to the effective administration, rehabilitation, and safeguarding of ecosystems to facilitate interventions to mitigate and adapt to climate change. Utilizing ecosystems to address climate change, known as natural climate solutions (NCS) or Nature-based solutions NbS, has attracted significant attention. NCS focuses on mitigating climate change through ecosystem protection, restoration, and utilization (Griscom et al., 2017). NbS can partially reduce the effects of global warming and simultaneously promote biodiversity and ecosystem services. However, it is crucial to avoid implementing ineffective NbS strategies, such as non-native monoculture plants, which might have negative impacts. Seddon et al. (2020) comprehensively explain the notion of NbS (Nature-based Solutions) and its growing significance in global policy. The authors introduce a novel conceptual framework that elucidates the function of Nature-based Solutions (NbS) in integrating the ecosystem with the socioeconomic system. They also demonstrate how, through meticulous and fair application, NbS can mitigate the susceptibility of the social-ecological system as a whole. This study emphasizes essential evidence supporting the importance of nature in decreasing vulnerability and sensitivity to the impacts of climate change. It also showcases instances where Nature-based Solutions (NbS) improve the ability of ecosystems and society to adapt. Seddon et al. (2020) also address the significant difficulties in assessing the efficacy of Nature-based Solutions (NbS) and the financial and governance barriers to widespread deployment.

Soto-Navarro et al. (2020) provide a comprehensive regional investigation of the correlation between the carbon storage potential of ecosystems and their biodiversity significance. While carbon value is primarily one-dimensional, biodiversity value is more complex to map due to its several dimensions and dependence on regional factors. For example, a tropical forest often exhibits a higher species richness level than an Arctic ecosystem, while the latter possesses distinct biodiversity significance. By utilizing various indices, they construct maps that depict the potential for proactive biodiversity conservation (areas with high levels of biodiversity that are not currently threatened but could benefit from proactive protection) and areas that require immediate reactive conservation efforts due to imminent threats. The study identifies areas where biodiversity and carbon priorities align, such as tropical and boreal forest regions, and areas where they diverge, such as grasslands. Focusing on carbon and climate mitigation may not necessarily benefit biodiversity and could even harm local biodiversity, as seen in the afforestation of natural grasslands for carbon purposes.

Griscom et al. (2017) analyze the capacity of tropical countries to implement Natural Climate Solutions (NCS), which can effectively mitigate climate change by using the carbon sink afforded by trees. In addition to safeguarding and reviving forests, they prioritize preserving other indigenous ecosystems, such as peatlands and mangroves, while focusing on enhancing the management of productive areas. Twelve NCS paths are evaluated as potential methods to achieve substantial climate change mitigation while offering biodiversity benefits and other ecosystem services, mainly by preventing the conversion of forests. Most tropical natural climate solutions (NCS) have potential in a small group of nations. Almost all of these countries have above-average metrics for governance, which suggests that they have the necessary feasibility and capacity to implement NCS utilizing protect-manage-restore methodologies (Malhi et al., 2020).

Hobbie & Grimm, (2020) specifically, examine the capacity of ecosystem-based strategies to address climate change adaptation in urban settings. By the year 2050, almost two-thirds of the global population will live in urban areas, making cities a significant focal point for both the effects of climate change and the measures taken to adapt to them. Cityscapes are highly susceptible to climate change hazards due to several factors. These include limited vegetation, extensive impervious surfaces, the production of pollutants, the formation of heat islands, a significant need for freshwater resources, and the concentration of population and infrastructure in vulnerable regions like coastal zones, river floodplains, and deforested hillsides. Nature-based methods can reduce the risks associated with climate change and the exacerbating impacts of urban areas on those risks. These techniques include increasing vegetation cover and green spaces, constructing buildings replicating natural hydrologic processes, including stormwater ponds, bioswales, green roofs, and riparian zones, and restoring natural protective habitats along coastlines. However, compared to technical approaches, a comprehensive evaluation of these nature-based techniques must consider the costs, including any adverse effects (Malhi et al., 2020).

The study conducted by (Sandom et al., 2020) investigates trophic rewilding as a management approach to restore ecosystems and potentially aid in mitigating climate change. Over the past 50,000 years, humans have significantly altered the composition of natural communities by impacting populations of large herbivores and predators. Across various regions, sizable herbivores that do not chew cud have been removed and substituted with domestic grazing animals that do chew cud. This substitution has led to significant alterations in the arrangement of vegetation, patterns of fire occurrence, and the cycling of biogeochemical elements, including carbon (Malhi et al., 2020).

Chapter 3

Data and Methodology

3.1. Methodology

Literature was collected from several reputed scientific literature databases, such as Scopus, PubMed, etc. The literature query was carried out using the keywords “carbon storage and sequestration”, “carbon storage estimation”, and “carbon storage and sequestration using InVEST”. The current study is based mainly on the published literature related to carbon storage and sequestration estimation. The documents were collected exhaustively through online literature databases, including Google Scholar, Nature, Springer Link, Science Direct, Plos, Wiley online library, Tandfonline, and Cabdirect. Literature reviews from different books, blogs, newspapers, thesis papers, term papers, essays, and statistical yearbooks have also been considered.

3.2. Study Area

The Kamalganj subdistrict (Moulvibazar district) lies between 24°08' and 24°27' north latitude and 91°46' and 91°50' east longitude, with a total geographical area of 485.26 sq km. It is one of Bangladesh's most beautiful natural settings due to its diverse nature (Chakrabarti & Mondal, n.d.). It is bounded by Rajnagar upazila to the north, Tripura state of India to the south, Kulaura upazila and Assam state of India to the east, and Sreemangal and Maulvibazar Sadar upazila to the west. There is one municipality and nine unions in Kamalganj subdivision such as Kamalganj, Admpur, Alinagar, Islampur, Madhabpur, Rahimpur, Samsernagar, Poton Usher and Munsibazar. The total population of the study area is 259130 (*Kamalganj Upazila - Banglapedia*, n.d.). It's among the most picturesque spots in the country; the region has hills, tea gardens, forests, and water bodies such as rivers, lakes, ponds, and plain fields with a greenish appearance from agricultural production. The eastern and western parts of this upazila (sub-district) are hilly mountains, with most of the area covered in forest (Singha et al., 2018). On the eastern side of the subdistrict, an old human dwelling has grown on plain ground. The hill forests rely heavily on local resources and unsustainable collecting practices (Miah et al., 2014). Kamalganj forests come under the Moulvibazar hill forests, where the hill forest experienced a net increase in carbon emissions. Geographical location of Bangladesh, including Moulvibazar district shown in (Figure 3), and area of my study is shown in (Figure. 4).

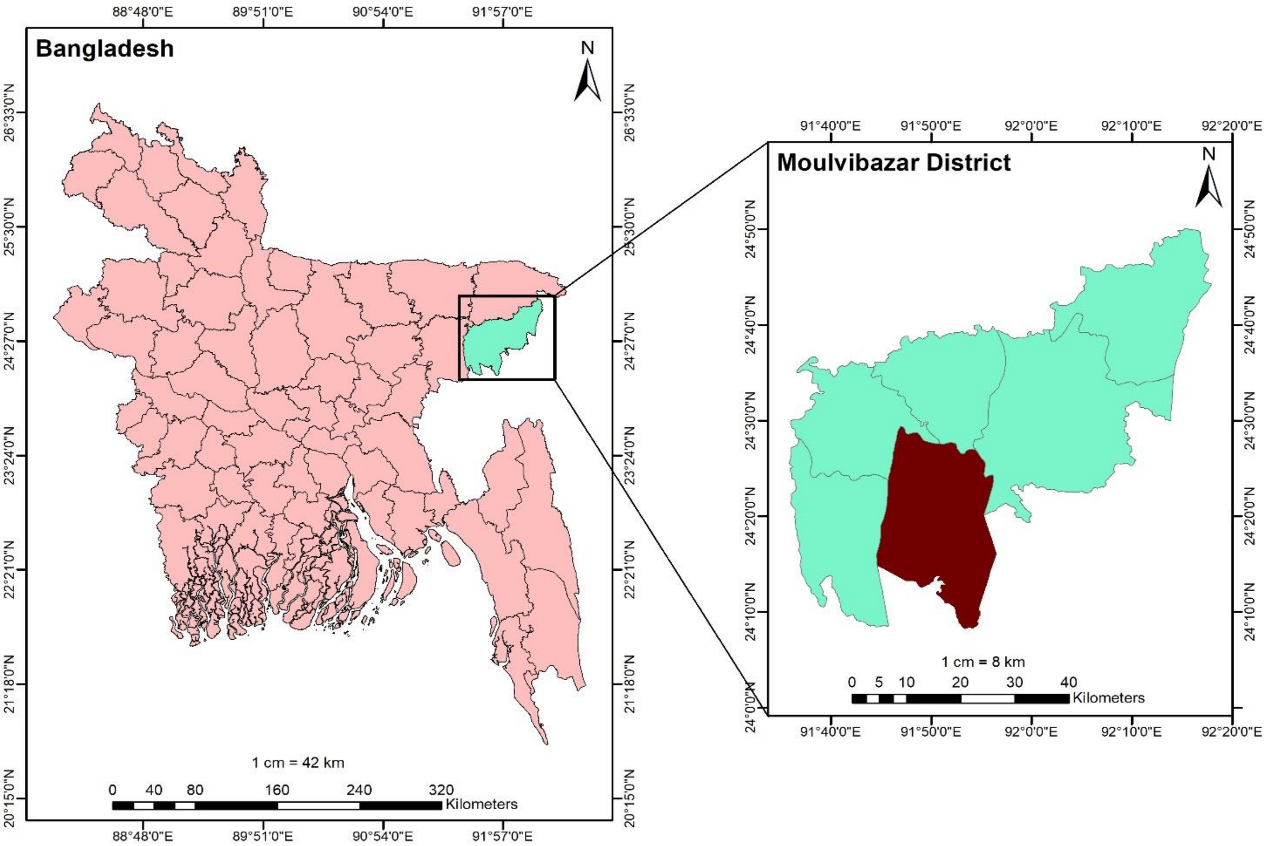

Figure 3. Geographical location of Bangladesh (Left), Moulvibazar District (Right)
(Source: Author)

