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THE ROLE OF FOREST ECOSYSTEMS FOR CARBON CAPTURE AND STORAGE IN INDIA

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ABSTRACT

Climate change poses a pressing global challenge, driven largely by rising atmospheric carbon dioxide (CO_2) levels from fossil fuel combustion and land-use changes. Forests play a pivotal role in mitigating these emissions through carbon sequestration—absorbing CO_2 via photosynthesis and storing it in biomass and soil. As the largest terrestrial carbon sinks, forests contribute significantly to the global carbon cycle, with soil and vegetation collectively storing more carbon than the atmosphere. However, ongoing deforestation—amounting to 420 million hectares lost since 1990—threatens these critical carbon reservoirs.

This paper explores the mechanisms, impacts, and potential of forest carbon sequestration. It discusses how forest type, management practices, and soil dynamics influence carbon storage capacity. India, for instance, with 21.71% forest cover, has demonstrated measurable increases in carbon stock, emphasizing the importance of effective forest monitoring and policy implementation. Global and regional data highlight trends in carbon fluxes, forest growth, and biomass distribution.

Rising CO_2 levels—exceeding 400 ppm—are linked to severe climate effects, including sea-level rise and ecosystem disruptions. Forest ecosystems buffer these effects but face threats from wildfires, degradation, and poor land-use practices. Sustainable forest management, including afforestation, reforestation, and conservation, is essential to enhancing carbon sequestration. Accurate carbon estimation through biometric methods and models, such as allometric equations, is vital for tracking progress.

The study underscores that while forests alone cannot offset all emissions, they remain an indispensable part of climate strategies. Protecting old-growth forests, optimizing reforestation efforts, and integrating sustainable land-use policies can significantly contribute to achieving global carbon neutrality goals. Forest-based carbon capture, supported by scientific measurement and sustainable practices, offers a resilient, long-term solution to mitigating climate change.

Keywords: Carbon Sequestration, Forest Ecosystems, Climate Change Mitigation, Carbon Storage, Sustainable Forest Management and Carbon Cycle

1. INTRODUCTION

Growing concern over global climate change has resulted in agreements to cut carbon dioxide emissions. In some cases, the extra carbon absorbed by soils and vegetation can also be counted toward emission reductions. Forests play a crucial role in the global carbon cycle. Through photosynthesis, plants use sunlight to transform carbon dioxide, water, and nutrients into sugars and carbohydrates, which are stored in their leaves, twigs, stems, and roots. Plants also undergo respiration, releasing carbon dioxide. When plants die, their stored carbon is either released into the atmosphere rapidly or transferred to the soil, where it decomposes slowly, contributing to soil carbon levels. The increasing global concern over climate change has led to extensive international negotiations. In 1992, during the Earth Summit in Rio de Janeiro, the United Nations Framework Convention on Climate Change was opened for signing. President George H.W. Bush signed the treaty, which was later ratified by the U.S. Senate.

Carbon sequestration (CS) involves the removal of carbon (C) from the atmosphere and its storage in a reservoir. This process transfers atmospheric carbon, particularly CO2, and securely stores it in long-term pools **(UNFCCC, 2007)**.

With the increasing global concern over climate change and its far-reaching impacts, the role of forests in mitigating these effects has gained significant attention. Forests possess an exceptional ability to absorb and store atmospheric carbon dioxide—at rates that are approximately 20 to 100 times greater per unit area compared to agricultural lands. This remarkable capacity for carbon uptake has positioned carbon sequestration as one of the most valuable ecosystem services provided by forests. As a result, forests are now recognized not only for their biodiversity and ecological functions but also as crucial natural allies in combating climate change through their ability to capture and store carbon over the long term.

Climate change is a pressing global issue that has led to an increase in the frequency of extreme weather events, making its effects increasingly evident **(NITI Aayog, 2022)**. According to the latest report by the Intergovernmental Panel on Climate Change **(IPCC)**, climate change presents severe threats to human societies and ecosystems, primarily due to greenhouse gas (GHG)

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emissions caused by human activities, especially carbon dioxide (CO2), which significantly contribute to global warming and its related impacts **(IPCC, 2018)**. The effects of climate change are diverse and include intense heatwaves, more frequent and severe storms, rising sea levels, altered rainfall patterns, disruptions to ecosystems and biodiversity, and a range of socio-economic challenges **(Fridahl *et al.*, 2020)**.

Different strategies are being explored to lower overall CO_2 emissions, but the primary method for reducing CO_2 output from major industrial sources is known as carbon capture and storage (CCS). This process involves capturing carbon dioxide at its source, transporting it and then storing burying it deep underground in and appropriate location. CCS can also refer to removing CO_2 from the atmosphere, either directly or indirectly from the atmosphere. The world's growing energy demand is largely satisfied through the burning of fossil fuels. According to British petroleum (2020),84% of global energy consumption is derived from fossil fuels. However, there is a global consensus in favor of renewable energy. By the end of 2019, 28 countries transition toward renewable energy sources **(REN21 2020)**.

Current levels of CO_2 in the atmosphere account for 26% of global warming **(Bhui 2021)**. Meanwhile, global energy demand is projected to double by 2030, with most of this increase likely to be met by fossil fuels due to their low costs and established infrastructure. This trend could raise the global average temperature by 2°C by 2065, surpassing the intergovernmental panel on climate change target of limiting temperature by 2°C by 2100 **(Paris Agreement, 2015; Bui *et al.* 2018)**. To reach the Paris Agreement targets, emissions would need to be reduced by 50-80% of 1990 levels by 2050 **(Yoro and Daramola 2020)**

Currently, CO_2 levels in the atmosphere are rising globally. If recent trends in CO_2 emissions continue, the world will fall short of stabilizing greenhouse gas concentrations. Between 1995 and 2001, average global CO_2 emissions increase in primary energy use, it is still higher than the rate of CO_2 emissions growth in the previous five years. **(IPCC, 2005)**.

Carbon sequestration is seen as a method to reduce greenhouse effects in today's context, while also addressing land degradation **(Olsson and ardo 2002)**. In line with this, much of the current research focuses on improving the understanding and measurement of carbon fluxes and storage **(post and kwon 2000)**. The terrestrial carbon pool, soil which contains an estimated 2,500 pg of C compared to 620 pg of C in terrestrial biota and detritus and 780 Pg of C in the atmosphere **(Lal, 2010)**. Forest vegetation absorbs carbon dioxide from the atmosphere through photosynthesis, removing CO_2 and storing carbon in various components like plant tissues, forest litter and soil. Forest plays a crucial role in the global carbon cycle, as the global carbon cycle as they hold about half of terrestrial carbon **(Nieder and Benbi 2008)**.

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The forest ecosystem is a vital part of terrestrial ecosystems and serves as the largest carbon reservoir. Its critical role in combating climate change is demonstrated by its ability to absorb carbon dioxide from the atmosphere through photosynthesis, facilitating carbon sequestration in both biomass and soil **(IPCC, 2019)**.

Forest has a strong connection to climate change, playing a crucial role in managing weather patterns, rainfall, groundwater and soil health. they act as both sources and storage for carbon from the atmosphere as they grow, mature forest serves as carbon storage sites. Today the world's forests and forest soils hold over a trillion tonnes of carbon double the amount found in the atmosphere **(FAO 2022)**.

The Earth Forest covers approximately 4.06 billion hectares or 31% of its total land area.However deforestation between 1990 and 2022 has resulted in a loss of 420 million hectares of forest **(FAO 2022)**. Although the rate of deforestation is decreasing an estimated 10 million hectares were lost annually from 2015 to 2020. Between 2000 and 2020, primary forest loss accounted for more than 47 million hectares **(FAO 2022)**.

