Department of

Biology and Environmental Science

Carbon Sequestration and Forest Management:

A Study of South Korean Forests' Challenges and Strategies

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Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
BAU	Business As Usual
DBH	Diameter of Breast Height
DOM	Dead Organic Matter
GHG	Green House Gas
HWP	Harvested Wood Products
IPCC	Intergovernmental Panel on Climate Change
KFS	Korea Forest Service
LCA	Life Cycle Assessment
NDC	Nationally Determined Contribution
NEP	Net Ecosystem Productivity
NFI	National Forest Inventory
RD	Relative Density
SDI	Stand Density Index
SK	South Korea
To-Be	The envisioned future state after changes and improvements have been made.
UNFCCC	United Nations Framework Convention on Climate Change

Abstract

The strategic management for forests of South Korea (SK) is crucial to enhancing carbon sequestration amidst challenges such as climate change, aging forests, and socio-economic constraints. This thesis explores an integrated approach that combines scientific understanding with forestry management practices to address these issues effectively. SK's forests boast growing stock levels that surpass the OECD average, achieved through rapid greening efforts. However, these efforts have led to an over-concentration of trees within the same age group, significantly complicating sustainable carbon cycle management. Additionally, long-standing forest conservation policies have led to one of the lowest forest utilization rates globally, weakening the related timber industries and increasing reliance on timber imports, thereby contributing negatively to global climate warming. The current ownership structure, with 66% of forests being privately owned and predominantly consisting of small holdings, necessitates active participation from owners. However, many small-scale owners neglect proper management due to their residence away from their properties, leading to further forest degradation.

The Korea Forest Service (KFS)'s policies aim to balance forest density and age structure to sustain and increase carbon absorption capacities. Controversies have recently challenged the basis of KFS's policies, causing a loss of momentum in promoting forest carbon management. However, empirical evidence supports the KFS's stance by demonstrating that biomass accumulation in smaller trees (with a Diameter at Breast Height (DBH) ≤10cm) is minimal, accounting for a very small fraction of the total forest aboveground biomass Further, several scientific researches indicates that tree productivity peaks between 11-30 years, aligning with KFS claims. Structural issues arising from the age concentration of trees necessitate management interventions, as evidenced by the relative density (RD) calculations for *Pinus densiflora*, indicating densely packed forests beyond the self-thinning threshold.

Crown closure surveys further reveal that nearly half of the forests are at the highest closure level (76%-100%), suggesting the need for artificial management. KFS's long-term plan involves harvesting about 41% of the total forest area by 2080, equating to an annual harvest of 0.68% (42,827 hectare). This practice, resulting in an annual production of 10-million m^3, mirrors the forest utilization rates of leading carbon cycle management countries like Germany and Sweden, where rates around 1% do not detrimentally affect the overall stock trend.

This research has scrutinized the historical and current management states of Korean forests through the lens of carbon dynamics. Dramatic rises in carbon storage in the biomass—from 36.4 Tg in 1954 to 440 Tg in 2012—follow extensive planting initiatives begun in 1973. Carbon storage in Dead Organic Matter (DOM), including soil, deadwood, and litter, has also increased, though not documented for the required 20 years of consecutive data per Intergovernmental Panel on Climate Change (IPCC) guidelines. Thus, not yet contributing to annual carbon absorption figures. The harvested wood products (HWP) sector is also projected to decrease due to poor domestic production. Establishing a forest circular management system, incorporating DOM into carbon accounting, and expanding the domestic production of HWPs are proposed to counter the expected decrease in biomass carbon absorption rates.

Keywords

Carbon Neutrality, Carbon Sink, Forest Management, Sustainability, Harvested Wood Products, Circular management, Greenhouse Gas, Carbon Sequestration, Climate Change

1. Introduction

1.1. Background

After Paris agreement, the concept of carbon neutrality has been the global common goal and leaded joint efforts of every country without differentiation. South Korea also declared an ambitious plan of 2050 Carbon Neutrality and suggested its 2030 Nationally Determined Contribution (NDC). As a country with manufacturing industrial structure and a large population, the plans included various efforts of emission reductions and technological developments for energy efficiency and carbon capture (Government of Korea, 2023).

However, contrary to the most steps forward, the national carbon absorption goals are decreasing with years to come. The observed carbon absorptions of Korean forest ecosystem peaked in 2008 with 62 $MtCO_{2eq}yr^{-1}$ and gradually decreased to 40.3 $MtCO_{2eq}yr^{-1}$ in 2018 (Korea Forest service, 2020). The expected levels of annual carbon absorption capacity will be dropped to 22.5 $MtCO_{2eq}yr^{-1}$ in 2030 and 15.6 $MtCO_{2eq}yr^{-1}$ in 2050 with current forest management (Korea Forest Service, 2023c)

According to the 3rd national plan of carbon sink promotion (Korea Forest Service, 2023c), KFS planned to expand the annual amount of carbon uptake by forest and forestry in domestic area to 30 $MtCO_{2eq}yr^{-1}$ until the year of 2027. The South Korean government has formulated a plan to take responsibility for a 5% offset (27 $MtCO_{2eq}yr^{-1}$) of total national emissions (512 $MtCO_{2eq}yr^{-1}$) in 2030 NDC (Government of Republic of Korea, 2023) as the first line of defense in slowing the rate of carbon absorption decrease. By setting the long-term goals as 27 $MtCO_{2eq}yr^{-1}$ in 2030 and 26.7 $MtCO_{2eq}yr^{-1}$ in 2050, it is to maintain a stable level of carbon absorption in Korean forests.

Practical measures to achieve this goal are mainly focusing on utilization of forests and post-harvest reforestation (An et al., 2019a, 2019b; Chang et al., 2022; H. Kim et al., 2022a; Y. Kim, 2017; W. Lee et al., 2022a; Son et al., 2017). In other words, the aim is to increase the turnover rate of forests to maintain carbon absorption levels. However, due to the successful establishment of the reforestation program since 1973 (J. Lee et al., 2014), there is a shortage of idle land for new afforestation, while domestic timber production has stagnated at the level of 5-million m^3yr^{-1} (Tak et al., 2007). This necessitates a significant restructuring of forest management for sustainability with relaxation of forest cutting rotation regulation and large-scale afforestation in government's point of view. Announced in 2021 by KFS, the forest sector's strategy for achieving 2050 carbon neutrality plan marked the first explicit target figures for sustainable management practices, such as 'planting 3 billion trees by 2050 to reduce carbon emissions by 24-million ton' (Korea Forest Service, 2021). This means increasing the annual afforestation from the current 29-million trees per year to 86-million trees per year. The KFS stated that expanding afforestation will allow for a diverse distribution of tree age classes, as well as improve urban forest creation, afforestation projects in unused land areas, restoration of areas affected by wildfires, and utilization of economic forests.

In response to the KFS's announcement, environmental organizations have issued successive statements of opposition. The Green Alliance strongly criticized the government for treating mature trees as mere garbage, only focusing on carbon sink function. It called for the withdrawal of the plan of reforestation to preserve the public value and biodiversity of forests (Green Alliance of Korea, 2021). The Environmental Movement Union expressed concerns that tripling the annual afforestation scale could entail the removal of existing forests. They argued that larger trees absorb more carbon annually, countering the KFS's claim that older trees have reduced carbon absorption capacity. The union also raised doubts about the carbon offset effects of increasing biomass power generation and expanding the use of domestic timber policies (Environmental Movement Union of Korea, 2021). In response to the strong opposition from environmental organizations, the Ministry of Environment, the overarching authority for carbon neutrality policies, has announced its intention to review the policy. The Forestry Agency, responsible for implementing various initiatives, appears to be retracting specific numerical targets from its plans and focusing once again on reassessment and persuasion efforts.