However, there has been a decline in the most recent decade from 2011 to 2020. The dominant tree species in the hill forests of northeastern Bangladesh are Tectona grandis, Artocarpus chaplasha, Lager stromia speciosa, Chikrassia tabularis, and Xylia dol abriformis (Afroz et al., 2023). Kamalganj can be viewed as a symbol of unity in diversity, as it is home to people of all races, cultures, languages, religions, and lifestyles (Chakrabarti & Mondal, n.d.). Notably, various groups, together with their diverse cultures, migrate there with an assimilationist and adapting approach to the mainstream, i.e., Bengali society. Along with other religious people residing in Kamalganj, Indigenous communities such as manipuri, khasia, tripura (Tipra), and Halam belong to this upazila (*Kamalganj Upazila - Banglapedia*, n.d.).

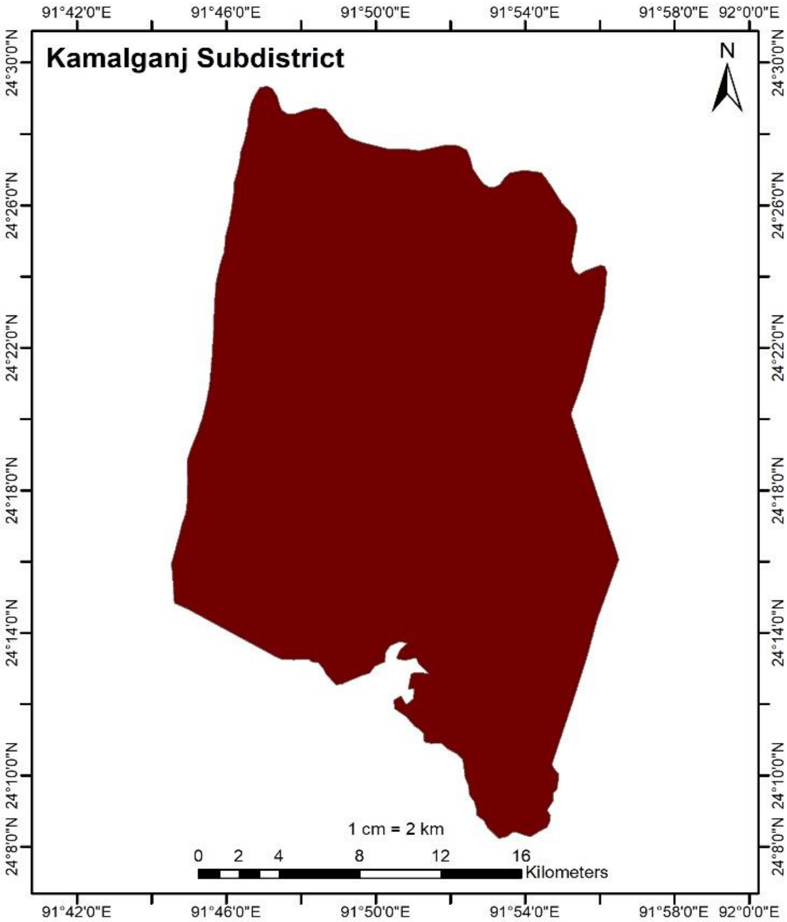

Figure 4. Study area map of Kamalganj subdistrict

The most common forests in Moulvibazar district are Lawachara National Park (LNP), Rajkandi Reserve Forest (RRF), Muraichara Eco Park, Madhovkundo Eco Park, and Lathitila Forest (LF). Two forests, LNP and RRF, are in the Kamalganj subdistrict.

3.3. Land Use Land Cover (LULC) Data

Land Use and Land Cover (LULC) products are crucial for analyzing land use and land cover changes and understanding environmental and socioeconomic concerns. They assist in comprehending the fundamental attributes, regional arrangement, and distribution features of different land use and land cover (LULC) categories, establishing the groundwork for subsequent examination of regional disparities in LULC alterations (Turner et al., 2007). In addition, they help assess the effects of Land Use and Land Cover (LULC) modifications on ecosystems, biodiversity, carbon equilibrium, water resources, and other variables. Thus, it is crucial to generate LULC goods of superior quality (Y. Wang et al., 2023).

For the InVEST carbon storage model software, the LULC data were set as a LULC raster map. To present the data in raster format, each land use and land cover (LULC) category is assigned a numerical number. These codes need not be in sequential order or follow a specific pattern *(Natural Capital Project, 2024)*. Landsat 9 satellite imagery was downloaded from USGS Earth Explorer (EarthExplorer (usgs.gov)) on 2024-03-10 (Path:136, Row:43). After that, processing of the LULC raster map was carried out using ArcGIS 10.3 mapping software. The LULC polygon shapefile of Kamalganj was clipped to extract the LULC of the Kamalganj in the ArcGIS environment. The clipped polygon map was then converted into a raster dataset by using the Feature to Raster tool in ArcGIS. As further explained by Sharp et al. (2018), by the time of conversion, each LULC type of attribute table was introduced with a specific LULC code corresponding to the carbon data that should be included in the carbon pools table, which required as one of the inputs for running the model.

3.4. The spatial arrangement of the land use/land cover (LULC)

The spatial arrangement of land use and land cover (LULC) refers to the organization and categorization of different land types and their utilization within a certain geographic region. This information is vital for comprehending the landscape, monitoring alterations over time, and making well-informed choices on land administration. The prepared LULC raster map of the study area is shown in (Figure. 5.) According to the prepared LULC raster map, the study area consisted of mainly 7 LULC types: *Forest, Built-up Area, Waterbodies, Row Crop Land, Fallow Land, Trees, and Rangeland*. Due to its diverse land use and land cover (LULC) types, the Kamalganj subdistrict can be a suitable location for studying the carbon storage capabilities of different LULC types.

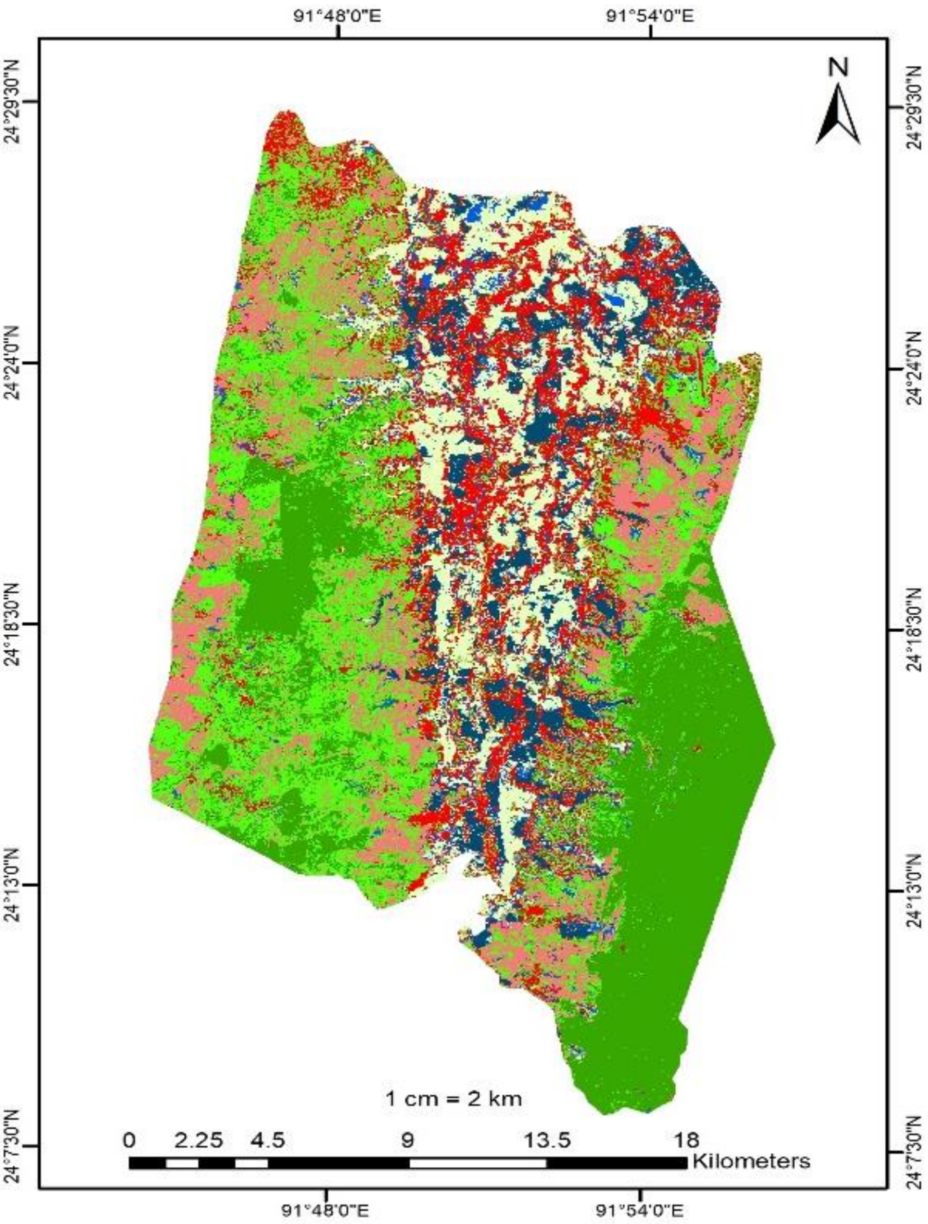

Figure 5. Raster map showing Land use Land Cover (LULC) types in the Kamalganj Subdistrict