The world's forest is estimated to store 283 gigatons (Gt) of carbon in their biomass and an additional 638 Gt of carbon in deadwood, litter and soil up to a depth of 30 cm **(FAO 2006)**. Forest hold about 86% of terrestrial above ground carbon and 73% of soil carbon **(Zhou *et al.* 2011)**. In a forest ecosystem, carbon is stored in various pools including both above ground biomass and below ground biomass such as timber, branches and roots and litter, woody debris, soil organic matter and forest products **(Malhi *et al.* 2006)**.

Between 2011 and 2021, India witnessed a notable enhancement in its forest carbon stocks, which rose from approximately 6,663 million tonnes to 7,204 million tonnes—reflecting a net increase of 541 million tonnes. This upward trend can be attributed to an expansion in tree cover, which grew from roughly 90,844 square kilometers in 2011 to about 95,748 square kilometers by 2021. Furthermore, the rise was supported by improvements across all carbon pools, including aboveground and belowground biomass, deadwood, litter, and soil organic carbon (SOC). Among these, SOC accounted for the largest share, contributing nearly 56% of the total carbon stock—equivalent to approximately 4,010 million tonnes.

Despite these positive gains in carbon storage, the same period also witnessed a substantial intensification in forest fire activity. The India State of Forest Report (ISFR) 2021 highlighted that around 22.3% of the country's forest area is now categorized as either highly or extremely fire-prone. Notably, the states of Odisha (with 51,968 recorded fire events), Madhya Pradesh (47,795), and Chhattisgarh (38,106) emerged as the most affected regions in terms of fire frequency. On a national scale, the forest fire season spanning November 2020 to June 2021 registered an alarming

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345,989 fire incidents—more than 2.7 times the number of fires reported in the previous season, marking the highest count recorded to date.

In India forest areas capture significant amounts of CO_2 from the atmosphere, contributing notably to carbon sequestration at regional, national and global levels. Terrestrial carbon (from plants and soil) was estimated at approximately 2000 500 petagrams (Pg) representing 25% of global carbon stocks **(FSI 2005)**. Forest ecosystems in India are crucial for carbon capture and storage, serving as natural carbon sinks and playing a significant role in mitigating climate change. India, with its diverse forest types spanning tropical, temperate and mangrove ecosystems, has a forest cover of approximately 21.71% of its geographical areas(FSI,2021)

The ability of forests to sequester carbon is affected by both the characteristics of the species planted and the management methods used **(Bremer and farley 2010)**. Measuring carbon levels in vegetation and soils is crucial for those aiming to assess and comprehend an ecosystems carbon sequestration potential **(Garcia- oliva and Masera 2004)**. Enhancing forest carbon sequestration to mitigate climate change can be a cost-effective approach and may provide additional environmental benefits. However, it comes with challenges, such as accurately measuring the additional carbon stored, monitoring and verifying results, and preventing carbon leakage. There are also various issues related to the forest carbon cycle, tracking changes in forest carbon levels, and the scientific uncertainties regarding the relationship between forest carbon and climate change.

Source of CO_2: - The potential of carbon capture and storage as a strategy for reducing global CO_2 emissions, the current global geographic relationship between large stationary CO_2 emission sources and their proximity to potential storage sites has been analysed. **(IPCC, 2005).** Emissions from residential, commercial, and transportation sectors were excluded from these analyses because these sources are typically small, dispersed, or mobile, making them unsuitable for capture ans storage **(IPCC, 2005).**

However, projections indicate that by 2050, their share of global CO2 emissions will decrease to about 50% **(IEA, 2002 & IPCC, 2005)**. India ranks as the third-largest CO2 emitter globally, following China and the United States, with estimated annual emissions of approximately 2.6 gigatonnes (gtpa). The Government of India has pledged to cut CO2 emissions by 50% by 2050 and achieve net zero emissions by 2070. **(NITI Aayog, 2022)**.

Atmospheric CO_2 levels:- The atmospheric CO_2 levels have shifted dramatically over the past 300 years. From the 1780s to the present, there have been remarkable and transformative changes, with CO_2 levels rising by over 100 ppm in roughly 250years. While pre- 1750 levels remained around 280 ppm **(Wigley, 1983)**, current levels have surpassed 400 ppm, well above the recommended limit of 350 ppm **(Azar and Rodhe, 1997)**. In the past decade, atmospheric CO_2

concentrations have been increasing at a rate of more than 2 ppm per year **(Yoro and Daramola).** China is responsible for the highest share of global emissions, contributing approximately 26%. The United States, India and Russia account for 13.7%, 7.0%, and 4.0% of global emissions, respectively **(Yoro and Daramola, 2020).** Each year, around 51 billion tons of greenhouse gases are released into the atmosphere, with the goal being to reduce this number to zero **(Gates, 2021).**

Carbon Cycle: - The cycle through which carbon dioxide is released into the atmosphere and absorbed back into Earth is called the Carbon Cycle. Carbon is stored and released through:

Atmosphere (CO_2 Released)

↓

Carbon Cycle Begins

↓

Photosynthesis (Plants absorb CO_2 to make food and grow)

↓

Decomposition (Dead organisms break down releasing CO_2)

↓

Respiration (Animals & plants release CO_2 back into air)

↓

Combustion (Burning of fossil fuels/wood releases CO_2)

↓

Back to Atmosphere

The potential for long term - shifts in Climate and temperature patterns due to disruptions in carbon cycle has become a critical environmental issue for our planet **(Soloman *et al.*, 2009, H. Bherwani *et al.*, 2022)**. Carbon moves through the global system via interactions within and exchange among key reservoirs, commonly known as Carbon pools **(H. Bherwani *et al.*, 2022)**. The Carbon Cycle is significant because Carbon based substances in the atmosphere play a vital role in regulating the earth climate. Over half of the recent climate warming is attribute to rising atmospheric carbon dioxide (CO_2) levels **(IPCC, 2014).** Since the beginning of the industrial era, atmospheric CO_2 concentration has risen from approximately 278 parts per million (ppm) in 1750 to 410 ppm today **(H. Bherwani *et al.*, 2022, Forster *et al.*, 2007, Tans & Keeling, 2012).**

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Consequences of the increasing atmospheric CO_2 level: - Rising sea levels have significant direct effects on coastal and island regions, home to a large portion of the global population **(Anthoff *et al.* 2006)**. Sea levels are currently rising and are expected to keep increasing for centuries, even if greenhouse gas emissions are reduced and their atmospheric concentrations stabilized **(Church and White 2011)**. Climate change has become an undeniable reality, with rising sea levels and increasing global temperatures as primary effects. We estimate the increase in global average sea level using satellite altimeter date from 1993 to 2009 and coastal and island sea-level measurements from 1880 to 2009 **(Church, J. A., & White, N. J. 2011, IPCC 2013).**

2. MACHANISMS OF CARBON SEQUESTRATION IN FORESTS

The forest ecosystem is a crucial component of terrestrial ecosystems and serves as the largest carbon reservoir, playing a vital role in the global carbon cycle within terrestrial ecosystems. Forest ecosystems have the highest productivity among all terrestrial ecosystems, with their sequestered carbon making up more than two-thirds of the total carbon fixed in terrestrial ecosystems annually **(Fang *et al.* 2001 a,b)**. Carbon storage in forest ecosystems primarily consists of vegetation carbon storage,soil carbon storage, and litter carbon storage. **(Zhang *et al.* 2005)**.

In recent decades, the terrestrial carbon (C) sink has been large, but its exact size and location are still uncertain. Based on forest inventory records and long-term studies of ecosystem carbon, researchers estimated that between 1990 and 2007, forests absorbed about 2.4 ± 0.4 petagrams (Pg) of carbon per year globally.