Recent studies on forest management from the perspective of carbon neutrality is actively underway both domestically and internationally(Böttcher et al., 2008; Gustavsson et al., 2017; Jandl et al., 2007, 2015; H. Kim et al., 2022b; Y. Kim, 2015; Lal & Lorenz, 2012; W. Lee et al., 2022b; Lewis et al., 2019; Martes & Köhl, 2022; Peckham et al., 2012; Peng et al., 2023; Repo et al., 2015). Policy examples of other countries are readily available to adapt to Korean cases. However, considering the unique ecological environment, characteristics, and related industrial structure of Korean forests, direct application may be challenging (J. Lee et al., 2014; Soo Bae & Kim, 2019; Tak et al., 2007). Moreover, there are diverse scholarly opinions advocating for natural based solutions through forest conservation (Hong, 2022; Lewis et al., 2019), as well as for artificial interventions and expansion of utilization (Cintas et al., 2017; Jandl et al., 2015; Y.-H. Kim, 2016; W. Lee et al., 2022). Also, some studies are aimed at analyzing the economic effects of carbon by different forest management techniques (Repo et al., 2015) or conducting climatic research on specific region's forests or individual trees (Allen et al., 2010; Beringer et al., 2005; Jandl et al., 2015; Y. Kim, 2015). To contemplate securing carbon absorption capacity and circular management methods for forests from a national perspective, it is necessary to assess the applicability of various cases.

1.2. Status of Forests in South Korea

Natural Conditions

The Korean landscape is characterized by rugged mountain ranges, rolling hills and coastal lines with intricate contours. Due to its highly complex topography, the forests of SK exhibit localized variations in weather and soil environment. According to the national statistics of forest in 2020, the total land area of SK is 10,041,000 hectares, with forest accounting for 62.7%, equivalent to 6,298,134 hectares. The forest area of the country has been decreased with approximately a 6% decreasing from 6,687,000 hectares in 1964. Estimated from satellite observations, around 7.2billion trees are growing with the stock of 165 m^3ha^{-1} which exceeds the OECD average of 131 m^3ha^{-1}. In the average forest, number of trees per ha is 1,129 stems. Among them, the number of trees with a DBH of 30cm or more, which have timber value, is around 90 stems ha^{-1}, more than double the 40 stems ha^{-1} in 2010 (Forest ICT Research Center & Korea Forestry Promotion Institute, 2021).

As of present, most areas of the country belong to the temperate climate zone. However, if the impacts of climate change worsen, it is forecasted that the southern region and the coastal lines of the Korean Peninsula will transition into a subtropical zone as shown in figure 1 (National Institute of Forest Science, 2023).

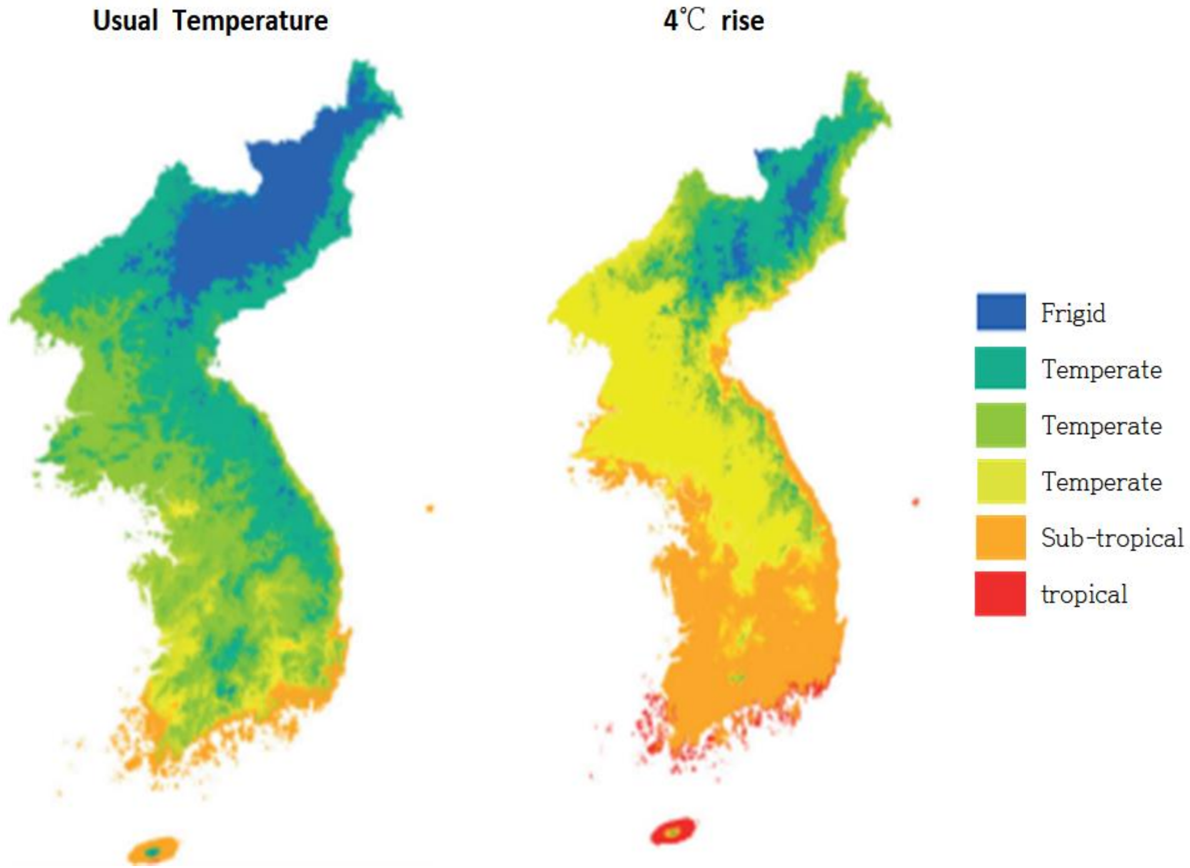

Figure 1. The Forest climate zones of Korean Peninsula can be classified into Frigid, Temperate, subtropical, and tropical forests. With the average temperature expected to rise by 4°C, it is predicted that most areas of the southern coast will transition into subtropical forests. Originally published in National Institute of Forest Science (2023).

Evidence of climate zone change is already apparent in the variations of major tree species as. In 2020, the area of coniferous forests was 36.9%, while deciduous forests and mixed forests cover 31.8% and 26.5% each, and 4.8% of the land are for bamboo and non-tree areas. It shows coniferous forests occupy the largest area among stand types. However, comparing with the past data, deciduous forests have shown an increasing trend since 1970s as shown in the figure 2 (National Institute of Forest Science, 2023). Furthermore, in mountainous areas, the increase in temperature leads to increased water stress, resulting in the death or reduced growth of major coniferous species (Allen et al., 2010).

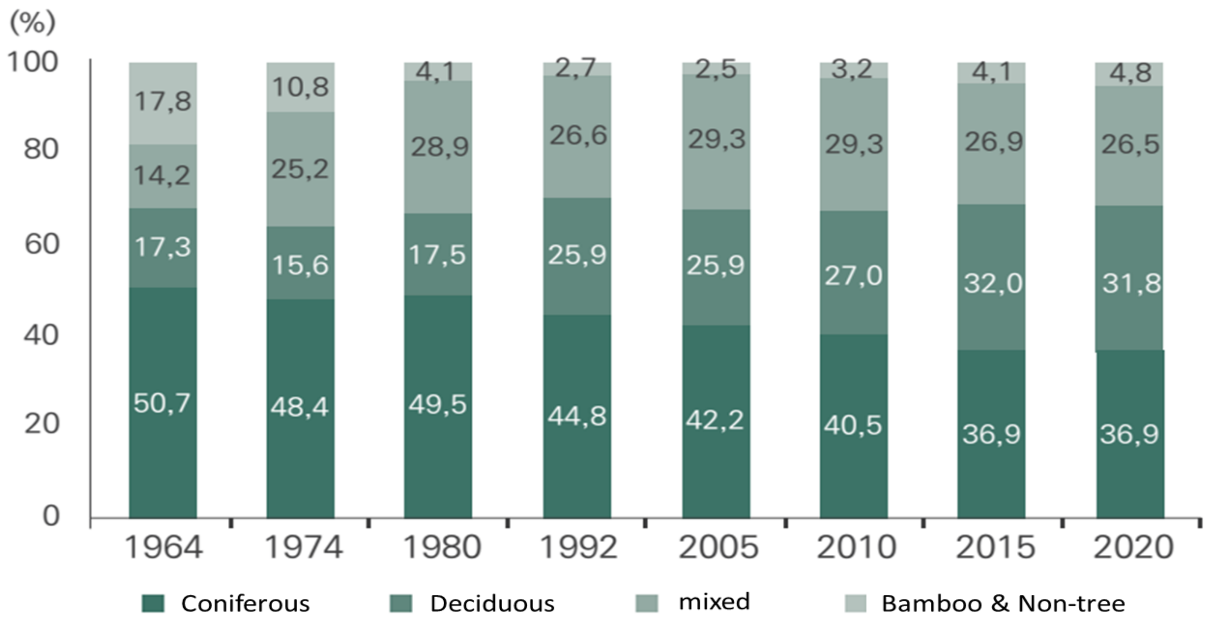

Figure 2. Forest area ratio by tree stand types show that there is a noticeable continuous increase in deciduous forest while coniferous forests dominate. Published initially by National Institute of Forest Science (2023).