The area percentages of each LULC type were calculated using an efficient method for estimating the area of a raster output that involves examining its properties, including pixel count and cell size, and then multiplying the cell size by the count to obtain the area in square units of the specified linear units (Buckley & Buckley, 2018). Based on the calculations, the

Kamalganj subdistrict is mainly covered by trees, which make up around 23.58% (12,080 ha) of the total area. Tree is the greatest land use and land cover (LULC) type out of the 7 types

Table 3. Classified Class (LULC) area and percentage in the Kamalganj subdistrict

No.	Classified Class	Area (Km^2)	Area (ha)	Percentage
1	Forest	117.05	11705	22.84
2	Waterbodies	22.68	2268	4.43
3	Built-up Area	75.31	7531	14.70
4	Fallow Land	34.70	3470	6.77
5	Row Crop Land	69.36	6936	13.54
6	Trees	120.80	12080	23.58
7	Rangeland	72.48	7248	14.15
	Total	**512.38**	**51238**	

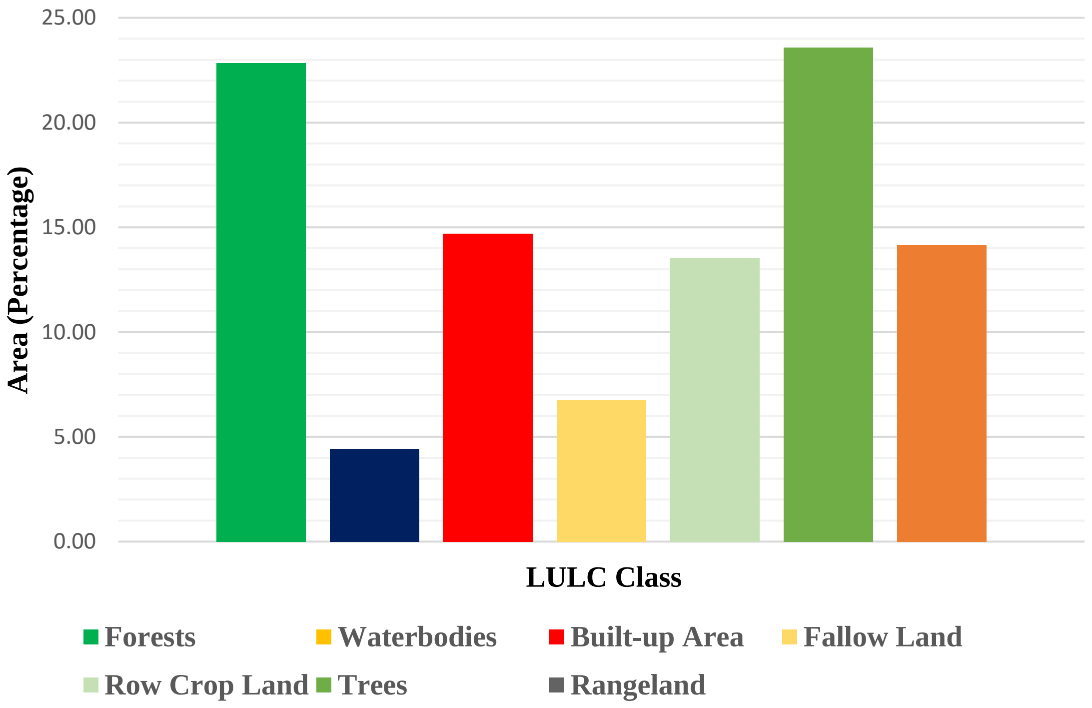

Figure 6. Graph showing the area percentages of LULC classes of the Kamalganj Subdistrict

considered. The area was thereafter covered by forests (national park and reserve forest), which accounted for approximately 22.84% (11,705 ha). In addition, the study region encompassed the built-up area, rangeland, row crop land, fallow land, and waterbodies, which covered approximately 53% (27,453 hectares) of the area (Figure. 6).

3.5. Carbon Pools

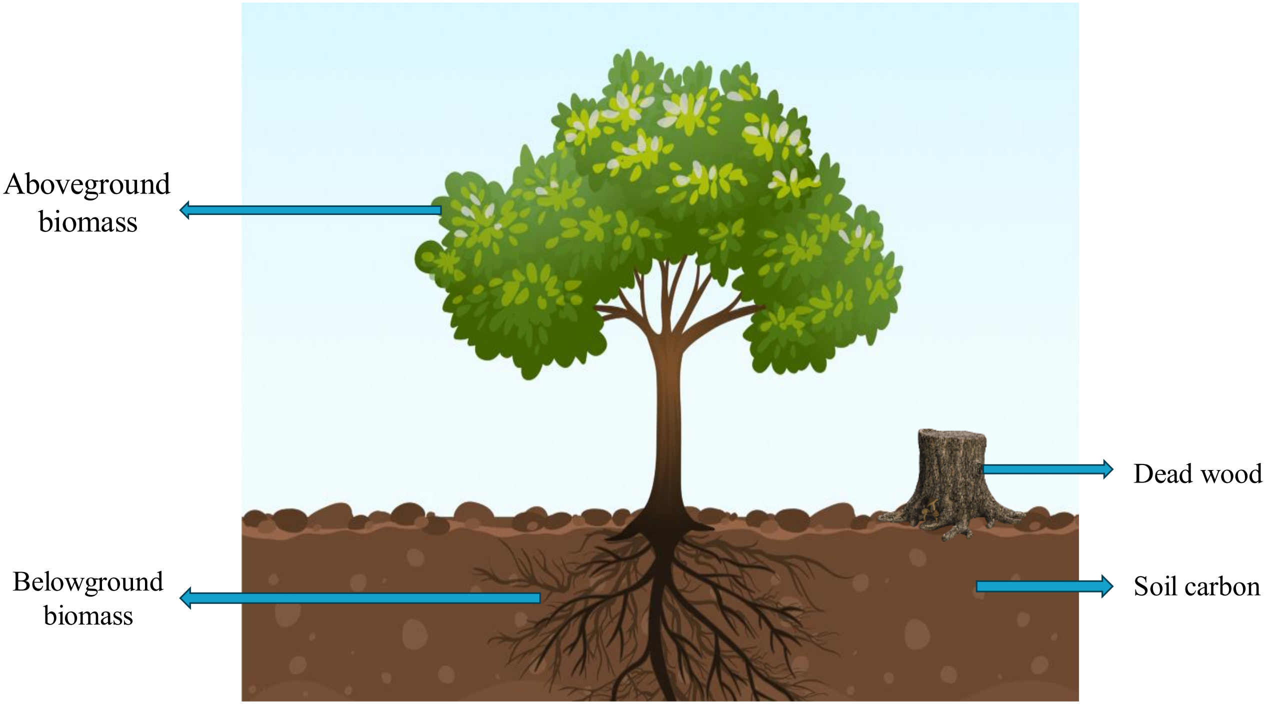

Figure 7. Carbon Pools

Carbon (C) is distributed worldwide among three reservoirs: the atmosphere, the ocean, and the land biosphere. The atmospheric pool contains 762 petagrams (1Pg = 10^15g) of carbon, primarily in the form of carbon dioxide (CO_2) (Das et al., 2017). The earth's soils retain a significantly more significant amount of carbon (C) than the atmosphere, approximately twice as much (1500Pg). Most of this carbon is organic C and has a turnover rate ranging from months to thousands of years (Lal, 2004). The soil is a highly effective reservoir for atmospheric CO_2, contingent upon the input-output carbon balance. In the past, the soil has lost approximately 55-78 gigatons (1 Gt = 10^{15} g) of carbon, indicating a significant capacity for carbon sequestration (Nieder & Benbi, 2008).

In accordance with the specifications of the InVEST carbon model program, a comma-separated value table (CSV file) was created, including carbon pool data. The illustration of carbon pool shown in (Figure. 7). The table contained carbon density data for each carbon pool (aboveground, belowground, dead organic materials, and soil carbon) for each land use and land cover (LULC) type. The carbon pool values for each land use and land cover (LULC) category were collected from previously published literature. Nevertheless, developing a precise carbon pool table is crucial to guarantee the accuracy of the outcomes produced by the InVEST carbon storage and sequestration model. Therefore, in most instances, the carbon statistics have been derived from the Intergovernmental Panel on Climate Change's (IPCC) 2006 report, as it is widely regarded as one of the most dependable sources of carbon data globally (Hiraishi et al., 2014; Sharp et al., 2018).