At the same time, carbon emissions from tropical land-use changes—such as deforestation—were estimated at 1.3 ± 0.7 Pg C per year. This included:

- Gross emissions from tropical deforestation: 2.9 ± 0.5 Pg C per year,
- Offset by carbon absorption from regrowing tropical forests: 1.6 ± 0.5 Pg C per year.

When both emissions and absorption are combined, the result is a net global forest carbon sink of 1.1 ± 0.8 Pg C per year. The largest uncertainties are found in the tropical region estimates.

Importantly, this forest carbon sink is roughly equal in size to the total land carbon sink that scientists calculate based on fossil fuel emissions and estimates of how much carbon is taken up by the oceans and atmosphere. **(Pan, Y. *et al.* (2011)**

2.1 Photosynthesis, Respiration and Carbon Storage: - Photosynthesis is a chemical process in which plants use sunlight to convert nutrients into sugars and carbohydrates. Carbon dioxide is a key nutrient required to form the organic compounds that make up leaves, roots, and stems. Every part of a plant—including the stem, branches, leaves, and roots—contains carbon, but the amount varies significantly depending on the plant species, age, and growth pattern. However, as

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photosynthesis increases, more CO2 is absorbed and converted into biomass, reducing carbon in the atmosphere and storing it in plant tissues both above and below ground.

The biosphere is essential in regulating the carbon cycle, with forests playing a key role due to their substantial and stable capacity to store atmospheric carbon. During photosynthesis, carbon is captured by leaves or needles and converted into biomass in parts such as stems, branches, foliage and roots, thereby reducing the amount of carbon in the atmosphere.

Plants also respire, using oxygen to sustain life and releasing carbon dioxide in the process. At certain times, such as at night or during winter in non-tropical climates, living and growing forests can become net emitters of carbon dioxide. However, over the course of their lifespan, forests typically act as a net carbon sink, absorbing more carbon than they release. When vegetation dies, carbon is released into the atmosphere. This can happen rapidly, such as during a fire, or gradually as fallen trees, leaves, and other organic matter decompose. In herbaceous plants, the above-ground portion dies each year and begins decomposing immediately. In contrast, woody plants continue to store carbon in their above-ground biomass until they eventually die and break down. This process defines the carbon cycle in forests—net carbon accumulation (sequestration) occurs as vegetation grows, while carbon is released when vegetation dies. As a result, the amount of carbon sequestered in a forest is constantly changing due to the ongoing processes of growth, death, and decomposition.

As forests grow, they absorb carbon dioxide from the atmosphere through photosynthesis and carbon assimilation, contributing to biomass accumulation and potentially, an increase in soil organic material. **(Gifford R.M., 2003)**

The loss of carbon dioxide from plants is a consequence of producing metabolites that serve as building blocks for synthesizing organic molecules, as well as providing the chemical energy and reducing power needed for this synthesis. This process takes place through complex biochemical pathways, including glycolysis, the tricorboxylic acid (TCA) cycle, the pentose phosphate pathway, and the mitochondrial electron transport chain. (**Gifford R.M., 2003).** The rate of cellular respiration is influenced by the relative demand for chemical energy, reducing power and carbon skeletons required for the biosynthesis of complex molecules. At the level of electron transport during ATP production, the availability of ADP and AMP may regulate the process. In sink tissues, respiration can sometimes be controlled by the supply of subtracts, such as translocated sucrose.

2.2 Soil Carbon Dynamics: - Soil carbon dynamics involves the storage of carbon in soil, a crucial ecosystem service arising from the interaction of ecological processes. Soil Organic Carbon (SOC) levels are shaped by multiple ecosystem functions, with photosynthesis, respiration and decomposition playing central roles. Photosynthesis facilitates the capture of atmospheric CO_2 and its conversion into plant biomass. However, deforestation releases carbon back into the

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atmosphere, primarily through the decomposition of above ground plant material. This loss of soil carbon has significantly contributed to rising CO_2 levels in the atmosphere. Nonetheless, reforestation offers an opportunity to sequester some of this carbon in the soil. (**Ontl, T.A. & Schulte., *et al.*, 2012)**

2.3 Forest Carbon Cycle: - Forest can store significant amounts of carbon, both in living organisms and in dead organic matter found on the forest floor and within the soil **(Olson *et al.*, 1983; Post *et al.*, 1982; Bouwman, 1990).** Forests typically go through cycles of growth and decay, during which they sequester and release carbon. Some forests begin on open sites with little or no existing vegetation, often cleared by natural disasters—most commonly wildfires—or by human activities such as agriculture. Other forests remain relatively continuous, with natural clearings usually limited to areas occupied by one or a few large trees that have died due to lightning, disease, or other factors. Regardless of the size or cause of a clearing, most forests start on nearly bare land, with some carbon already stored in the soil.

Understanding and quantifying the role of forest ecosystems in the carbon cycle requires measuring both the net annual carbon fluxes and the total carbon storage in representative forest ecosystems, including soil carbon stocks and flows. Only by addressing these aspects can the viability of afforestation as a method for capturing and storing atmospheric carbon be properly evaluated.

3. FOREST CARBON SEQUESTRATION

Forest ecosystem plays a crucial role in sequestering carbon form the atmosphere, helping to reduce the carbon footprint and mitigate global warming and its associated climate changes **(Ramachandra T.V & Bharaths, 2020)**. Atmospheric carbon is stored in above ground and below ground biomass, dead organic matter and soil organic matter **(Ramachandra T.V & Bharaths, 2020)**.

Forest ecosystem holds the largest share of carbon stored in terrestrial ecosystems (IPCC, 2000). They sequester and store more carbon than all other terrestrial ecosystems combine, accounting for 90% of the annual carbon exchange between the atmosphere and the Earth's land surface **(Winjum *et al.*, 1993)**. Carbon is stored both as biomass (including trunks, branches, foliage, roots, etc.) and as organic carbon in the soil. Forests cover approximately 4 billion hectares of the Earth's Surface, accounting for over 30% of the land area. They store around 120 gigatons (Gt) of Carbon in the for CO_2, which exceeds the total amount of carbon present in the atmosphere **(Forestry Commission, 2009)**. Forest hold 77% of the carbon stored in terrestrial vegetation with approximately 60% of this carbon located in tropical forest, 70% in temperate forests, 23% boreal forests are responsible for 90% of the annual carbon exchange between the atmosphere and land,

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and their growth is one of the few natural processes that remove CO_2 from the atmosphere. (IPCC, 2000).

Forest and wood lands are among the most effective natural terrestrial sequestration system because of the massive amounts of CO_2 they capture through photosynthesis. In fact, they have captured nearly 30% of the CO_2 emission caused by humans over the last several decades. *(Hogan J.A et al 2024)*. In forest ecosystems, the balance between carbon stocks and emissions significantly impacts the climate. A forest is considered a net carbon sink when it absorbs and stores more carbon than it releases over a specific period.

The flux or flow of carbon dioxide and other greenhouse gases into the atmosphere is the dominant contributor to the observed warming trend in global temperatures **(U.S forest carbon data, 2023, Wuebbles D.J. *et al.*, 2018)**. Trees, however, store CO_2 from the atmosphere, accruing significant stores of carbon over time. Trees also release some CO_2 back into the atmosphere (e.g. emissions). This process is known as Forest Carbon Cycle.

(Million metric tonnes (MMT) per year, CO_2 Eq.)