For sustainable forest management as a carbon sink, it is ideal for forest age structure to be diverse and evenly distributed (Y. Kim, 2017; J. Lee et al., 2016; Pregitzer & Euskirchen, 2004). However, in SK, most forests have been artificially planted according to national policies over a certain period (J. Lee et al., 2014; Soo Bae & Kim, 2019; Tak et al., 2007). Consequently, as depicted in Figure 3, SK's forests exhibit unique age structures, rarely seen in other countries. As of 2020, 75% of trees are distributed between the ages of 30 to 49. However, the proportion of newly planted trees is decreasing over time. The reasons of this unique age structure will be explained through the historical background of SK's forests (National Institute of Forest Science, 2023).

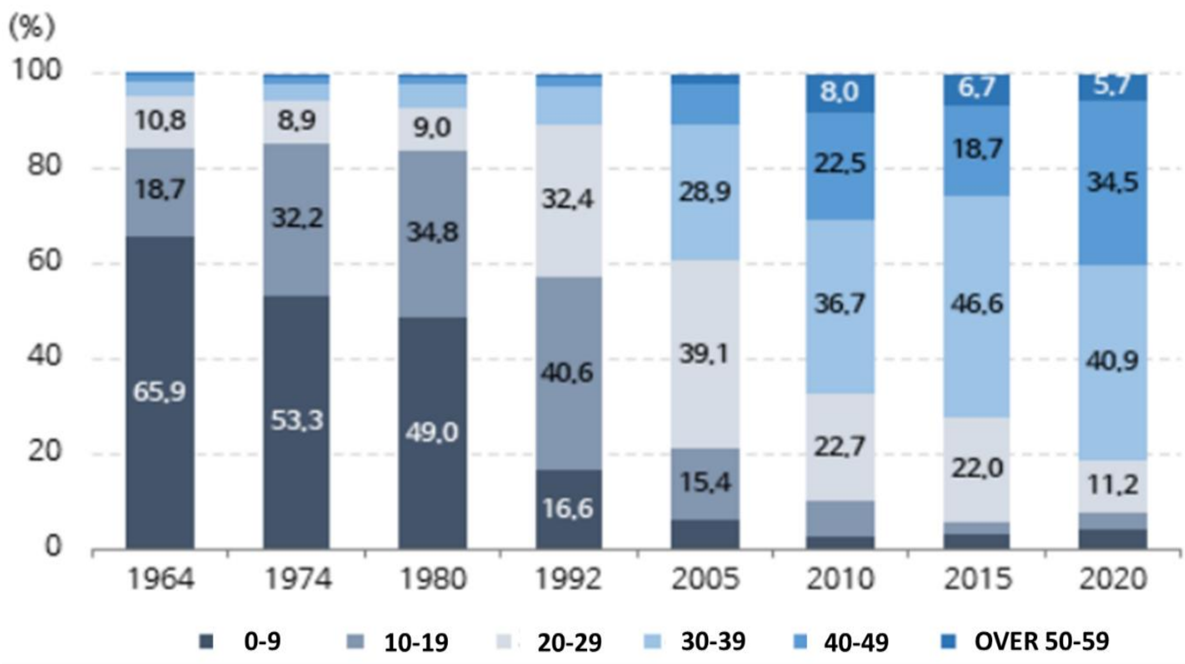

Figure 3. Age class distribution of trees indicate the decreasing trend of young trees aged 20 or younger when the year get closer to the present. Originally published by National Institute of Forest Science (2023)

Historical Background & National Forest Policies

For 5,000 years of history, Koreans used locally grown timber for constructions, cooking, and heating. However, in the early 1900s, Japan, during its colonial period of the Korean Peninsula, procured materials to support its war economy from Koea and China through unequal treaties such as the 'Forest Cooperation Agreement of 1906'. With a long period of colonization spanning 35 years and Japan's participation in World War II, the devastation of Korea's forests was extensive and severe, with approximately three-quarters of the entire forest destroyed. Without a chance to recover, the remaining of forests were cut down just for military operations or the war refugee shelters during the Korean War from 1950 to 1953 (Tak et al., 2007).

Figure 4. Denudated forest land in 1954 after colonization and war. The original of this photograph is exhibited at the Korea Forest Museum (n.d.).

The forests, excluding remote government-owned forests, were completely devastated across the entire nation as the picture shows in the figure 4. The utter desolation led to various adverse effects. Even a slight rainfall would cause flooding with soil erosion and extensive sedimentation. Conversely, during dry spells, rivers would run dry. Winds would carry dust and blow directly to village without obstacles, exacerbating the severity of winter. As figure 4 shows, it was enough to concern about desertification of the land (National Mountain Museum, n.d.). The Forest Conservation Temporary Measures Act in 1951 and Forestry Act in 1961 were enacted to address the urgent situation. Efforts were made to plant fast-growing species such as acacia, alder, and red pine in barren lands, but, during the initial 20 years of afforestation drive, the soil in the mountainous areas was so barren that trees could not take root. Even surviving trees were washed away during heavy rains due to soil erosion (National Archives of Korea, n.d.).

With the establishment of the specialized agency, the Korea Forest Service, in 1967, the comprehensive planning and long-term goals enabled the initiation of the national land greening project. To avoid using domestic forest resources until the forestry resources could meet domestic timber demand, the government imported a large amount of foreign timber and set the annual logging limit at 15% of annual growth, actively preventing forest resource depletion. Building on this foundation and spurred by the country's economic development, the 1st Forestation Project commenced in 1973. It focused on land greening as the primary goal, aiming to quickly stabilize land and waterways by setting the planting ratio of economically valuable trees to fast growing trees at 3:7. The project engaged not only landowners but also the entire nation so that trees were planted and nurtured throughout the year over all the country. The national land greening goal, originally set to be achieved in 10 years, was accomplished in just 8 years. During the period, nurseries produced 3billion seedlings and the project completed covering the entire forest area of 6.67-million hectares, which included afforestation of 1.08-million hectares of treeless land (Ministry of Interior, 1973).

Although the 1st Forestation Project was unprecedentedly successful at the rate of afforestation in the world, it did not consider the tree species' local adaptation and domestic timber demand. With the heavy industry development and the increase in overseas imports, the timber self-sufficiency rate, which was 21% in 1970, decreased to 15% by 1980. Consequently, in the 2nd Forestation Project, 80 large-scale economic forest complexes were established for forest resource development, and continuous forest management was implemented (Korea Forest Service, 1979). The rapid industrialization and urbanization had a dual effect on the afforestation projects. On one hand, it alleviates pressure on forest resources by moving slash and burn farmers to city. On the other hand, rural areas faced labor shortages, leading to difficulties in labor recruitment and high labor costs, which in turn deterred investment in forestry. The difficulty in post-afforestation management is evident from the proportion of artificial forests in the current forest cover. While most forests in SK have clearly been planted artificially, only about 20% are distinctly classified as artificial forests as of now. The rest have experienced natural succession due to inadequate or no management (Korea Forest Research Institute, 2011).