3.5.1. Carbon Stored in Aboveground Biomass

Aboveground biomass refers to the total amount of live vegetation, including trees, plants, shrubs, and woody materials from trees, that is present on the soil (Federici et al., 2008). Timber inventories, commonly conducted by forestry ministries on designated plots, can be used to determine aboveground biomass (and therefore carbon stocks). To estimate the amount of carbon stored aboveground in a forest stand measured for its merchantable volume, where VOB represents the volume of trees per hectare measured from the tree stump to the crown point, WD is the wood density of the trees, Biomass Expansion Factor (BEF) is the ratio of total aboveground dry biomass to the dry biomass of the inventoried volume, and CF is the ratio of elemental carbon to dry biomass, by mass (Brown, 1997).

3.5.2. Carbon Stored in Belowground Biomass

Belowground biomass refers to the total mass of root systems comprising the vegetative cover (Federici et al., 2008). Fine roots with a diameter of less than 2 mm (recommended) are occasionally not considered, as they cannot be reliably differentiated from soil organic matter or debris using empirical means (UNFCC, 2015). For land use and land cover (LULC) categories where woody biomass is the main component, an approximate estimation of belowground biomass can be obtained using the "root to shoot" ratio, representing the ratio of belowground biomass to aboveground biomass. The root-to-shoot ratio estimations for different eco-regions may be found in Table 4.4 on page 4.49 of the (IPCC, 2006) report. Section 3.5 of (Brown, 1997) also provides approximate values for this ratio. Specific land use and land cover (LULC) categories have minimal or no woody biomass, but they do have significant amounts of carbon stored below the ground. Such LULC types include natural grasslands, managed grasslands, steppes, and scrub/shrub areas. The root-to-shoot ratio mentioned earlier is not applicable in these situations. For these land use and land cover (LULC) types, the most accurate estimates of below-ground information can be obtained at the local level. However, if local data is inaccessible, global estimates can be utilized as an alternative *(Natural Capital Project, 2024)*.

3.5.3. Carbon Stored in Soil

Soils contain more carbon than the atmosphere and plants combined(*BSSS_Science-Note_Soil-Carbon_Final_May22_75YRS_DIGITAL.Pdf*, n.d.). After the world's oceans, soil is the world's most significant active carbon storage, accounting for 80% of total terrestrial carbon, about three times that of the atmosphere (Keenor et al., 2021). The proportions of organic and inorganic carbon in soil are important and constantly changing parts of the carbon cycle on a global scale. Typical soil profile shown in (Figure. 8).

Soil organic carbon (SOC) encompasses carbon found in soils, including small plant roots, fungi, microorganisms, and decaying organic matter from plant litter or animal byproducts like manure (World Bank, 2021). Soil organic matter (SOM) refers to the amount of organic carbon present in the soil (Federici et al., 2008). SOM is the main reservoir of carbon (C) in soil and plays a vital role in determining soil quality by affecting its physical, chemical, and biological characteristics (Holeplass et al., 2004). In addition, soils also contain inorganic carbon in the form of minerals. Soil inorganic carbon (SIC) refers to chemical compounds found in soil, such as calcite or chalk, which are composed of calcium carbonate (CaCO3) (World Bank, 2021).

The capacity of soils to sequester organic carbon is influenced by the physical structure, or aggregation, of the organic and inorganic particles found in the soil profile and the biotic variables that influence the carbon inputs and outputs in the soil, including living plants, animals, and microbes that reside in the soil (World Bank, 2021).

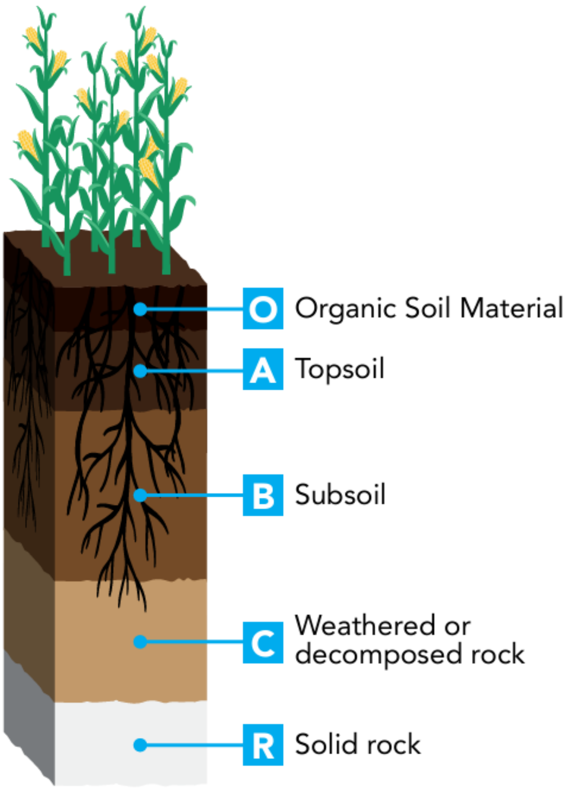

Figure 8. Typical Soil profile (Source: (World Bank, 2021))

The physical and biotic characteristics vary as we go deeper into the soil, with the upper layers being more susceptible to environmental influences. These characteristics are also influenced by how the land is used and managed. (World Bank, 2021). Typically, when conducting studies to determine the rates at which carbon is stored and sequestered in a particular area, measurements of the soil pool focus solely on the amount of organic carbon present in mineral soils (Post & Kwon, 2000). However, it is crucial to incorporate the presence of organic soils, such as marshes or paramo, into the mineral soil content when modeling an ecosystem. In regions where the transformation of wetlands into alternative land uses is prevalent, closely monitoring carbon emissions from organic soils is crucial (IPCC, 2006).

3.5.4. Carbon Stored in Dead Organic Matter

Dead organic matter includes all the dead trees and the litter that is connected with them (Federici et al., 2008). Deadwood pool consists of stems and branches with a diameter of 10 cm or more, whereas litter comprises smaller pieces. Incorporating the dead organic matter pool improves the accuracy of the projected changes in the total carbon stock. The dynamics of deceased organic matter differ depending on the specific forest or plantation type and the underlying objective of forest conservation or establishment.

In fuelwood plantations or community forestry projects, the lignified portion of the deceased organic material is prone to be extracted and utilized as fuelwood. Dead organic matter is unlikely to be the primary carbon reservoir for grassland reclamation, agroforestry, and cropland management programs. It typically represents approximately 10% of the total carbon stocks in forests and tree plantations. However, they may be largely absent in other land-use types ("Methods for Dead Organic Matter," 2008).

DOM = DW + LT where DOM = dead organic matter, DW = deadwood and LT = litter.

Source: ("Methods for Dead Organic Matter," 2008).

3.6. Calculation of the Carbon Storage

3.6.1. Carbon Pool Data

The carbon pool values for each land use and land cover (LULC) category were gathered from previously published literature (Piyathilake et al., 2022; Fakir et al., 2015). Sharp et al. (2018) evaluated the belowground carbon storage values of land use and land cover (LULC) types that have woody biomass using the "root to shoot" ratio approach, as described by Cairns et al. (1997) and Grace et al. (2006). According to Brown (1997), accurately measuring the amount of carbon stored above the ground is complex, requiring much effort and time. The aboveground carbon data were acquired from the Intergovernmental Panel on Climate Change's (IPCC) 2006 report, widely regarded as one of the most dependable sources of carbon data globally (Hiraishi et al., 2014; Sharp et al., 2018). In a study conducted by Upadhyay et al. (2005), Carbon stored in soil data for hill forests was obtained. Four carbon pool values in each LULC are given in (Table. 4). This table presented the carbon density values for each carbon pool (aboveground, belowground, dead organic materials, and soil carbon) for each land use and land cover (LULC) type. The final maps and data tables resulting from this model run were in a user-defined workspace folder (Piyathilake et al., 2022).

Table 4. Carbon values of above-ground, below-ground, soil, and dead carbon (in Mg/ ha) pools in the study area.

LUCODE	LULC	C_above	C_below	C_soil	C_dead
1	Forests	195.8	37	38.59	12.4
2	Built-up Area	0	0	50	0
3	Waterbodies	10	5	20	0
4	Row Crop Land	3	2	10	0
5	Fallow Land	1	1	10	0
6	Trees	45	65	60	17
7	Rangeland	6	6	20	2

3.6.2. Estimation of the Carbon Storage based on the InVEST Model

According to Sharp et al. (2018), the research area's LULC data and the carbon density data for each type of LULC in the study area were the first data sets needed to run the InVEST carbon storage and sequestration model. The InVEST carbon storage and sequestration model software, initially developed by the Natural Capital Project (www. naturalcapitalproject.org), is used to calculate the carbon stock in the research area. The InVEST carbon model accurately tracks the carbon cycle and estimates the total carbon stored in the entire study region by combining carbon pool values assigned to each land use and land cover (LULC) type (Sharp et al., 2018). According to the model, the carbon density of each LULC type (i) is as shown in Eq. (1).

$$\boldsymbol{C_i = C_{i(above)} + C_{i(below)} + C_{i(dead)} + C_{i(soil)}} \quad \textbf{(1)}$$

Where$C_{i(above)}$, $C_{i(below)}$, $C_{i(dead)}$), and $C_{i(soil)}$ represent the carbon density of aboveground biomass, belowground biomass, dead organic materials, and soil in the ith LULC type, measured in (tons/ha). The model calculates the total carbon storage of the study area using Equation (2).

$$\boldsymbol{C_{total} = \sum_i^n C_i * A_i} \quad \textbf{(2)}$$

where, C_{total} is the total carbon storage in the study area (tons), n is the number of LULC types in the study area, and A_i is the area of each LULC type (ha).