Carbon Pool	1990	1995	2000	2005	2010	2015	2020	CO_2 Eq.	% of total
Forest Ecosystem	-796	-789	-763	-707	-727	-645	-709	-691	87%
Above Ground Biomass	-555	-540	-524	-499	-496	-481	-474	-464	58%
Deadwood	-112	-109	-105	-100	-99	-96	-93	-91	12%
Below Ground Biomass	-112	-113	-113	-110	-113	-109	-114	-113	14%
Litter	-19	-28	-22	2	-18	38	-22	-18	2%
Soil	2	1	1	0	-1	2	-6	-4	1%
Harvested Wood Product(HWP)	-124	-112	-93	-106	-69	-92	-97	-103	13%
HWP in Disposal	-55	-52	-32	-43	-7	-27	-32	-38	5%
HWP in Use	-69	-61	-62	-63	-62	-64	-65	-65	8%
Total Carbon Flux	-920	-901	-857	-813	-796	-737	-806	-794	-

Source: - U.S. Forest Carbon Data,2023

Change in carbon stock in India's Forests between 2019 and 2021 is presented in the table

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TABLE 1.1: Change in forest carbon stock in India between 2019 and 2021 (FSI 2021)

Component	Carbon Stock In Forest in 2021	Carbon Stock In Forest in 2019	Net Change in Carbon Stock	Annual Change in Carbon Stock
Above Ground Biomass	2,319.9	2,256.5	63.4	31.7
Below Ground Biomass	718.9	700.8	18.1	9.1
Deadwood	47.7	35.8	11.9	6.0
Litter	107.3	127.9	-20.6	-10.3
Soil	4,010.2	4,003.6	6.6	3.3
Total	7,204.0	7,124.6	79.4	39.7

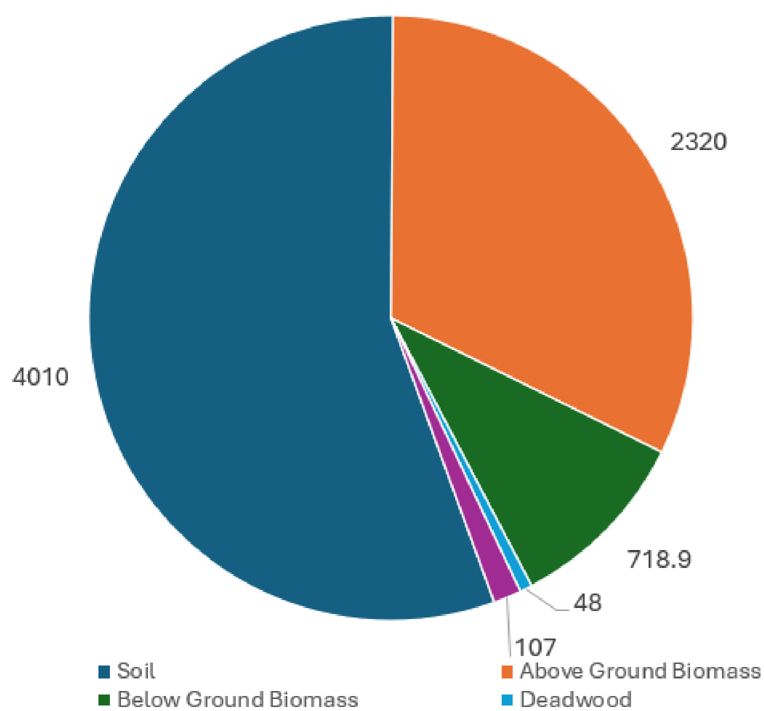

Figure 1.1: Forest Carbon Stock in different pools

4. CARBON CYCLE IN FOREST ECOSYSTEMS

Trees act as a sink for CO_2 by fixing carbon during photosynthesis and storing excess carbon as biomass. (**Nowak D J. *et al.*, 2001).** The net long term CO_2 source/sink dynamics of forests change through time as trees grow, die, and decay (**Nowak D J. *et al.*, 2001**). Plant biomass plays a crucial

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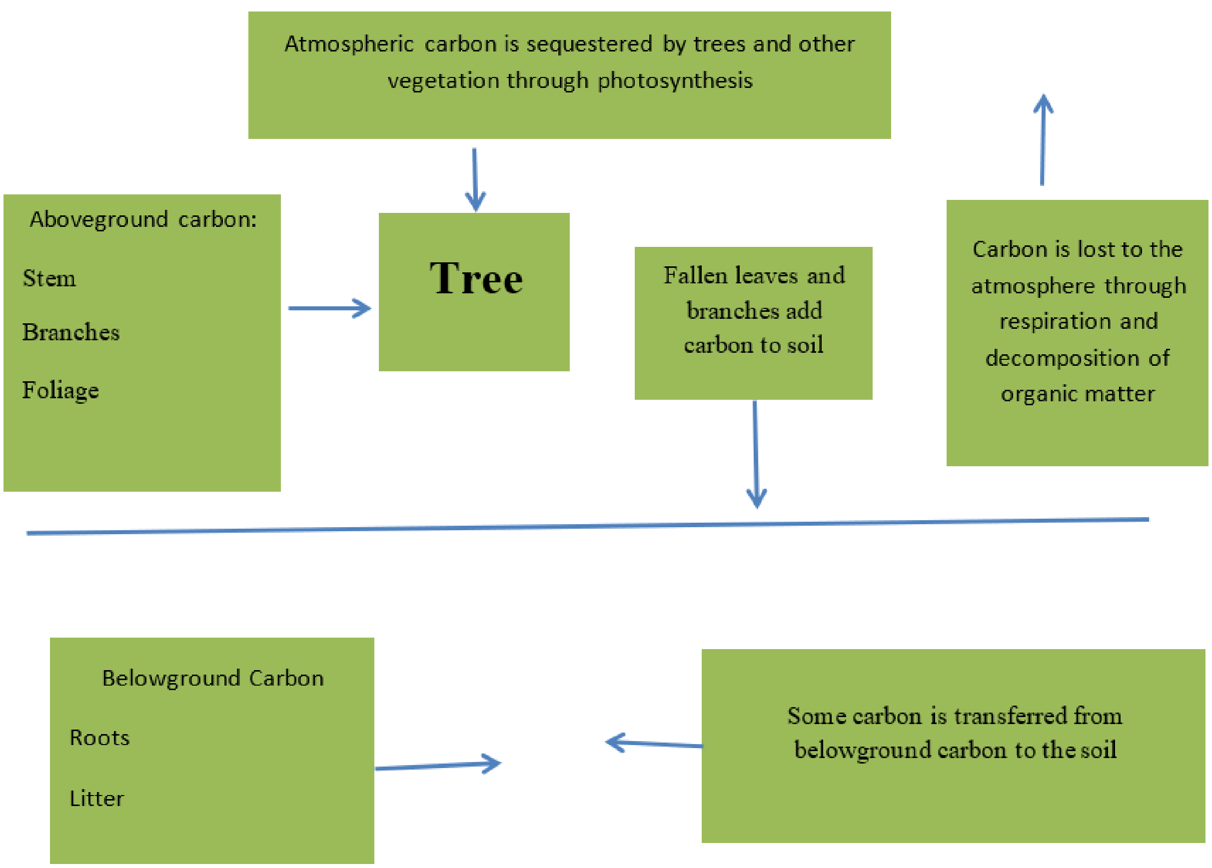
role in the global carbon cycle, and its proper management is essential for addressing climate change (**Houghtonn *et al.*, 2009; Souza *et al.*, 2017; Nath *et al.*,2021).**

By 2020, global forest C was predicted to reach 662 Gt (or 163 tha^{-1}) (**FAO,2020**)

Carbon pool size: - Forest ecosystems represent the largest terrestrial carbon pool, storing over 80% of all terrestrial aboveground carbon and more than 70% of all soil organic carbon. **(Jandl R. *et al.*, 2006)**

Carbon Dynamics: - Net growing forests actively sequester carbon. After harvesting, the carbon balance depends significantly on the lifecycle of the wood products. Both forest management practices and societal decisions play a critical role in influencing the carbon balance. **(Jandl R. *et al.*, 2006)**