Since 1990s, the focus of forest policy shifted from land greening towards promoting the public functions of forestry and fostering the forest industry until now (National Archives of Korea, n.d.). The trees are still too young to be harvested, but forests have gained value as spaces for recreation and culture as the picture of Figure 5 shows (Jangtae Mountain Recreational Forest, 2021). The ecological axis connecting major forested areas from north to south is recognized for its public functions in preserving biodiversity and mitigating pollution.

Figure 5. Jangtae Mountain Recreational Forest of tall Meta-sequoia trees and a red clay path provide nearby residents with a place for relaxation. The photograph is originally uploaded on the Jangtaesan Recreational Forest website (https://www.jangtaesan.or.kr:454/index.asp, 2021)

Forest Ownership and Structure

As of 2020, the forest area by ownership in SK is divided into 26% for national forests, 8% municipal forests, and 66% privately owned forests. Korean government takes efforts to nationalize the forests by purchasing about 10,000ha every year. As a result of the government's continuous acquisition of private forests, the ratio of national forests increased from 20% in 1964 to 26% in 2020 as shown in figure 6. However, since a high ratio of the forest area is still owned by ordinary citizens, the most forests are occupied privately so that improving the management level of privately owned forests remains crucial in national forest management (Forest ICT Research Center & Korea Forestry Promotion Institute, 2021).

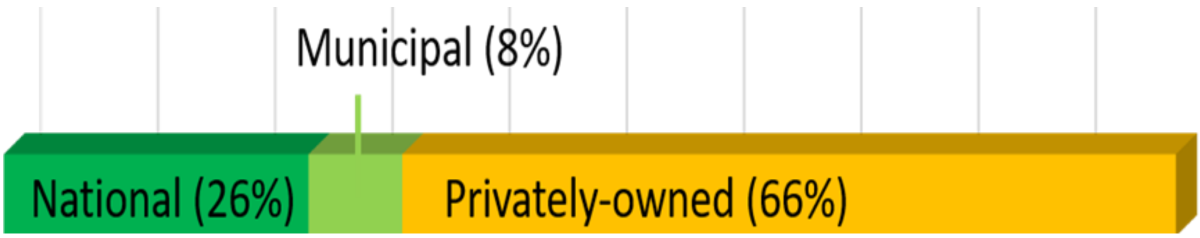

Figure 6. Privately-owned forests take the majority of 66% among the total forest lands in 2020. The graph is created by the author using the data from Forest ICT Research Center & Korea Forestry promotion Institute (2021).

Here comes another challenge for forest policy implementations. There are around 2.18-million private forest owners with an average ownership size of 1.9 hectares as shown in figure 7. This is largely due to the prevalence of forest purchases for burial purposes. Many of these small-scale forest owners, who often reside far away from their forest land, neglect proper forest management and leave their forests unmanaged. This widespread indifference has led to a lack of forest management infrastructure. The forest road density for SK's forests is very low at 3.2m/ha, and investment in forestry equipment is also minimal. Given the low selling value of timber in an industry with high costs, it is only natural that forest owners have very little interest in forest management (W. Lee et al., 2022).

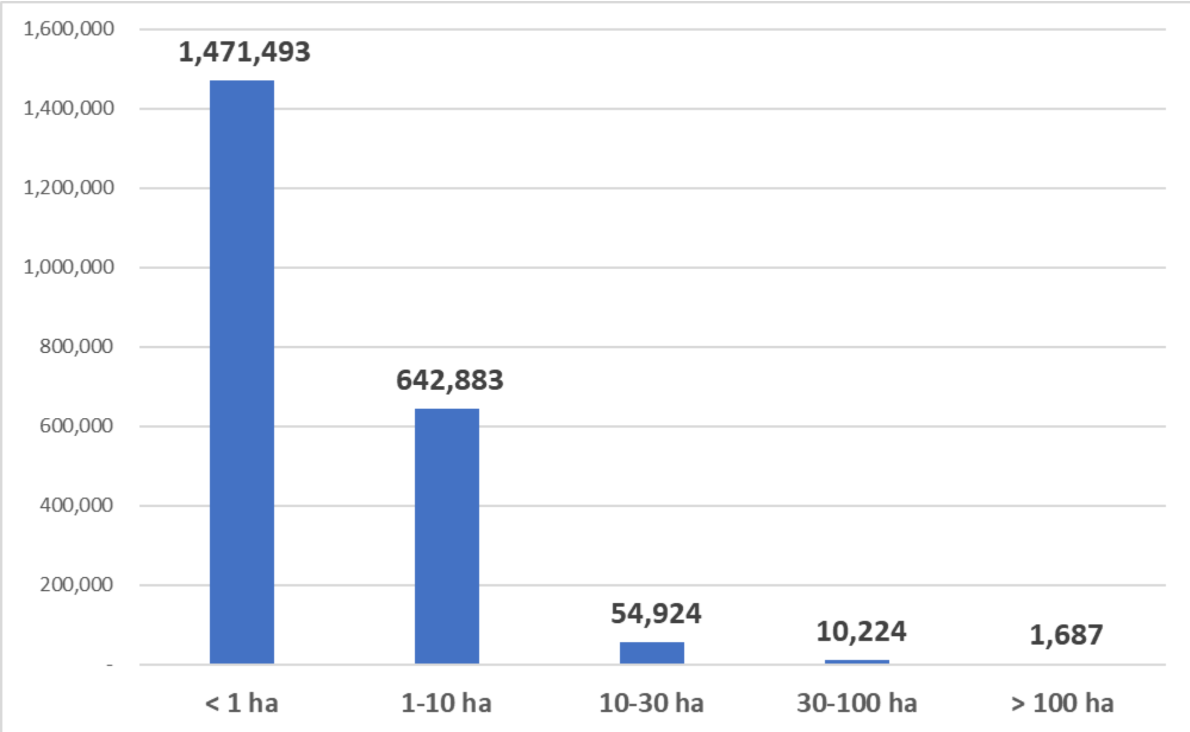

Figure 7. Distribution of private forest ownership sizes. Less than 10 hectares of land ownership accounts for 97% of the total. The graph is redrawn by the author using the data from W. Lee et al. (2022).

To address this issue, and scale up forest management, the KFS has embarked on a project where forest cooperatives manage forests on behalf of forest owners and return the income to them. KFS designated forest areas of over 500 hectares as 'Leading Forest Management Areas' and are focusing investments on them from 2013. However, the designated area is only 57,572 hectares, which accounts for only 1% of the total forest area in 2022 (Leading Forest Management Complex, 2022). Therefore, it is observed that national forests still serve as the main entity for forest management with constraints on their scale.

Forest Products Industry

SK consistently ranks among the top 10 net importers of timber and timber products globally. The fundamental reason for this is that Korea's forests still fall short of meeting domestic demand. Recently, there has been an increasing demand in timber construction and biomass power generation. However, out of the annual timber consumption of 30,800396 m^3 in SK, 85% relies on imported timber (Korea Forest Service, 2023d). This heavy reliance on imported timber has drawn criticism for exacerbating global warming due to deforestation in other countries' forests and increased carbon emissions from long transportation distances (International Centre for Sustainable Carbon, 2022).

Most of the domestically produced timber, which accounts for only about 15%, is primarily used for pulp or board production, with a low proportion being utilized for high-value-added products that can expect long-term carbon fixation such as sawn woods and boards (Korea Forest Service, 2023b). Examining the production volume of domestic timber over the past seven years reveals a steady decline, as shown in the figure 8, indicating a contraction of the domestic timber market. Despite of the ongoing increase in tree biomass in recent years, this decreasing production rate serves as evidence that the domestic timber industry infrastructure is not adequately prepared (Korea Forest Service, 2023d).