The InVEST model is based on fundamental assumptions about carbon reservoirs, where the carbon density of each land cover type is considered to have a constant value. This method involves determining the amount of carbon stored in vegetation in a particular location by multiplying the carbon density measurements of different species of vegetation by their corresponding surface areas (Babbar et al., 2021; Cong et al., 2020). However, research has identified significant variations in carbon density among other locations. Therefore, this study concentrates on the Northeastern part of Bangladesh, particularly Kamalganj, a subdistrict of Moulvibazar district.

3.7. InVEST Model

3.7.1. Background

Mapping and valuing ecosystem services tools are crucial for comprehending the functions and advantages that ecosystems offer to humans. They facilitate well-informed decision-making for policymakers, land managers, and enterprises in relation to land use, conservation, and development. These methods assist in the optimal allocation of resources by prioritizing conservation efforts according to the value of ecosystem services. Quantifying the economic worth of ecosystem services can guide conservation efforts and ensure their consideration in decision-making. These instruments are vital in advancing sustainable practices, enhancing resilience to climate change, and involving stakeholders in conservation endeavors.

The Natural Capital Project (www.naturalcapitalproject.org), Stanford University has developed an innovative tool to apply Ecosystem-Based Management (EBM) principles. This tool combines reliable and practical models based on ecological production functions and economic valuation methods. The main goal is to integrate biophysical and financial information about ecosystem services to inform conservation and natural resource decisions at an appropriate scale. The tool is named InVEST®, which stands for Integrated Valuation of Ecosystem Services and Tradeoffs (Tallis & Polasky, 2009). In this study, InVEST version 3.14.1 is used to estimate total carbon storage through the Carbon Storage and Sequestration model in the Kamalganj subdistrict of Bangladesh.

3.7.1. What is InVEST?

InVEST® is a collection of complimentary software models that are freely available and open-source. These models are utilized to accurately map and assess the worth of the many resources and benefits provided by nature, which are essential for the sustenance and satisfaction of human life. When ecosystems are effectively controlled, they provide essential services to humanity, such as producing goods like food, supporting life processes like water purification, creating conditions that enhance our well-being, like beauty and recreational opportunities, and preserving options for the future like genetic diversity. Despite its significance, this natural capital is inadequately comprehended, barely managed, and, in numerous instances, experiencing rapid deterioration and exhaustion (*Natural Capital Project, 2024)*.

Various entities, including governments, non-profit organizations, international lending institutions, and companies, oversee natural resources for multiple purposes. Inevitably, these entities must assess and consider the tradeoffs involved in managing these resources. InVEST's multi-service, modular architecture offers an efficient solution for reconciling these varied entities' environmental and economic objectives. InVEST empowers decision-makers to evaluate measurable tradeoffs linked to different management options and pinpoint regions where investing in natural resources might improve human development and conservation efforts. The toolbox comprises several models for ecosystem services tailored to terrestrial, freshwater, marine, and coastal ecosystems. Additionally, it offers various auxiliary tools to aid in identifying and processing input data and in comprehending and visualizing the resulting outputs (*Natural Capital Project, 2024)*.

3.7.2. How InVEST Works

The InVEST models are designed to incorporate spatial information, utilizing maps as both input data and output results. InVEST provides outcomes expressed in either biophysical units (such as metric tons of carbon sequestered) or economic units (such as the net present value of the sequestered carbon). The spatial resolution of analysis is adjustable, enabling users to investigate inquiries at several levels, including local, regional, or global dimensions.

The InVEST models utilize production functions to determine the impact of changes in an ecosystem's structure and function on the flows and values of ecosystem services within a specific landscape or seascape. The models consider both the provision of services (such as using living habitats to protect against storm waves) and the presence and actions of individuals who benefit from these services (such as the location of people and infrastructure that coastal storms could impact). The InVEST models are self-contained applications that operate independently of any GIS software. Mapping software such as QGIS or ArcGIS is necessary to visualize your results. Proficiency in Python programming is optional to use InVEST properly. However, it is essential to have a solid understanding of GIS software at a basic to intermediate level. The modular tool allows users to selectively model ecosystem services based on their preferences without the need to model all the specified services (*Natural Capital Project, 2024)*.

The interconnections among ecosystem processes, ecosystem services, and the value of ecosystem services included in InVEST are depicted in (Figure. 9). For more detailed information on how supply and demand are included in specific models for these services and others, refer to the works of (Nelson et al., 2008; Nelson et al., 2009; Kareiva et al., in press). Land use and management decisions significantly impact ecosystems and the ecological processes that occur within them. Ecological processes are responsible for creating the biophysical supply of ecosystem services (first column). The combination of ecosystem-service supply and demand produces actual ecosystem services, as seen in the second column. By utilizing economic or social valuation techniques, one can obtain estimates of the monetary worth of environmental services (as shown in the third column). Arrows are used to illustrate significant connections between ecological processes or ecosystem services (Tallis & Polasky, 2009).

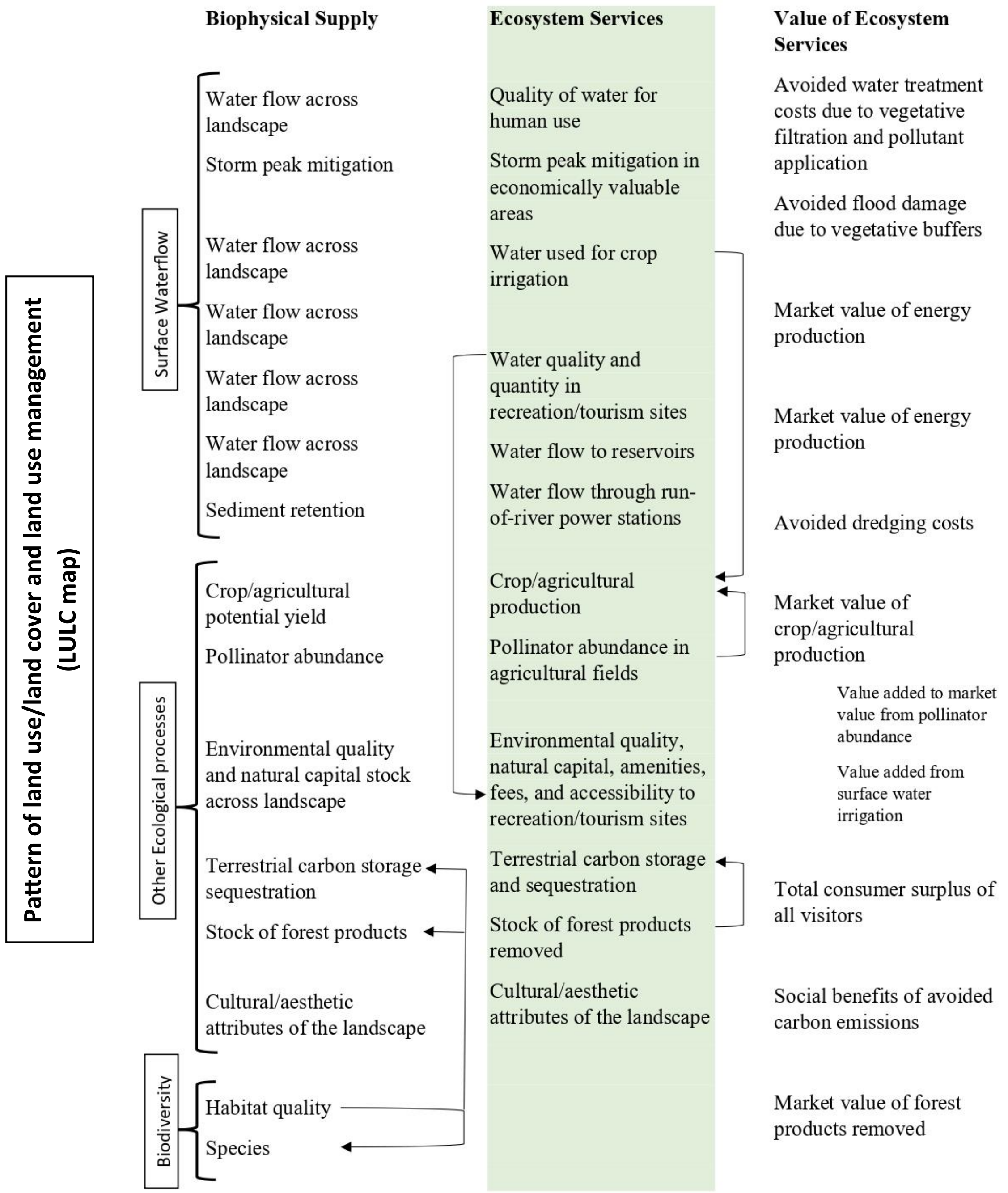

Figure 9. Links between the biophysical supply, ecosystem services (which combine supply and demand for services), and the value of ecosystem services for ecosystem services currently Modeled in InVEST. Source: (Tallis & Polasky, 2009).