Chemical form of Carbon: - The stabilization of carbon in terrestrial ecosystems varies. In biomass, the most stable form is wood, while carbohydrates and proteins are quickly recycled. Soil carbon consists of a complex mix of compounds. Stable forms of carbon include organic molecules chemically bound to mineral soils, which can persist for many decades. **(Jandl R. *et al.*, 2006).**

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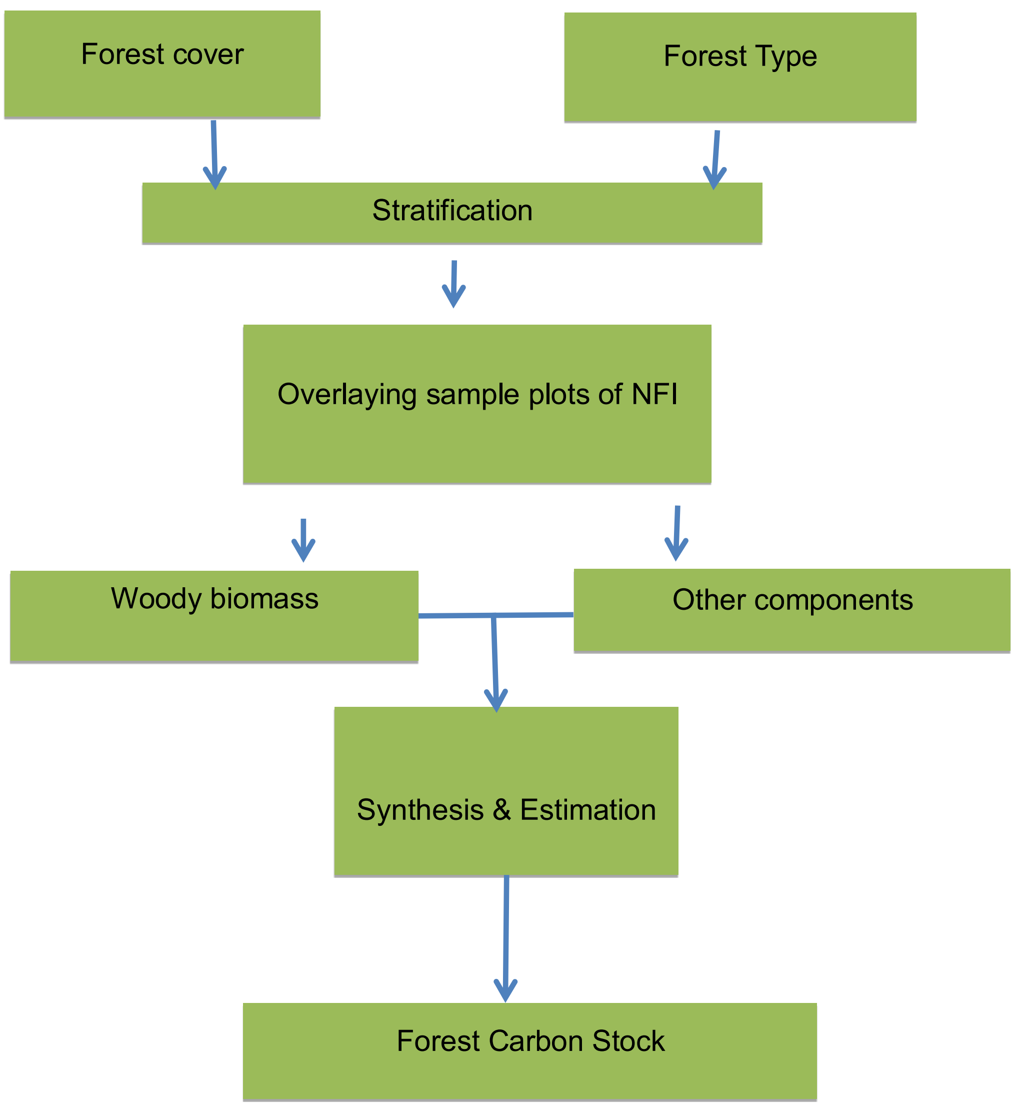
Source: - Journal of forestry and Natural Resources (2024)

5. STATUS OF FOREST

Forests play a crucial role as carbon reservoirs, continuously interacting with the atmosphere through the exchange of carbon dioxide, influenced by both natural processes and human activities.

Methodology for Forest Carbon Estimation



The Global Forest Resources Assessment report of 2020 estimated that the deforestation rate decreased to 10 million hectares annually between 2015 and 2020, compared to 12 million hectares per year between 2010 and 2015 (FAO, 2020). Forest carbon stocks are mainly composed of

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aboveground biomass (AGB), belowground biomass (BGB), litter biomass, deadwood, and the soil organic carbon (SOC) pool (IPCC, 2007).

Forest biomass and carbon stocks serve as essential indicators of forest productivity, energy potential, and their capacity to capture and store carbon. Over the past 25 years, significant global changes have occurred in forest management practices. Forest cover worldwide declined from 31.8% in 1990 to 30.8% in 2015.

As per the India State of Forest Report 2015, the total forest and tree cover in India spans 794,245 square kilometers (79.42 million hectares), representing 24.16% of the country's total geographical area. This marks an increase of 3,775 square kilometers in forest cover compared to the 2013 assessment (ISFR,2015).

The total forest cover of the country as per current assessment is 7,13,789 sq km which is 21.71% of the total geographic area of the country. (FSI, 2021)

TABLE 1.2: Forest Cover of India

Class	Area (sq km)	Percentage of Geographical Area
Very Dense Forest	99,779	3.04
Moderately Dense Forest	3,06,890	9.33
Open Forest	3,07,120	9.34
Total Forest Cover	7,13,789	21.71
Scrub	46,539	1.42
Non-Forest	25,27,141	76.87
Total Geographical Area	32,87,469	100.00

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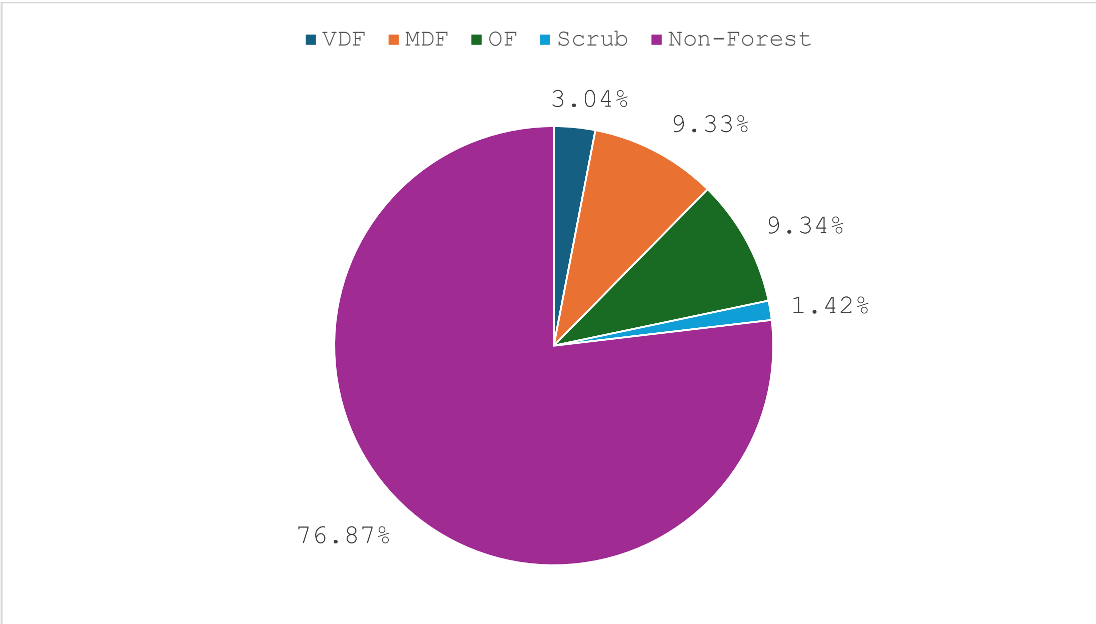

Figure 1.2: Pie Chart showing forest cover of India

6. FOREST AS CARBON SINKS

Forests play a vital role in mitigating climate change by sequestering CO_2 through photosynthesis. This process converts atmospheric carbon into biomass stored in trees, vegetation, and soil. Old-growth forests are especially important due to their capacity to store large amounts of carbon over centuries **(Pan *et al.*, 2011)**. Reforestation and afforestation efforts also contribute significantly to reducing greenhouse gas concentrations and enhancing global carbon storage.