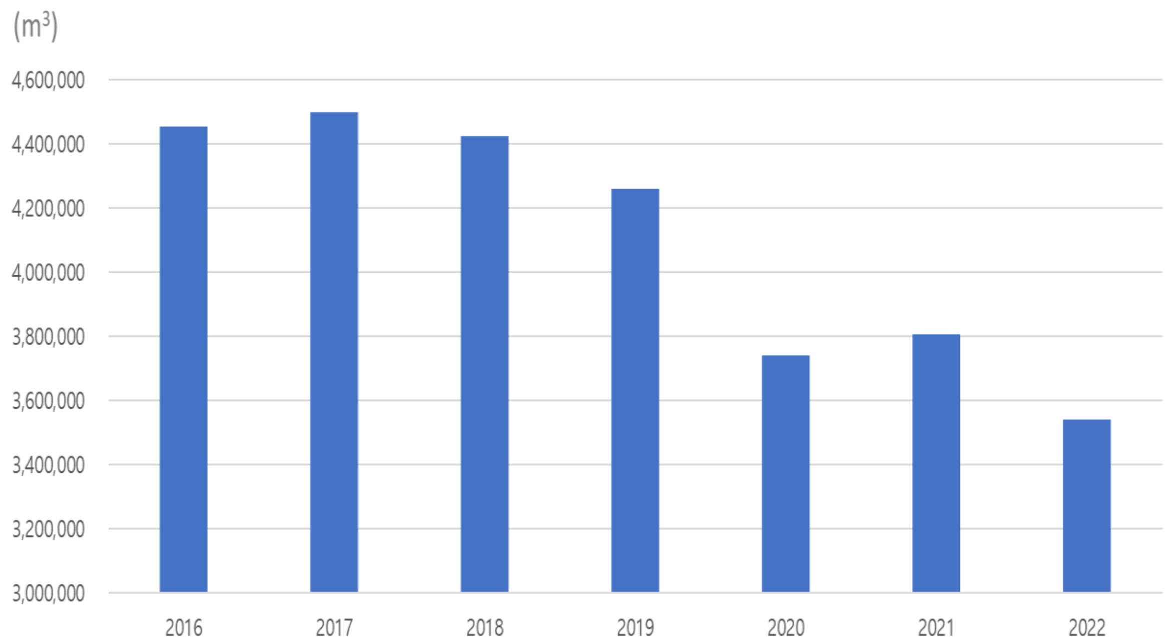

Figure 8. The production volume of domestically produced timber is declining. The bar-graph is redrawn by the author using the data from Korea Forest Service (2023d).

As of 2021, the total revenue of the entire timber industry is approximately 35 billion dollars (Korea Forest Service, 2023a). Out of the 1,700 domestic manufacturing companies, 1,190 companies (70%) are small businesses with fewer than 10 employees (Korea Forest Service, 2023d). The weakening of the timber industry's foundation can be attributed to the fact that existing forest policies have primarily focused on restoration and conservation efforts. A comparison of the utilization rates relative to the total growth of trees among different countries, as shown in the figure 9, also indicates that SK's Forest policy has historically prioritized conservation over utilization (OECD, 2019). However, with the current establishment of dense forests through restoration efforts over the past 50 years, it is imperative to reassess the role of forests and the direction of policies from a carbon-neutral perspective.

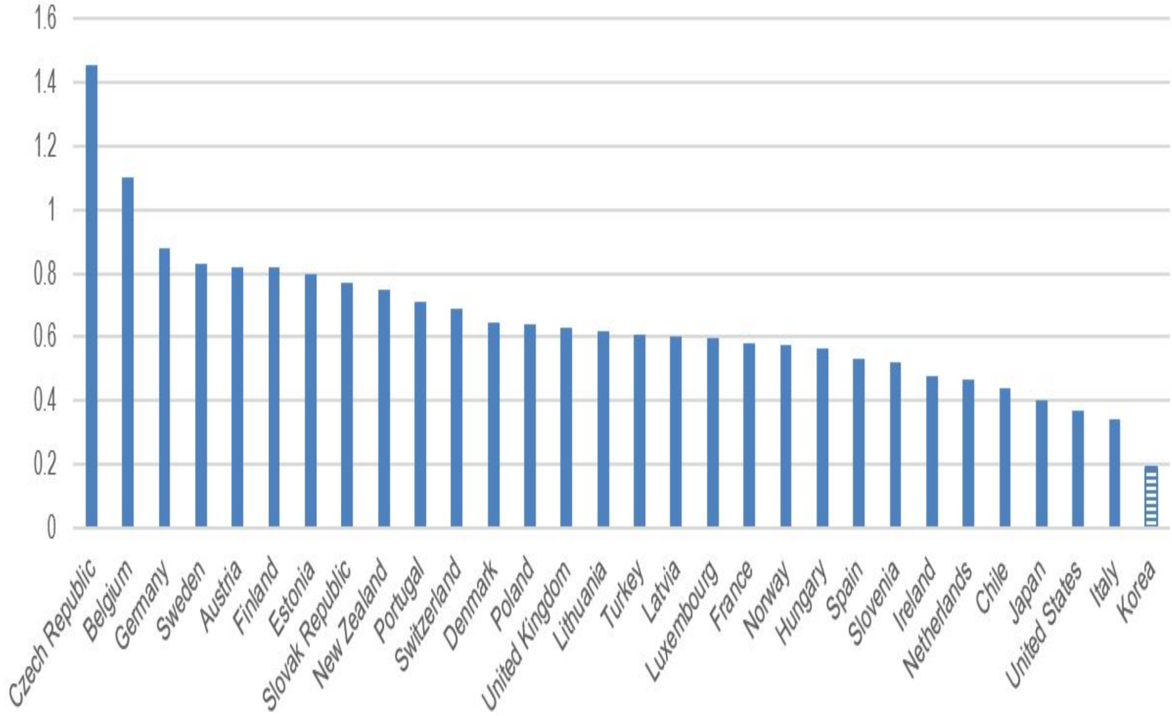

Figure 9. This graph shows forest resources intensity of use ratio (The ratio of annual timber harvest to forest growing stock) by country in 2019. Korea's use ratio ranks the lowest. Originally published in Kim et al. (2022).

1.3. Objective and Research Questions

Forests breathe and grow. In this process, human society interacts with forests and can gain many benefits (Marzano et al., 2014; Noble & Dirzo, 1997), but can also cause disasters through destruction (Lidskog & Sjödin, 2016; McNeely, 2003). The recent 100-year history of the Korean Peninsula proves that the nation's trials and triumphs are deeply engraved on the land and forests where the people live. Korea's forests have experienced devastation from foreign invasions and war, followed by reforestation efforts through movements like Saemaul Undong (New Village Movement), as well as pruning and thinning activities through forest conservation projects. The young Korean forests today are the collective achievement of the people meeting the demands of each era (J. Lee et al., 2014; X. Li et al., 2010; Tak et al., 2007). The challenge we face now is climate change and carbon neutrality. However, most of our citizens do not understand the relationship between this enormous task and our forests.

This study aims to provide an easily understandable summary of the relationship between forests and carbon, and how managing forests can help address the climate crisis. To restore momentum in policy implementation, it aims to make the necessity of sustainable forest management policies understandable to the general public, not just experts. Additionally, it seeks to summarize conflicting opinions on forest carbon management and examine them alongside with scientific assertions and case studies of other countries. In order to contribute to a sustainable forest management system and achieving carbon neutrality by 2050, this study intends to propose forest management policy initiatives in the carbon sequestration field.

To understand Korea's forests and find solutions for forest circular management policies, the following research questions can guide the process:

(1) What is the past and present status of forest and forestry in South Korea (SK)?

(2) Which argument about effect of forest aging is right? How does forest density and structure influence the growth of forest?

(3) What would be the appropriate strategy to have circular management for South Korean forests?

(4) How much Green House Gas (GHG) do SK's forests currently absorb and how is this absorption rate changing in BAU (Business-As-Usual) and To-Be (The envisioned future state after changes and improvements have been made) scenario?