InVEST commonly employs a production function methodology to measure and assign an economic value to ecological services. A production function delineates the quantity of ecosystem services the environment generates based on its state and processes. Once a production function is defined, we can measure the effect of alterations in land or water on the level of ecosystem service output (*Natural Capital Project*, *2024)*.

3.7.3. Carbon Storage and Sequestration Model

The four carbon pools comprised of aboveground biomass, belowground biomass, soil, and dead organic matter are the primary factors that impact the amount of carbon stored on a different piece of land. The user is responsible for providing the InVEST Carbon Storage and Sequestration model with land use maps and classifications, which are then used to determine the overall amount of carbon stored in the various pools. The total amount of living plant matter that is located above the ground is referred to as aboveground biomass. This includes parts such as bark, trunks, branches, and leaves. In the context of aboveground biomass, the term "belowground biomass" refers to the systems of living roots. Soil organic matter refers to the organic substances found in soil and is the most significant reservoir of carbon on land. Dead organic matter encompasses litter and dead wood, whether lying on the ground or standing upright.

This model utilizes maps of geographical Use and Land Cover (LULC) categories and the quantity of carbon stored in carbon pools to calculate the net carbon storage in a specific geographical area over time. It calculates the quantity of organic carbon the ecosystem stores, measured in Megagrams (Mg) of carbon. This includes the amount of carbon trapped or the rate at which carbon is extracted or exhaled into the atmosphere within a specific period (Gupta et al., n.d.). It also predicts the market value of the carbon sequestered in the remaining stock. The model has several limitations, including a simplified representation of the carbon cycle, an assumption of linear changes in carbon sequestration over time, and the possibility of erroneous discounting rates. The model does not incorporate crucial biophysical factors that contribute to carbon sequestration, such as photosynthetic rates and the existence of active soil organisms (*Natural Capital Project, 2024)*.

3.7.4. Data Interpretation of Carbon Storage and Sequestration Model

The resulting final maps and data tables were found within a user-defined workspace folder for the Carbon Storage and Sequestration model in the InVEST software model run.

Table 5. The "Workspace" directory description

No	File Name	Description
1	**Parameter log**	Every time the model is executed, a text file in the format of .txt will be generated in the Workspace. The file will contain the parameter values and output messages for the specific run and will be labeled based on the service, date, and time. When contacting NatCap regarding inaccuracies in a model run, kindly provide the parameter log.
2	**report_[Suffix].html**	This document provides a concise overview of all the data generated by the model. Additionally, it contains explanations of all the other output files generated by the model, making it an ideal starting point for investigating and comprehending the model's outcomes. Since this is an HTML file, it is compatible with any web browser and may be easily accessed.
3	**tot_c_cur_[Suffix].tif**	Rasters depict the quantity of carbon stored in individual pixels for the present scenarios. The sum is the total carbon stored in

		all carbon pools in the biophysical table. The units are expressed in metric tons per pixel.
4	**c_above_[Suffix].tif**	Contains a raster file representing aboveground carbon values. These values are derived from the Carbon Pools table and are mapped onto the Land Use and Land Cover (LULC) data. The units are expressed as metric tons per pixel.
5	**c_below_[Suffix].tif**	contains a raster representation of carbon values below the ground. These values are derived from the Carbon Pools database and are mapped to the Land Use and Land Cover (LULC) data. The units are expressed in metric tons per pixel.
6	**c_dead_[Suffix].tif**	contains a raster representation of carbon values associated with dead vegetation. These values have been mapped from the Carbon Pools table to the Land Use and Land Cover (LULC) data. The units are expressed in metric tons per pixel.
7	**c_soil_[Suffix].tif**	contains a raster of soil carbon values. These values have been mapped from the Carbon Pools table to the Land Use and Land Cover (LULC) data. The units are expressed in metric tons per pixel.

Note: No. 1, 2, and 3 are in the [Workspace] directory. No. 4, 5, 6, and 7 are in the folder called "intermediate_outputs" under the [Workspace] directory.

Source: (*Natural Capital Project, 2024)*.

3.7.5. Limitations and Simplifications of the carbon storage and sequestration model

The model streamlines the carbon cycle, enabling it to operate with minimal data, although it also entails significant constraints. For instance, the model assumes no net carbon gain or loss over time for any land use and land cover (LULC) types in the landscape. Instead, all land use and land cover (LULC) types are presumed to maintain a constant storage level equivalent to the average reported storage levels within that specific LULC type. Assuming this condition, the carbon storage variations over time are only caused by transitions between different land use and land cover (LULC) types. Consequently, any pixel that maintains its Land Use and Land Cover (LULC) type without any changes will have a sequestration value of 0 as time progresses. Indeed, numerous regions are currently undergoing a process of healing from previous land utilization or are experiencing natural ecological succession. To resolve the issue, one possible approach is to categorize land use and land cover (LULC) types into different age classes, hence expanding the number of LULC kinds. For instance, this could involve splitting forests into three distinct age categories. Parcels can transition between different age classes in scenarios, leading to changes in their carbon storage values.

Another constraint is that the accuracy and dependability of the model's outcomes are contingent upon the precision of the land use and land cover (LULC) classification employed and the carbon pool values provided. Carbon storage varies noticeably between land use and land cover (LULC) types, such as tropical forests and open woodlands. However, there can also be substantial variance within the same LULC type. This illustrates the impact of temperature, elevation, rainfall, and the duration since a significant disruption (such as clear-cutting or forest fires) on carbon storage in a "tropical moist forest." The range of carbon storage values within broadly defined land use and land cover (LULC) categories can be partially restored by employing a LULC classification system and a corresponding carbon pool table. This approach categorizes the defined LULC types based on critical environmental and management factors. Forest land use and land cover (LULC) types can be classified based on elevation, climate zones, or time intervals following significant disturbances. Undoubtedly, this more comprehensive strategy necessitates data about the quantity of carbon stored in each specific carbon reservoir for each of the more particular Land Use and Land Cover (LULC) categories.

Another drawback is the model's inability to account for carbon that shifts across pools. For instance, a large portion of the carbon stored in aboveground biomass in a forest becomes stored in other (dead) organic material if trees in the forest die from disease. In addition, slashes of branches, stems, bark, and other materials are left on the ground after trees are taken from a forest. According to the model, carbon from wood chips "instantaneously" enters the atmosphere (*Natural Capital Project, 2024)*.

Chapter 4

Result and discussions

4.1. InVEST carbon storage and sequestration model outputs

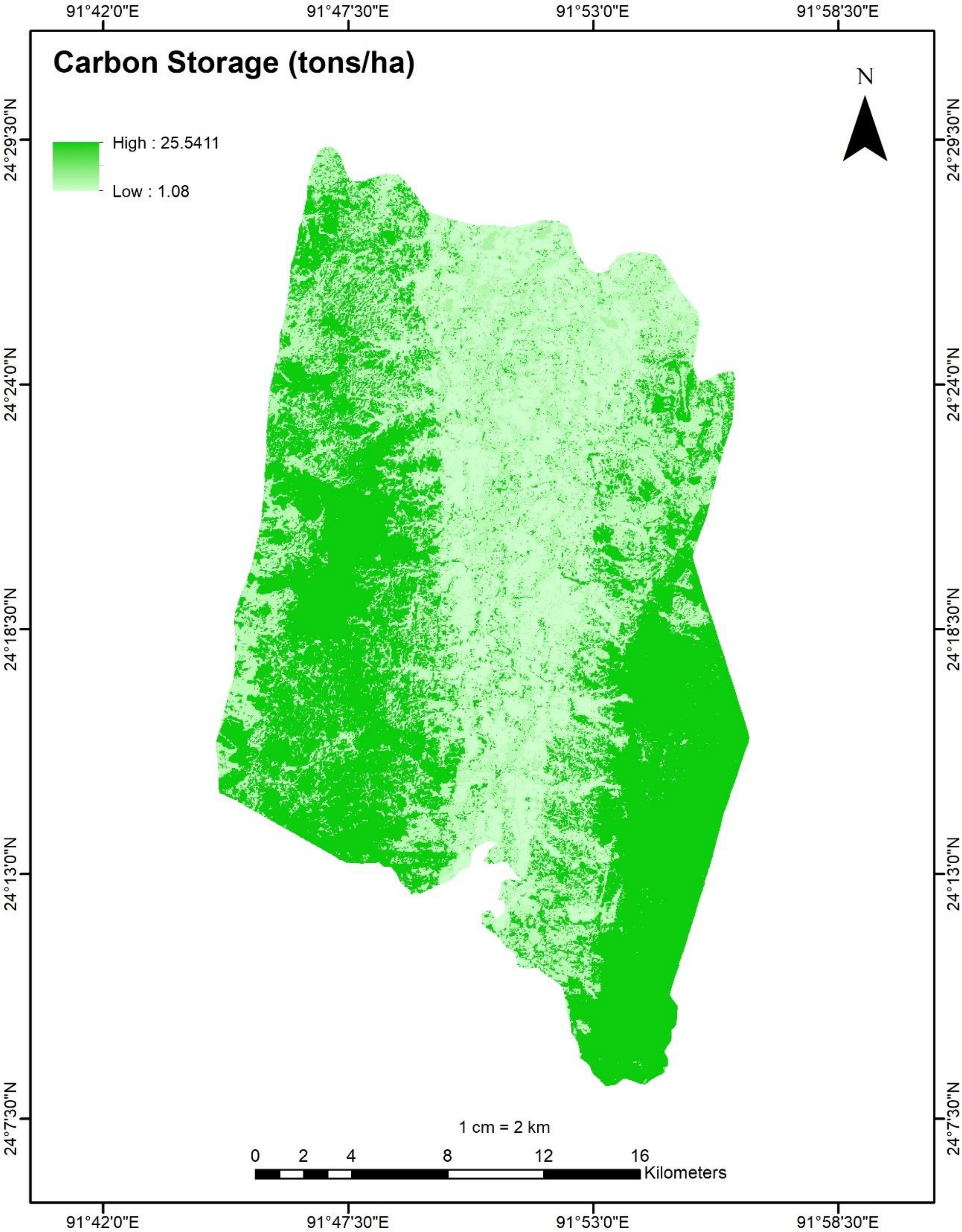

Figure 10. Map showing the spatial arrangement of carbon storage in the Kamalganj Subdistrict