Carbon emissions from net forest conversion were substantial, with a global average of 3.7 Gt CO_2 per year between 1990 and 2020. Overtime the global average decreased by 20% from 1990 to 2015, dropping from 4.3 to 3.3 Gt CO_2 per year - less than previously estimated using the FRA 2015 (-40%). Emissions declined further by 10% to 2.9 Gt CO_2 per year during 2016-2020. During this period, the Americas and Africa contributed nearly equal amounts, but with significantly different trends compared to 1991-2000.

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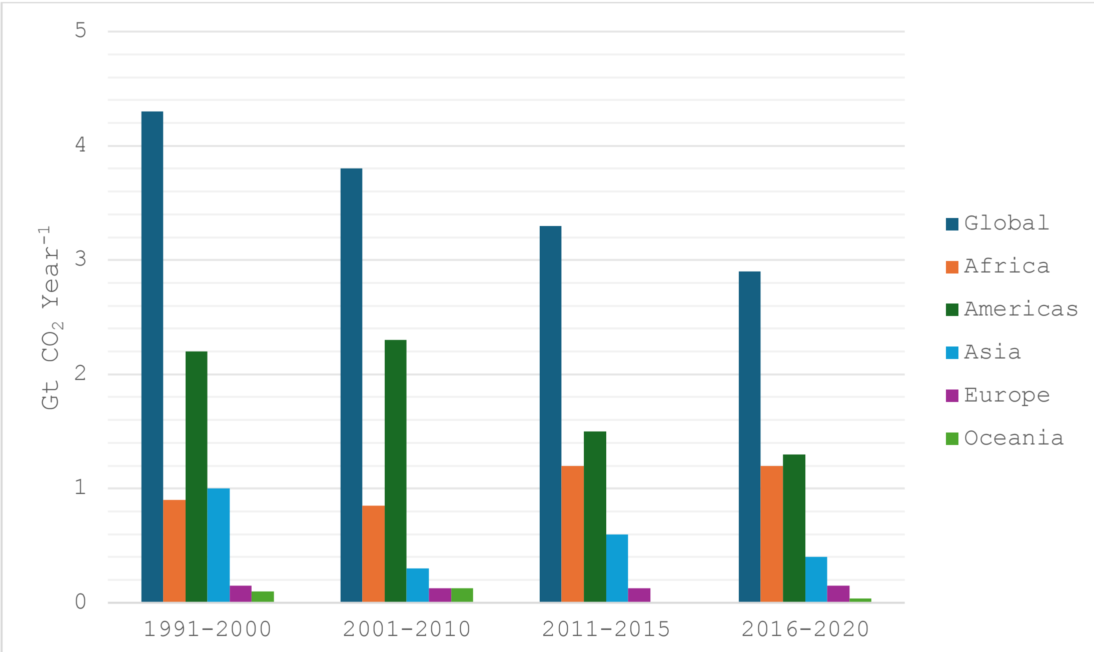

7. METHODOLOGY

Carbon estimation in tree species can be conducted using two primary methods: the destructive method and the non-destructive method. In non-destructive approach, while eliminates the need to cut down or destroy the tree. To analyze carbon storage quantitatively, a range of bio- statistical tools based on programming is often utilized, including SPSS Software, ANOVA, and regression models.

The tree's girth is measured at breast height (GBH), which is 1.32 meters above the ground surface. The tree diameter (D) was calculated by dividing the measured girth by 3.14. **(Bohre *et al.*, 2012)**. Biomass for the tree species was evaluated using bio-statistics -based allometric equations. Above Ground Biomass (AGB) was estimated by multiplying the tree bio- volume by the gree wood density of the species. Tree bio-volume (TBV) was determined by multiplying the tree's diameter and height by a factor of 0.4.

$$\text{Bio-volume } (T_{BV}) = 0.4X(D)^2 x\ H \qquad \text{Eq-1}$$

$$AGB = \text{Wood density x } T_{BV} \qquad \text{Eq-2}$$

Where; D=(GBH/¶), diameter(meter) calculated from GBH, assuming the trunk to be cylindrical, H = Height (meter). Wood density values are sourced from the Global Wood Density Database *(***Zanne *et al.* 2019**). If the wood density for a particular tree species is unavailable, a default average density of 0.6g/cm^3 is used.

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Below Ground Biomass: - Below ground biomass (BGB) is calculated by multiplying the Above Ground Biomass (AGB) by a factor of 0.26, representing the root-to-shoot ratio. **(Hangarge *et al.*, 2012)**

$$BGB = AGB \times 0.26 \qquad \text{Eq-3}$$

Total Biomass: - Total biomass (TB) is determined by adding the aboveground biomass (AGB) and the belowground biomass (BGB) (Sheikh *et al.*,2011).

$$\text{Total Biomass} = \text{Aboveground biomass} + \text{Belowground biomass} \qquad \text{Eq-4}$$

Carbon Estimation: - In general,50% of the biomass of any plant species is considered as carbon (Pearson *et al.*,2005).

$$\text{Carbon Storage} = \text{Biomass} \times 50\% \text{ or Biomass}/2 \qquad \text{Eq-5}$$

Biomass: - Biomass is defined as the total amount of aboveground living organic matter in trees expressed as oven dry tons per unit area. (FAO,1997).

To address the various issues related to forest biomass, it is essential to estimate the biomass of all forest components, including the above ground and below ground living mass of trees, shrubs, saplings, palms, wines, understory vegetations, epiphytes and dead plant material, such as fine litter and wood. (FAO, 1997). Understanding how the mass of these component changes over time and under natural or human disturbances is also critical however for practical purposes, this guide focuses on estimating the biomass of live above ground organic matter in trees, which includes leaves, twigs, branches, the main trunk and bark (FAO, 1997). These components generally represent the largest proportion of total living biomass in a forest and are relatively easier to estimate.

For most forests or trees formations, biomass density estimates are typically based on trees with diameters of 10cm or more, as this is the standard minimum diameter recorded in forest inventories (FAO, 1997).

General Equation: - Biomass density can be calculated from VOB/ha by first estimating the biomass of the inventoried volume and then expanding this value to take into account the biomass of the other above ground components as follows **(FAO,1997, Brown & Lugo, 1992)**.

$$\text{Aboveground biomass density (t/ha)} = VOB * WD * BEF$$

where:

WD = volume-weighted average wood density (1 of oven-dry biomass per m3 green volume)

BEF = biomass expansion factor (ratio of aboveground oven-dry biomass of trees to oven-dry biomass of inventoried volume) (FAO,1997).