2. Methods

This study focuses on the forests and forestry in SK to improve the capacity of carbon sequestration in national GHG inventory reporting format. For this research, a comprehensive literature search was conducted using databases such as Google scholar, and DBPIA Korea. The key words used for the literature search were carbon dynamics, forest management, carbon sequestration, carbon absorption, forest productivity, forest density, forest age, carbon neutrality, sustainability, Korean forest, forest history, forest industry. The basic statistics are from National Forest Inventory (NFI) and national GHG inventory report of Korea and some other countries. For management methodologies or policy directions of Korea, administrative reports from the Ministry of Environment, KFS, and Korea Meteorological Administration were reviewed. All the literatures and data were used to analyze the reasons of the current problems and to assess the projections of GHG accounting. To synthesize of findings, some weighted literatures are referred several times. Excel was used to calculate the density of chosen species, forest utilization rate under the goal of 2050 carbon neutrality. Carbon and GHG accounting are based on the other studies' results, but some studies without either of carbon or GHG amounts were converted by self-calculations.

Temporal scope covers from the past of 1954 to 2050 or 2080 in the future to see the embedded problems hidden in the status of forests and project the flow of changes in Carbon and GHG. The spatial scope of the research is limited to SK forests, excluding forests in North Korea and other countries. For the forest products, only domestic productions are included. Additionally, substitution effects of forest resources, such as biomass energy instead of fossil fuels, are not studied here because it is only counted as emission when logging and the used amounts for power generating are not reported in the formal form in the GHG inventory report system to avoid double counting.

To better understand the flow of this study and interrelationships, I used the conceptual diagram as shown in figure 10. This diagram illustrates that the motivation for the research is to analyze the reasons behind the loss of momentum in the Korean forests' carbon sink management plan. By analyzing the factors in forests and forestry, unique characteristics specific to SK will be discovered. Among those, key challenges that SK's forests face will be more deeply analyzed to offer scientific evidence for proposed suggestions of forest management. Then, carbon dynamics of forests and GHG inventory system will be studied to make it clear for the relationship between forest management and carbon neutrality. Finally, I will see how the amount of GHG removal in forests' biomass, DOM and HWP sectors in national GHG inventory be changed in BAU scenario and To-Be scenario in 2050.

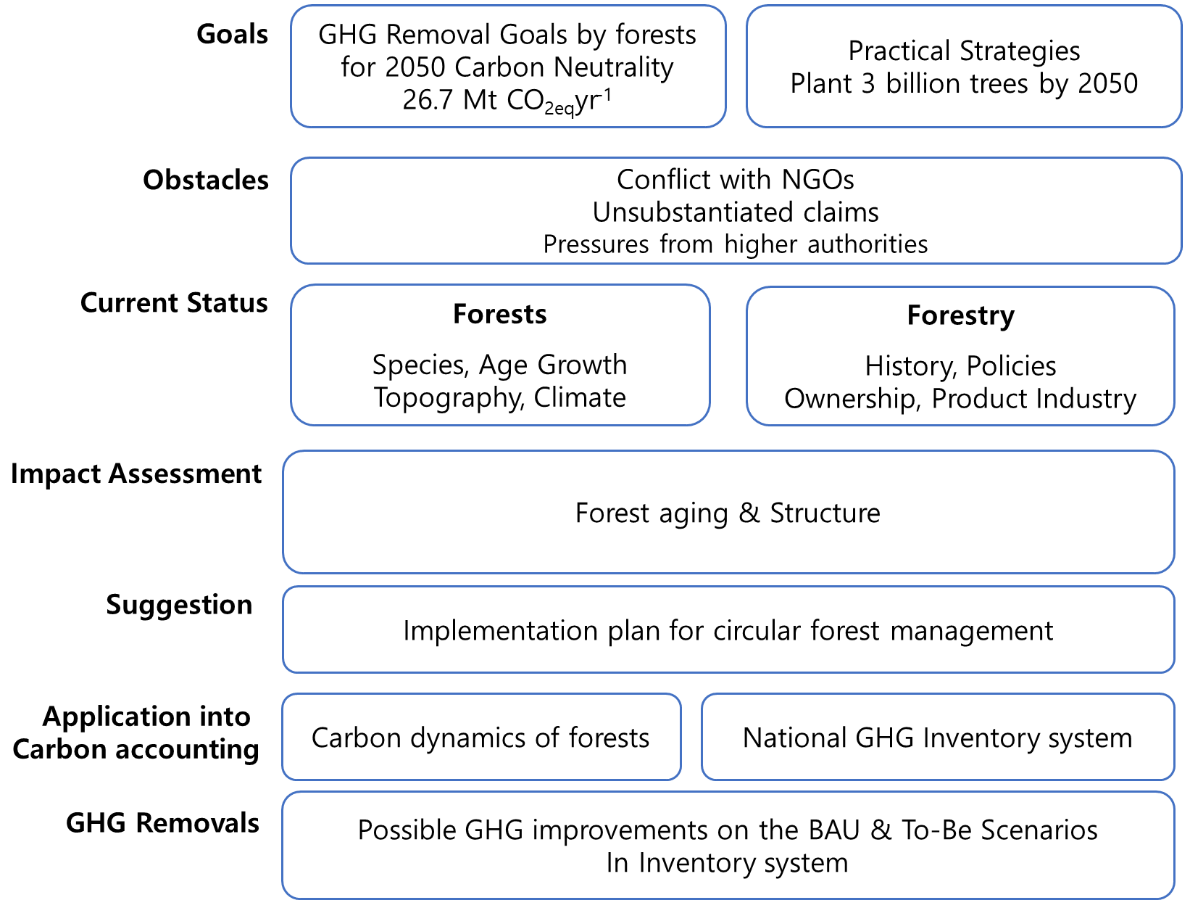

Figure 10. A conceptual diagram of the research components and their sequence, originally created by the author.

2.1. Impact Assessment

Forest-aging

As mentioned earlier in this paper, there are contrasting claims regarding the impact of tree age on annual carbon absorption capacity. Environmental organizations argue that older trees absorb more carbon annually, while KFS present the opposite. Reviewing scientific literatures would give answer for forest carbon neutrality policies.

Carbon sequestration increases in tandem with tree volume growth. Therefore, the annual changes in carbon sequestration align with variations in tree volume growth. The forest sector's stock volume reported in the national greenhouse gas inventory for 2020 is 1,017,508,000 m^3 (Greenhouse Gas Inventory & Research Center, 2022). It is 165 m^3ha^{-1} on average which is higher than Italy (149 m^3ha^{-1}), Sweden (131 m^3ha^{-1}), Finland (109 m^3ha^{-1}), and Turkey (76 m^3ha^{-1}) among 38 OECD countries (FAO, n.d.). The Figure 11 shows that the accumulation of forest stock has been rapid and steady so far, but the growing stock annual increment experienced a significant increase in the early 2000s, reaching its peak growth rate during this period and then the growth rate began to decline from 2010. However, it is important to consider that over 70% of trees in SK forests were planted within 14 years of extensive reforestation projects initiated in 1973 (Forest ICT Research Center & Korea Forestry Promotion Institute, 2021).