InVEST carbon storage and sequestration model expands the findings into a raster output that displays the spatial distribution of carbon storage in the research area (Figure. 10). The model necessitates estimating the carbon quantity in at least one of the four primary pools mentioned above, expressed in metric tons per hectare (t/ha), for every Land Use and Land Cover (LULC) category. Having data for multiple pools will enhance the comprehensiveness of the modeled results. The model utilizes these estimations to directly apply them to the LULC map, resulting in a comprehensive picture of carbon storage in the included carbon pools *(Natural Capital Project, 2024)*. Total carbon refers to the quantity of carbon presently stored in megagrams (Mg) within each grid cell in a given landscape. Furthermore, the results revealed that with a land area of **51238 hectares**, the Kamalganj subdistrict currently stores **6350252.62 million** tons of carbon, whereas carbon storage varies within different LULC types. The vegetative land use and land cover (LULC) types often contain more carbon than other LULC types (Chacko et al., 2019; Kumarasiri et al., 2022).

Table 6. Carbon storage in each LULC type in the Kamalganj subdistrict

LULC Type	**Total Carbon (Mg)**	**Carbon in each LULC (%)**
Forests	3322028.65	52.31
Waterbodies	113436	1.79
Built-up Area	263591.99	4.15
Fallow Land	41640.48	0.66
Row Crop Land	104045.85	1.64
Trees	2259057.23	35.57
Rangeland	246452.41	3.88
Total	**6350252.62**	

For the current scenario, i.e., 2024, the highest value of total carbon was obtained for forests (national park and reserve forest), i.e., 3322028.65 Mg of C, which comprises ~ 52% of the total carbon storage in Kamalganj subdistrict, shown in (Figure. 11). The lowest is for the fallow land, which is 41640.48 Mg of C, and it comprises 0.66%. On the other hand, trees value of total carbon is 2259057.23 Mg, shown in (Table. 6). In the study area in Kamalganj, the maximum areas are covered by trees, which is 23.58% of the total study area, and forests are 22.84%.

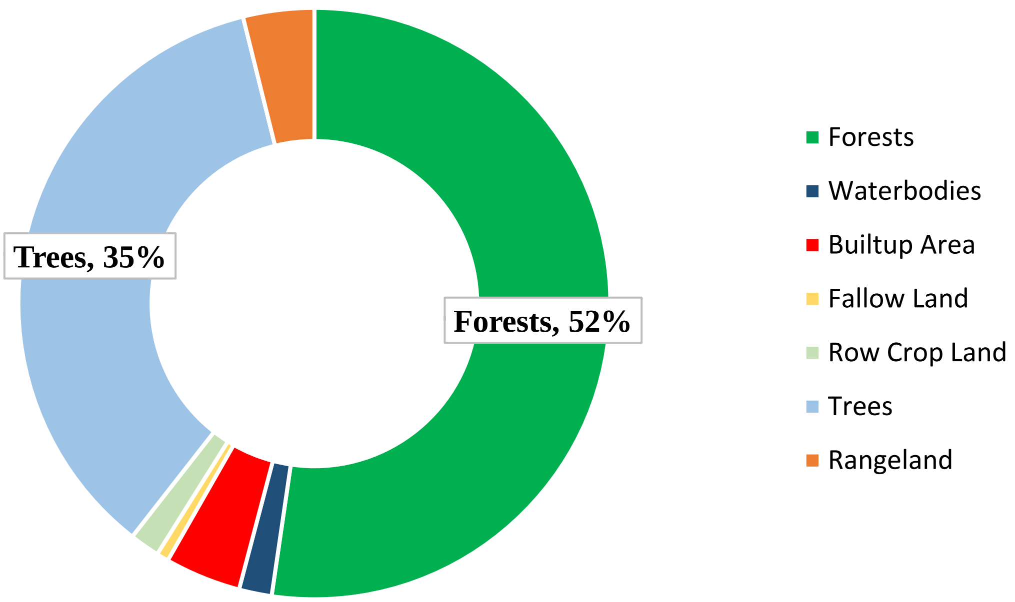

Figure 11. Pie chart showing the percentages of Carbon pools in each LULC class in Kamalganj subdistrict

Furthermore, it is discovered that despite the proportion of the forests in the research area being approximately 22.84%, the amount of carbon stored in the forest accounts for around 52% of the total carbon storage. The area percentages of the total carbon pools of the Kamalganj subdistrict by LULC type are illustrated in Fig. 6. Moreover, the Carbon storage percentages of waterbodies, row crop land, rangeland, and built-up area were calculated as 1.79%, 1.64%, 3.88%, and 4.15%.

4.2. Discussions

Preserving Lawachara National Park (LNP) forest cover preserves a carbon stock (CO2) of around 323.8 tons per hectare, aiding in mitigating climate change. The Climate Resilient Ecosystems and Livelihoods (CREL) was established in 2014 with financial assistance from USAID. The study involved surveying to measure the carbon content in 8 protected sites in Bangladesh (Fakir et al., 2015). In this study, they found carbon stock of 323.8/ha in 2014, whereas, in the current study in the Kamalganj subdistrict where LNP is situated, found a carbon stock of 283.81 tons/ha in 2024. In both scenarios, the forest area of 2583 ha comprises half of the West Bhanugach Reserve Forest, and LNP covers 1,250 ha of semi-evergreen tropical forest. In this study, two main protected areas (LNP and RRF) have a total area of 5033 ha altogether, whereas the total forest area calculated in the Kamalganj subdistrict is 11705 ha. According to the study, the InVEST carbon storage and sequestration model (version 3.14.1) has been used to assess carbon storage in the kamalganj subdistrict in Bangladesh. In the context of Lawachara National Park (LNP), there were studies conducted previously along with other protected areas in Bangladesh. Dhar & Sarker (2021) conducted a study about Environmental Correlates of Vegetation Distribution in the Rajkandi Hill Reserve Forest. The authors emphasized the significance of understanding the relationship between plant species and environmental variables for effective conservation strategies in Bangladesh's Rajkandi Hill Reserve Forest. There is no estimation of Carbon Storage in RRF. In both forest types and the Kamalganj subdistrict of Moulvibazar, the InVEST model was not utilized to assess the carbon storage on different land use land cover types. The estimate of Carbon in the Bangladesh forest ecosystem was calculated in a study by (Upadhyay et al., 2005). Where it mentioned that, the estimated average carbon density in the forests of Bangladesh is around 175.5 Megagrams per hectare. Despite their deterioration, the Sal forests exhibit the highest carbon density (202.2 Mg ha-1). This could be attributed to a small number of research (n=1) on biomass carbon and potential sampling bias. This hypothesis could also apply to soil carbon accumulation in mangrove forests. Mangrove forests account for the most significant proportion (54%) of the country's biomass carbon store, with hill forests (36%) and Sal forests following closely after.

Many researchers worldwide have used the same modeling approach to estimate the spatial distribution of carbon storage and predict the total carbon storage in specific study areas (Babbar et al., 2021; Chacko et al., 2019; He et al., 2016; Jiang et al., 2017; Kumarasiri et al., 2021; Lyu et al., 2019; Zhao et al., 2019; Piyathilake et al., 2022). Kumarasiri et al. (2021) have demonstrated that the InVEST carbon storage and sequestration modeling approach is a valuable tool for studying forest quality and assessing the importance of forests in carbon sequestration and storage. In addition, this modeling approach can be efficiently utilized to evaluate the potential consequences of urban expansion on the overall carbon storage capacity (He et al., 2016; Lyu et al., 2019). Furthermore, this method can be utilized in different situations to chart the spatial arrangement of carbon storage in conjunction with GIS approaches (Chacko et al., 2019). According to Sharp et al. (2018), the InVEST carbon storage and sequestration model can be used to calculate carbon sequestration or carbon loss over time if both the current land use and land cover (LULC) data and future forecasted LULC data are available. Several researchers have effectively illustrated this phenomenon using the InVEST model with other modeling methodologies in different studies (Babbar et al., 2021; He et al., 2016; Jiang et al., 2017; Lyu et al., 2019; Zhao et al., 2019). Formulating future Land Use and Land Cover (LULC) data and acquiring carbon pool values for each LULC type is crucial in scenario analysis. These two key data inputs are essential for running the entire model, as stated by Sharp et al. (2018). According to Wu et al. (2015), the CLUE-S (conversion of land use and its effects at a small regional extent) model is a valuable tool for creating future land use and land cover (LULC) maps related to urban expansion. Many researchers, including Jiang et al. (2017), Kucsicsa et al. (2019), and Liang et al. (2017), have employed the same approach to generate future LULC maps. In addition, He et al. (2016) have indicated that the LUSD urban model can be utilized as a valuable tool for predicting the future growth of the research area. Furthermore, prior studies have used the SLEUTH-3r model (Lyu et al., 2019) and the Markov chain model (Babbar et al., 2021; Zhao et al., 2019) to simulate and anticipate urban development and land-use change for future LULC maps. Nevertheless, developing a precise carbon pool table is crucial to guarantee the accuracy of the outcomes produced by the InVEST carbon storage and sequestration model. Therefore, in most instances, the carbon statistics have been derived from the Intergovernmental Panel on Climate Change's (IPCC) 2006 report, as it is widely regarded as one of the most dependable sources of carbon data globally (Hiraishi et al., 2014; Sharp et al., 2018).