Volume - Weighted Average Wood Density (WD):- Wood density is defined as the oven-dry mass per unit of green volume, expressed either in tons per cubic meter (tons/m^3) or grams per cubic centimeter (g/cm^3). For trees in tropical American forests, wood density is commonly reported using these units. However, for trees in tropical Africa and Asia, data on wood density are often expressed differently, using the mass of wood at 12% moisture content per unit of volume at the same moisture level **(Reyes *et al.*, 1992)**. To address this difference, Reyes *et al.* (1992) developed a regression equation to convert wood density measurements based on 12% moisture content to wood density based on oven-dry mass and green volume. (FAO,1997)

$$Y = 0.0134 + 0.800\ X$$

(r2= 0.99; number of data points n = 379)

where:

Y = wood density based on oven-dry mass/green volume

X = wood density based on 12% moisture content

Ideally, a weighted average wood density value should be used, taking into account the dominance of each species as measured by its volume. This can be calculated using the following approach.

$$WD = \{(V1/Vt\ WD1 + (V2/Vt) *WD2 +..........\ (Vn/Vt)\ Wdn$$

where:

V1, V2,.... Vn = volume of species 1, 2,.. to the nth species

Vt = total volume WD1 WD2,..... Wdn = wood density of species 1, 2,...... to the nth species (FAO,1997).

Biomass Expansion Factor: - The biomass expansion factor (BEF) is defined as the ratio of the total aboveground oven-dry biomass density of trees with a minimum diameter at breast height (dbh) of 10 cm or more to the oven-dry biomass density of the inventoried volume. These ratios have been calculated using inventory data for various broadleaf forest types, ranging from young secondary forests to mature forests, growing in moist to seasonally dry tropical climates.

The inventory sources provided sufficient data to independently calculate aboveground biomass density and the biomass of the inventoried volume (Brown *et al.*, 1989). The inventoried volume reported in these studies was based on the definition provided above. Analysis of this data shows

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that BEFs are significantly correlated with the biomass of the inventoried volume, as demonstrated by the following equations (Brown and Lugo, 1992):

$$BEF = Exp\{3.213 - 0.506*Ln(BV)\} \text{ for } BV < 190 \text{ t/ha}$$

$$1.74 \text{ for } BV>=190 \text{t/ha}$$

(sample size = 56, adjusted r2 = 0.76)

where:

BV = biomass of inventoried volume in t/ha, calculated as the product of VOB/ha (m3/ha) and wood density (t/m3) (FAO,1997)

Adjustment to Approach Using Volume Expansion Factors: - Forest inventories often report volumes based on varying standards, such as minimum diameters larger than 10 cm. Since these inventories may be the only available data, it is essential to develop a method to standardize the volume data for consistent use in estimating biomass density. (FAO,1997)

To standardize inventoried volume measured to a minimum diameter greater than 10 cm, volume expansion factors (VEF) were introduced (Brown, 1990). A common minimum diameter for inventoried volumes after 10 cm falls within the range of 25–30 cm. Data from inventories reporting volumes to this range were combined into a single dataset to ensure a sufficient number of studies for analysis. The VEF is defined as the ratio of the inventoried volume for all trees with a minimum diameter of 10 cm and above (VOB10) to the inventoried volume for all trees with a minimum diameter of 25–30 cm and above (VOB30).

Extrapolating inventoried volume from a minimum diameter larger than 30 cm to a minimum diameter of 10 cm is likely to result in significant uncertainty and is therefore not recommended. Estimates of VEFs were derived from a limited number of inventories from tropical Asia and America that provided sufficient detail for analysis (see Brown, 1990). Based on these inventories, the VEFs ranged from approximately 1.1 to 2.5 and were found to be related to the VOB30 as follows:

$$VEF = Exp\{1.300 - 0.209*Ln(VOB30)\} \text{ for } VOB30 < 250 \text{ m3/ha} = 1.13 \text{ for } VOB30 > 250 \text{ m3/ha}$$

(sample size = 66, adjusted r2 = 0.65)(FAO,1997).

8. MANAGEMENT OF CARBON IN TREES

The fate of carbon captured by trees plays a crucial role in determining the carbon storage potential of both natural and planted forests. Some of the carbon stored in trees biomass eventually transfers to the soil through litterfall and rhizodeposition, where it can remain for decades to millennia

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(Hemingway *et al.*, 2019). Since soils hold more carbon than terrestrial plants and the atmosphere combined, even small changes in soil carbon levels can significantly affect the strength of forests as carbon sinks. Reforestation and afforestation generally promote soil carbon accumulation over decades **(Paul *et al.*, 2022; Nave etal., 2018)**. However, in certain cases- such as in high-carbon soils like peatlands or grasslands- tree planting may lead to carbon loss **(Berthrong *et al.*,2009; Chen *et al.*, 2019; Richards *et al.*, 2017)**.

current research shows that specific biomolecules, such as lignin, are not necessarily preserved in the formation of soil organic matter **(Schmidt *et al.*, 2011)**. Instead, the fate of plant-derived carbon in soils is largely controlled by the activity of decomposer microorganisms and their interactions with soil minerals **(Dungait *et al.*, 2012; Cotrufo *et al.*, 2013)**. This new understanding highlights the importance of studying soil properties to enhance carbon storage **(Hemingway *et al.*, 2019)**. Forest management practices also significantly influence soil carbon turnover. For example, older tropical soils and sandy, light-textured soils often require substantial nutrient inputs to maximize productivity **(Adams and Pfautsch, 2018)**. The use of fertilizers, however, can affect the cycling and stabilization of soil organic matter **(Averill and Waring, 2018)**.

The way wood from plantations is used also matters for carbon storage. Substituting wood products for steel and cement, which are more fossil fuel-intensive, can reduce the climate impact of the construction sector **(Lippke *et al.*, 2014; Leskinen *et al.*, 2018)**, which is responsible for roughly 20% of global greenhouse gas emissions **(Lucon *et al.*, 2014)**. Using wood in place of materials like steel, stone, or concrete can offset between 1 and 3 tons of carbon emissions per ton of wood carbon **(Sathre and O'Connor, 2010)**, and contributes to carbon storage in buildings and infrastructure **(Churkina *et al.*, 2020)**. The climate benefits can be further enhanced by replacing fossil fuels with wood biomass energy. However, caution is needed, as poor land-use decisions or inadequate long-term management can negate these benefits. For instance, plantations specifically grown for bioenergy are land-intensive and often conflict with biodiversity conservation; using wood residues for bioenergy may be a more sustainable alternative **(Groom *et al.*, 2008)**. Additionally, increasing the longevity of wood products can build on existing knowledge of forest growth and structure. Thinning, for example, can focus growth on fewer but larger trees, leading to a greater supply of durable wood products **(Braun *et al.*, 2016)**. Sustainable wood production not only supports carbon storage but also generates revenue for rural communities, which can be reinvested in expanding forest areas.

9. ALIGNING FOREST CONSERVATION, ASSISTED REGENERATION, AND RE/AFFORESTATION

One major challenge in establishing plantation forests is ensuring that the economic and societal benefits they provide are retained within local communities **(Schirmer and Bull, 2014)**. Crafting

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policies that balance these goals is complex. Ideally, decision-making should be guided by the principles of natural capital (e.g., Bekessy and Wintle, 2008). Ignoring social dynamics, incentives, and valuation systems can lead to unintended outcomes, such as plantations replacing natural forests, which can result in the loss of biodiversity and ecosystem services **(van Oosterzee *et al.*, 2010)**. A promising solution is the TRIAD model, which divides landscapes into three zones: fully protected natural forests, selectively logged natural forests, and intensively managed plantations **(Paquette and Messier, 2010)**. When adapted to specific locations, this approach can promote timber production while also enhancing carbon sequestration and supporting conservation goals **(Carpentier *et al.*, 2017)**.

The protection of natural forests, both mature and secondary, is essential for mitigating climate change, as these forests store more carbon than plantations **(Liao *et al.*, 2010; Lewis *et al.*, 2019b)**. Although forest productivity slows as they age **(Gower *et al.*, 1996)**, the total carbon stored in living biomass, coarse woody debris, and soils continues to increase even in forests over 200 years old **(Pregitzer and Euskirchen, 2004)**. Remarkably, a single large tree can produce more wood in a year than the total biomass of a smaller tree **(Stephenson *et al.*, 2014)**. However, quantifying the carbon contributions of large trees can be challenging due to assumptions (e.g., absence of internal decay) underlying allometric equations used for calculations **(Clark, 2002; Roxburgh *et al.*, 2006)**.