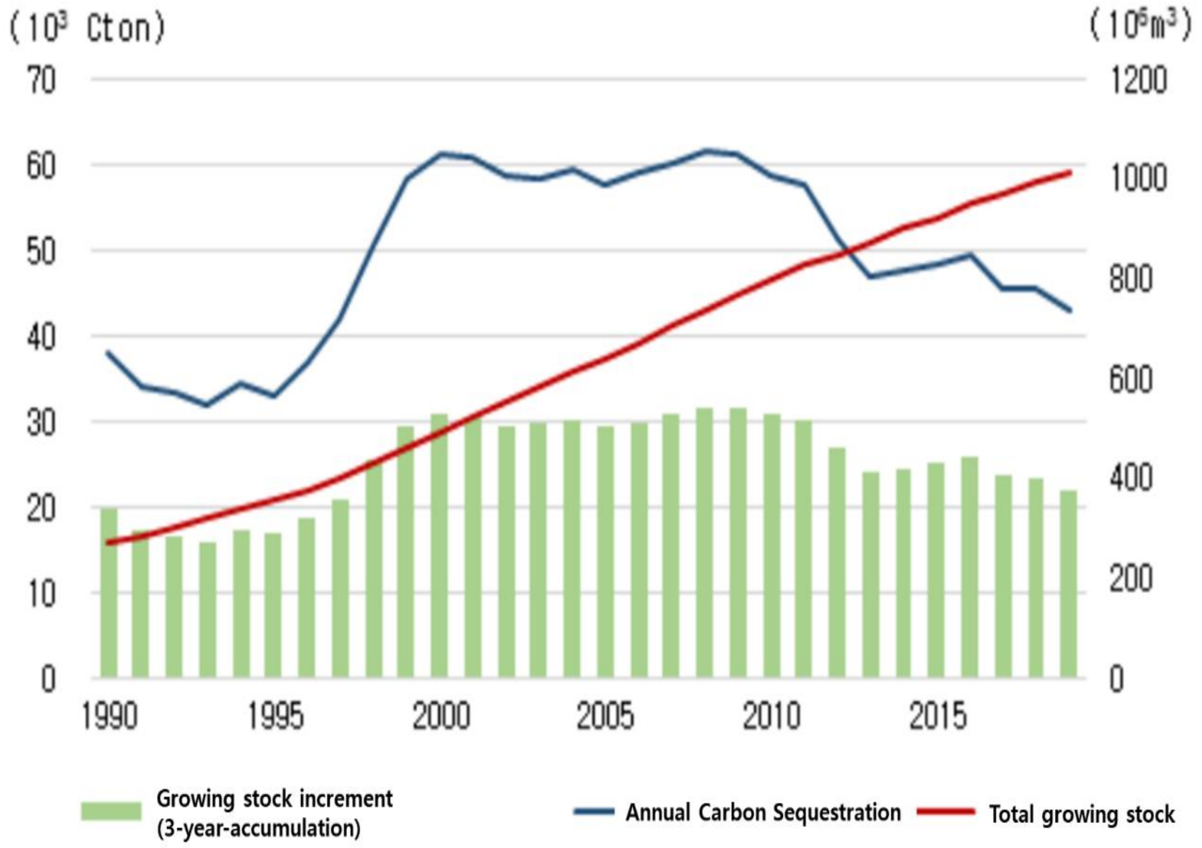

Figure 11. Annual carbon sequestration aligns with growing stock increments. However, they started to decrease from the year of 2009. Originally published by Forest ICT Research Center & Korea Forestry Promotion Institute (2021).

According to analysis by W. Lee et al. (2022), the annual diameter growth of pine and oak trees, based on field measurements from National Forest Survey, generally exhibits an initial phase of over-proportional increase followed by under-proportional growth trends after reaching peak of annual gross production around their age of 20s. As most of SK's Forest trees are between 30s and 40s of their age, their growth rates are expected to decrease over time. SK has already entered a period of declining annual growth rates.

With the opposing position of KFS and support of environmental NGOs, Hong (2022) argued that the forest carbon accumulation survey method used by KFS, which targets only trees with DBH of over 6 cm, excludes the understory vegetation below the canopy layer from the survey. He claimed that this leads to an underestimation of total growing stock of forests. He further attributed significance that active forest management practices, such as harvesting understory vegetation, reduce the actual biological carbon accumulation of forests. As evidence, he pointed a case of Environmental Impact Assessment conducted in a national park protected area. The case report included trees and shrubs with a DBH of over 2cm in the survey, resulting in 2.6 times more forest growing stock than reported by KFS.

To assess which perspective is based on scientific evidence, non-commercial research material is required to calculate the ratio of general forest understory biomass accumulation. In a study from China, which shares similarities with SK both geographically and climatically, Yuan et al., (2016) divided the trees into different DBH classes with a 10-cm interval and surveyed all trees with a diameter at DBH exceeding 1cm within a 25-hectare (500m X 500m) temperate forest plot. Census of trees was conducted, and forest biomass calculated using allometric regression equations. As shown in the table 1, 60% of aboveground biomass of the forest plot is concentrated in the DBH 40cm-70cm range, with the proportion of biomass in the less than 10cm of DBH range amounting to only 0.6%. The results proved that Hong (2022)'s assertion is unscientific.

Table 1. Aboveground biomass stock and ratios in the different diameter classes in old growth forest of Baek-du mountain in China, originally published in the study of Yuan et al. (2016).

Diameter class (cm)	Abundance		Mean diameter (cm)		AGB stock (Mg ha^{-1})	Biomass (% total)	Cumulative biomass (%)
	2004	2014	2004	2014			
1–10	48,161	48,092	2.54	2.70	1.59	0.6	0.6
10–20	3925	3709	14.46	14.33	7.17	2.7	3.3
20–30	2110	1922	24.76	24.78	17.39	6.5	9.7
30–40	1572	1455	35.05	35.04	29.23	10.9	20.6
40–50	1348	1308	44.89	45.01	49.25	18.3	38.9
50–60	968	990	54.61	54.78	63.20	23.5	62.3
60–70	437	507	64.55	64.53	49.51	18.4	80.7
70–80	174	219	74.36	74.19	28.16	10.5	91.2
80–90	49	64	84.81	84.36	11.34	4.2	95.4
90–100	18	21	94.13	94.49	4.07	1.5	96.9
100–120	14	11	109.96	110.43	3.65	1.4	98.3
>120	12	14	136.28	139.11	4.69	1.7	100.0
Total	58,788	58,312	740.4	743.75	269.3	100%	

Moreover, excluding trees below certain thresholds for the purpose of forest biomass calculation is not unique to SK. Table 2. below summarizes the restrictions on calculating forest biomass in National Forest Inventories by country (Swedish Ministry for the Environment, 2019; Vidal et al., 2016).

Table 2. Austria, Bosnia and Herzegovina, Czech Republic, Slovakia, and Sweden have DBH threshold for their National Forest Inventories, similar with SK. The table is remade by the author using the information based on Vidal et al. (2016) and Swedish Ministry for the Environment (2019).

Country	DBH Threshold for Assessment	Sampling Method	Plot Radius (m)
Austria	> 20.4 cm	Specific dbh threshold	Not specified
Bosnia and Herzegovina	≥ 5 cm	Specific dbh threshold	Not specified
Czech Republic	> 7 cm	Specific dbh threshold	5 m and 12.62 m
Denmark	Proportional to size	Random selection	Not specified
Estonia	Every 3rd tree	Systematic selection	Not specified
Slovakia	7-12 cm, > 12 cm	Different thresholds for ranges	3 m and 12.62 m
Sweden	≥ 10cm	Specific dbh threshold	Not specified

Hong (2022) also argued against KFS's long-term prediction about forest aging effect on growing stock by citing studies from (Pregitzer & Euskirchen, 2004) and Lewis et al. (2019). According to his assertion, annual carbon sequestration typically increases gradually from 30 to 80 years and then accelerates in older temperate forests after 80 years of tree age, but KFS can have only up to 60 years of observational data about SK's forests. Therefore, KFS's approach is scientifically unsound.

However, I could find no such acceleration of annual growth in old forests. Instead, Pregitzer & Euskirchen (2004) explained that Net Ecosystem Productivity (NEP) in temperate forests is higher in intermediate age forests as shown in the table 3.

Table 3. Annual NEP values per age classes. Mean NEP in temperate forests is highest in the age range of 11-30. The table is made by the author using the data from Pregitzer & Euskirchen (2004).

Age Class	0 - 10	11 - 30	31-70	71-120	121-200
Net Ecosystem Productivity (NEP) (Mg C ha-1yr-1)	-1.9	4.5	2.4	1.9	1.7

Another research indicates that the age–class structure of a forest significantly impacts its carbon sequestration dynamics. Younger forests, characterized by a left-shifted age–class structure, tend to exhibit higher productivity and carbon uptake. This is supported by model experiments demonstrating that landscapes with younger age–class structures gain more carbon annually compared to those with older age–class structures. Specifically, younger forests accumulate biomass carbon more rapidly due to their enhanced growth rates and higher photosynthetic activity. Conversely, older forests, which have a right-shifted age–class structure, tend to lose carbon or maintain a neutral balance as their growth rates decline. Therefore, effective forest management strategies should prioritize maintaining a balanced age–class distribution to optimize carbon sequestration and enhance the forest's overall carbon sink capacity (Böttcher et al., 2008).