4.3. Limitations of the study result

The LULC classes employed in this study are obtained from remote sensing data with a medium spatial resolution of 30m. According to the limitations of imagery with medium resolutions (i.e., fine details compared to higher resolution imagery), the calculations of landscape pattern changes might not be entirely consistent with real-world processes. Small objects are challenging for capturing medium-resolution images because of their large pixel size. Therefore, medium-resolution imagery is helpful for large-area mapping but often involves a high degree of generalization. For more accurate studies at finer scales, I recommend the application of high-resolution imagery to increase the accuracy and robustness of ecosystem services mapping, vegetation analysis, trade-off analysis, and different scenario prediction.

4.4. REDD + or carbon trading potential areas

Preserving the world's forests is essential for maintaining the climate. Forests can absorb significant quantities of carbon dioxide and contribute to releasing greenhouse gases if they are destroyed or harmed. Countries designed the 'REDD+' framework to safeguard forests under the Paris Agreement. REDD + is a United Nations-supported system that mitigates climate change by preventing forest destruction. REDD is an acronym for "Reducing Deforestation and Forest Degradation Emissions." The "+" symbol signifies the importance of conservation, sustainable forest management, and increasing forest carbon stores (Angelsen & Rudel, 2013). Several mapping techniques are now being created to assist in selecting sites for REDD initiatives. These tools aim to identify places with high levels of carbon and biodiversity (UNEP-WCMC 2008). The Intergovernmental Panel on Climate Change (IPCC) stated in its 2014 fifth assessment (AR5) that the primary driver of global warming is the rising levels of greenhouse gases (GHG), primarily resulting from human activity (IPCC, 2014). The AR5 climate model predicted that global surface temperatures would increase by 0.3–1.7°C and 2.6–4.8°C under the lowest and greatest emission scenarios (Stocker et al., 2013). The AR6 report from the IPCC (2018) aims to restrict global warming to a maximum of 1.5°C. This will be achieved by implementing internationally enforceable measures to control greenhouse gas (GHG) emissions. These measures include carbon quotas, the Clean Development Mechanism (CDM), and REDD+ (Mehling, Metcalf, & Stavins, 2018; Weitzman, 2017).

The Environmental Protection Agency - USA has developed the Greenhouse Gas Equivalencies Calculator, which may determine the total amount of stored carbon by equating it to the amount of CO2 emitted by activities such as gasoline consumption and coal burning (EPA, 2024). According to the current study, the total carbon stored in the Kamalganj subdistrict, Bangladesh, is equal to CO2 emissions from 2,376,856,539 million gallons of gasoline consumed, 23,279,301,491 pounds of coal burned, greenhouse gas emissions from

5,027,342 passenger vehicles driven for one year, and 4,168,779 home's electricity for one year. As the natural forests in the Kamalganj subdistrict possess the most significant amount of carbon stored, providing robust protection for these trees and strictly restricting deforestation is imperative. These pristine forest regions are critical in mitigating climate change and can be identified as crucial locations for REDD+ or Carbon Trading. The potential impact of these programs could involve providing a foundation for decision-making regarding preserving and safeguarding these wooded regions, given their capacity to mitigate carbon dioxide emissions.

Houghton and Nassikas (2018) highlighted the importance of halting deforestation and promoting the growth of secondary forests to decrease global carbon emissions by approximately 120 PgC from 2016 to 2100. REDD mechanisms are highly likely to promote biodiversity and can be specifically developed to benefit local resource users simultaneously. The task is to create regulations that achieve both objectives, preventing any negative impact on biodiversity or livelihoods. Overall, methods that encompass the reduction of forest degradation are expected to have a more significant beneficial effect on biodiversity than those focused on reducing deforestation. Reforestation activities can also benefit biodiversity, as demonstrated by studies conducted by Strassburg (2007) and Strassburg et al. (2008), as well as by TCG (2008). Nevertheless, afforestation can frequently result in adverse effects on biodiversity.

Forests, trees, and vegetation serve as carbon sinks and can be utilized in developing strategies to mitigate the adverse effects of global climate change (Rahman et al., 2013; Shin et al., 2007). However, Saimun et al. (2021) have reported a gradual decline in the carbon storage capacity of tropical forest ecosystems. This is a significant concern as forest deterioration negatively impacts the structure, composition, and diversity of forests and carbon stocks, functioning, and biological processes (Gao et al., 2020). Tropical deforestation is projected to rise from 0.467

Pg·yr–1 in the 2010s to 0.628 Pg·yr–1 in the 2090s, representing a 35% increase. This will result in tropical forests being a significant contributor of carbon in the 21st century (Vieilledent et al., 2022).

To fully achieve the potential for carbon mitigation, it is necessary to estimate the carbon stocks at the country level using statistically verified methodologies (Mahmood et al., 2016). Being a party to the Kyoto Protocol, Bangladesh requires precise assessments of the current carbon reserves across the nation to carry out carbon trading CDM projects (Saatchi et al., 2011). The Government of Bangladesh is now implementing measures to gather comprehensive carbon stock data nationwide and has developed the REDD+ Readiness Roadmap (BFD, 2018). REDD+ encompasses the execution of the subsequent measures to mitigate climate change (UNFCCC, 2010):

(a) Reducing emissions from deforestation;

(b) Reducing emissions from forest degradation;

(c) Conservation of forest carbon stocks;

(d) Sustainable management of forest; and

(e) Enhancement of forest carbon stocks.

Consequently, all forest resources in developing nations have the potential to be subjected to responsible measures to reduce or offset their negative impact. The Cancun agreement also mandates the development of solid and transparent national monitoring systems for the mentioned mitigation activities. Therefore, it is essential to ascertain carbon stocks' spatial and temporal fluctuations to execute REDD+ (Petrokofsky et al., 2012).

Chapter 5

Conclusions

This study provides new insights based on a combination of the literature surveys, remotely sensed data, and InVEST models to assess and evaluate carbon storage and ecosystem services in the Kamalganj subdistrict in 2024.

5.1. Conclusions

The discrepancies in carbon estimations among published publications arise from the divergent models and assumptions in estimating carbon stock. Global research indicated a rising trend in carbon stock in Bangladesh; however, local studies have demonstrated the opposite. However, the research focused on only some significant forest areas, and there is a widespread absence of carbon estimating models relevant to species and ecosystems. Additionally, the existing models need more rigorous statistical validation (Majumder et al., 2019). The InVEST carbon storage and sequestration model is helpful for accurately estimating the total carbon storage in various land use and land cover (LULC) types. This model can effectively assist in identifying viable sites for REDD+ or carbon trading. Moreover, this model can be utilized to chart the spatial arrangement of carbon storage in specific research regions. Based on the latest study, the primary land use and land cover (LULC) category in the Kamalganj subdistrict is natural forests, which have the highest carbon storage capacity per hectare. The trees have the second-highest amount of carbon storage, with built-up areas coming in next. The mapping of carbon storage in various geographical areas highlights the significance of vegetative land use and land cover (LULC) types, particularly natural forests, in terms of carbon sequestration and storage.

Moreover, these maps provide information on the carbon sequestration potential of various land use and land cover (LULC) types, the patterns of carbon sequestration in these LULC types, and the amount of carbon loss over time resulting from human activities such as deforestation and agricultural practices. Furthermore, these calculations and maps of carbon storage can be efficiently utilized in formulating environmental management plans, devising ecological laws, and constructing national development plans implemented by the government.

Furthermore, while determining the order of importance for preserving lands, maps displaying carbon storage and sequestration are beneficial in aiding the decision-making process. Moreover, these maps can facilitate various decision-making processes undertaken by NGOs, the government, and other environmental groups about ecosystem services. Governments could use this data to identify opportunities to earn carbon credits by reducing automobile emissions. Furthermore, the maps and data that are produced could have a significant impact on climate change mitigation. Moreover, this study can provide a foundation for preserving the natural forests throughout the country, considering the significant human-induced stresses. Additionally, these databases could be utilized to categorize reforestation locations to optimize their ability to absorb and store carbon.

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2.	Student Id / Registration No.	020222010
3.	Title of Dissertation / Thesis	Assessing Carbon Storage in Kamalganj of Bangladesh: A Quantitative Approach with InVEST Model
4.	Name of the Supervisor / Guide	Dr. Kishore K. Dhavala
5.	Name of the School	School of Ecology and Environment Studies
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