The unique structural and ecological characteristics of natural forests—such as diverse tree sizes and significant carbon storage in dead wood, litter, and soil—are challenging to replicate in plantations, particularly those managed for timber. Facilitating the regeneration of natural forests is a highly effective and cost-efficient strategy for increasing carbon storage at the landscape scale. For instance, in Latin America and the Caribbean, secondary forests cover nearly one-third of the land area and account for a substantial portion of the region's carbon sequestration potential **(Chazdon *et al.*, 2016)**.

10. CHALLENGES TO CARBON CAPTURE AND STORAGE

Forest plays a vital role in mitigating climate change by serving as natural carbon sinks, absorbing carbon dioxide (CO_2) from the atmosphere and storing it in biomass and soil.

Deforestation and Land use change: - The total area of forest worldwide spans 4.06 billion hectares(ha), making up 31% of the planet's land area. On average, this equates to 0.52 hectares of forest per person. However, forests are unevenly distributed both geographical and among the global population. The tropical region holds the largest proportion of forests globally (45%), followed by the boreal, temperate, and subtropical regions. Remarkably, more than half (54%) of the world's forests are located in just five countries: Russia, Brazil, Canada, the United States, and China. (FAO,2020)

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Since 1990, the world has lost 178 million hectares of forests, an area comparable to the size of Libya. However, the pace of net forest loss has decreased significantly from 1990 to 2020. This improvement is due to reduced deforestation in some countries and increases in forest cover in others through afforestation and natural forest regeneration. The annual net forest loss dropped from 7.8 million hectares in the 1990s to 5.2 million hectares between 2000 and 2010, and further to 4.7 million hectares from 2010 to 2020. In the most recent decade, the rate of decline in net forest loss slowed as forest expansion rates decreased.

The majority of forest carbon is stored in living biomass (44%) and soil organic matter (45%), while the remainder is found in dead wood and litter. Between 1990 and 2020, the total carbon stock in forests decreased from 668 gigatonnes to 662 gigatonnes. Despite this decline, carbon density per hectare saw a slight increase, rising from 159 tonnes to 163 tonnes per hectare during the same period. (FAO,2020).

Climate change impacts: - Humanity is facing one of its most significant challenges and must be ready to respond and adapt efficiently. Despite a unified and global effort, the resolution will not be instantaneous. **(Sange, P.M *et al.*, 2008, Hart, S.L. et al, 2005)**

The increasing concentration of CO2 in the atmosphere is the main cause of the rapid acceleration of climate change. Without examining the origins of this CO2, it is evident that the initial measures to mitigate the effects should focus on reducing CO2 concentrations. Nevertheless, the rise in atmospheric CO2 is primarily due to human activities, with annual increases of 7.8 ± 0.8 PgC from fossil fuel consumption and 1.1 ± 0.8 PgC from land use changes. (Finkl C.W. *et al.*,2018)

Over the last century, the global average surface temperature has increased by about 0.74 °C. If no substantial measures are taken to mitigate this warming, the climate in this century is expected to become highly unusual, with the global temperature potentially rising between 2 °C and 5.8 °C, as indicated in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) from 2007. **(IPCC., 2007, Bogner J. *et al.*, 2008)**

Forest Events- wildfires: - Fires in forests and grasslands are common events that have a significant impact on the carbon cycle. Fire is a self-sustaining chemical process that rapidly breaks down organic matter, converting it into minerals, water vapor, and carbon dioxide within minutes. Wildfires are a major source of atmospheric carbon dioxide, making wildfire control important not only for reducing emissions but also for safety.

Wildfires are a natural phenomenon, though efforts are made to manage them. Some have proposed wildfire protection by reducing biomass levels in forests.

Forest ecosystems play a crucial role in mitigating the adverse effects of climate change by storing large amounts of carbon dioxide (CO_2) in the form of biomass. However, the amount of carbon stored in a forest can vary depending on several factors such as species composition, forest structure, age, forest type, as well as climatic conditions and disturbance events like forest fires. **(Collins L *et al.*, 2014, Salunkhe O *et al.*, 2014, Pekin BK., 2009)**

Forest Practices: - Forestry practices serve four main purposes: planting trees on a site, reducing competition from other vegetation, promoting tree growth, and harvesting wood for commercial use.

In climate change negotiations, carbon sequestration credits for forests were intended to be granted only for the additional carbon stored as a result of changes in forestry practices. (Leenhouts B.,1998)

Stand Establishment: - A key goal of forestry is to establish tree growth. When trees are planted on land that was recently cleared but previously had trees, the process is called reforestation. Planting trees on land that has not had forests for a long time, such as pastures, is known as afforestation.

Reforestation can occur naturally or through artificial methods. Natural regeneration relies on seeds from nearby forests to grow new trees. Establishing a forest generally stores more carbon than leaving the land without tree cover, as savannas and other non-forest ecosystems hold much less carbon in their vegetation. As forests grow, they continue to absorb and store additional carbon in trees and roots for many years—often for decades and even centuries in some ecosystems.

Reducing competition- involves clearing the forest of unwanted vegetation that competes with commercially desired trees for space, light, and nutrients. This practice is called "release" when the competing vegetation is as tall as or taller than the desired trees or belongs to a different species. Release can be carried out using herbicides (chemically) or through mechanical methods using machines or tools to remove the unwanted vegetation. The forestry practice of removing some desired tree species along with undesired ones is used when competition for space, light, and nutrients slows the growth of commercial timber.

Thinning and release are commonly recommended as forest management techniques to enhance carbon sequestration. Some models estimate total carbon on a site based on a fixed relationship with commercial wood volume. Since thinning and release promote commercial timber growth, these models would also predict an increase in carbon sequestration as a result of these practices.

11. OTHER GROWTH IMPROVEMENT

Other forestry practices are also aimed at increasing growth rates. Pruning involves removing the lowest branches of a commercial tree, which may encourage some upward growth but primarily focuses on improving wood quality rather than overall growth.

However, pruning is not widely used, as it has been found to be unprofitable in most cases.

Fertilizing forest stands is another practice used to enhance growth. Applying fertilizers to forests can significantly boost growth rates if the nutrient being added is limited in the soil.

Moreover, fertilization is likely to stimulate overall vegetative growth, not just tree growth. This has been observed in research studying the effects of forestry practices on carbon sequestration. Some have suggested that greater atmospheric CO_2 levels could fertilize forests, stimulating tree growth. A number of studies artificially increased CO_2 levels in tree plantations, and found that growth did increase. **(DeLucia E.H. *et al.*, 2005)**

12. CONCLUSION

Forests pay a critical role in carbon capture and storage, serving as one of the most effective natural systems for mitigating climate change. Through photosynthesis, trees absorb carbon dioxide (CO_2) from the atmosphere, converting it into biomass stored in their trunks, branches, roots, and soil, thus reducing atmospheric CO_2 levels- a key driver of global warming (**Pan *et al.*, 2011)**. Forests, particularly old-growth ecosystems, act as a long-term carbon sinks, storing substantial amounts of carbon for centuries **(Bonan, 2008).** Strategies like afforestation, reforestation, and forest conservation enhance this capacity, while deforestation and forest degradation release stored carbon, significantly contributing to global greenhouse gas emissions **(IPCC, 2021)**. Consequently, protecting and restoring forests is vital for sustaining their role in carbon sequestration and addressing climate change. Sustainable forest management should be prioritized by policymaker, industries, and communities to maintain these critical ecosystem services.

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