The study of Colombo et al. (2012) also explored the impact of forest age structure on carbon sequestration under various management scenarios. It found that forest protection resulted in the greatest carbon stocks in the near term, reaching 95% of its maximum within 30 years. However, protected forests largely lacked younger age classes, which are crucial for sustained carbon uptake. Harvesting at higher and historical average rates resulted in less carbon stock initially compared to the protected forest, but after 100 years, the total carbon storage in regenerating forests and wood products was equivalent to or greater than that of protected forest. As younger forests tend to sequester carbon more efficiently than older forests, age-class distribution is important to enhance carbon storage capacity.

A study on China's planted forests demonstrated that age-related growth is the largest contributor to biomass carbon increments, significantly outweighing the impacts of climatic factors. From 2010 to 2050, age-related growth accounted for 1.23 Pg C, whereas climatic factors only 0.087 Pg C. The findings emphasize that younger forests, due to their rapid growth phases, are more effective in sequestering carbon annually compared to older forests. Therefore, maintaining a balanced age structure with a higher proportion of younger trees is essential for optimizing carbon sequestration and enhancing the overall carbon sink capacity of forests

However, the study of Lewis et al., (2019), another basis for Hong (2022) to refute KFS, suggested that while natural forests continuously store carbon, managed forests periodically release carbon. Therefore, to stem climate warming, it is advantageous to leave forests as natural ones rather than managed ones. Although it is agreeable assertion about carbon storage, Lewis et al., (2019) did not discuss about annual carbon absorption of forests by silviculture. There is no relevant information to support that managed forests have inferior carbon absorption capabilities on annual basis compared to natural forests.

Amidst the heated debate over forest management methodologies for achieving carbon neutrality, which included commercial and unscientific arguments, scientific evidences consistently supported the efficacy of younger forests in sequestering carbon more efficiently. The impact of forest age structure on carbon sequestration underscores the importance of maintaining a balanced age-class distribution. Younger forests, due to their rapid growth rates and higher photosynthetic activity, sequester more carbon annually compared to older forests. Effective forest management should prioritize having a substantial proportion of younger trees to optimize carbon storage and enhance the forest's overall carbon sink capacity. A strategic approach that includes both young and mature trees is essential for achieving long-term carbon sequestration goals and mitigating climate change.

Forest Structures: Density & Crown Closure

Another factor to consider in SK's forests is the general factor that the volume growth of trees is directly associated with forest density (Ali, 2019; Cao et al., 2021; Franklin et al., 2009; Jandl et al., 2007). To assess the level of competition in forests, Reineke (1933) provided Stand Density Index (SDI) as a measure of the size-density relationship for even-aged forests (Chivhenge et al., 2024). The equations to show forest Density (Long', 1985) showed below.

$SDI = tpha \times (DBHq/25)^{1.6}$ (Long', 1985)

$\max SDI = 1{,}041 \times (25/25)^{1.6}$ (D. Lee & Choi, 2019)

$RD = SDI/\max SDI$ (Shaw & Long, 2007)

SDI : Stand Density Index

tpha : observed trees ha^{-1}

DBHq : diameter(cm) of trees of average basal area

Max SDI : maximum Stand Density Index

RD : Relative Density

Reineke (1933)'s SDI measures the degree of crowding within stocked areas for same species and ages. To make it simple to understand, I choose pine trees (*pinus densiflora*) as a representative example of Korean forest situations because *pinus densiflora* is the dominant species in SK. In the study of S.-T. Lee et al., (2021), he analyzed the mean DBH (23.9 cm) and tpha (1309 stems) of this pine trees in SK using 2016-2017 survey data in Korean National Forest Inventory (NFI). Basal area for this is 58.81 m^2ha^{-1} so that DBHq becomes the same value of 23.9cm as mean DBH in this case. Therefore, the SDI value for average *pinus densiflora* forests is 1,218. However, we should compare to max SDI, which is developed under the regional and ecological condition of the species. According to D. Lee & Choi (2019), the DBHq of 25cm has maximum stem number of 1041 for this pine species in Korea. maxSDI is 1041, thus RD of *pinus densiflora* forest becomes 1.17.

When RD is ≥ 0.6, self-thinning and density related mortality should begin (Long', 1985; Shaw & Long, 2007). And the study about maximum stand density for Korean pines applied RD $\geq$0.7 needs further management(D. Lee & Choi, 2019, 2020). Therefore, one can see that the pine tree forests in SK is over-crowded.

This is the problem not only for tree mortality rates, but also for the volume growth of the trees slowed down (Cao et al., 2021; Chivhenge et al., 2024; Franklin et al., 2009; Q. Li et al., 2022). In the study of Ryan et al., (1997), photosynthesis and dry-matter production decline as the forest reaches a maximum leaf area. In the 5^{th} NFI of Korea (2006-2010) by Korea Forest Research Institute (2011), almost half of the forest area already rank the highest crown closure level (76%-100%). Considering there was no large increase of forest managing activity since then, the forest cover density might have increased further as of present. In other words, half of carbon absorption capacity in SK forests is limited by forest density (An et al., 2019a; Ryu et al., 2016).

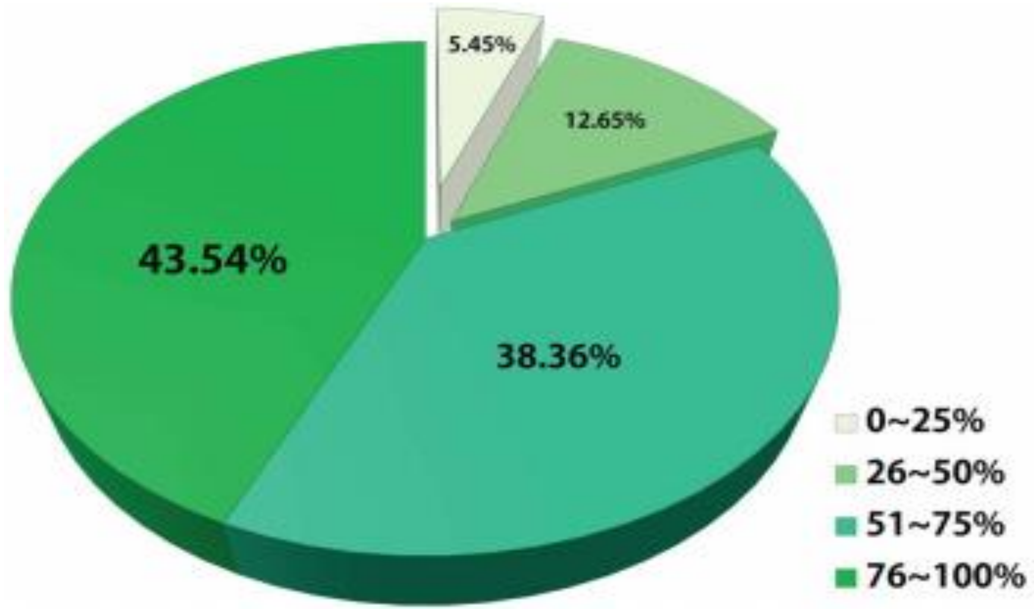

Figure 12. Crown closure was measured between 2006 to 2010. The largest pie of 43.54% corresponds to the highest crown closure percentage. The graph is originally published by Korea Forest Research Institute (2011).

Based on these meta-analyses, the claim made by KFS regarding the impact of tree age on carbon sequestration was substantiated with scientific evidences. In fact, annual forest carbon sequestration peaked around 2009 at approximately 60-million-ton $CO_{2eq}yr^{-1}$ and has since decreased to about 40-million-ton $CO_{2eq}yr^{-1}$ in 2020. KFS anticipated that this figure will further decrease to 15-million-ton $CO_{2eq}yr^{-1}$ by 2050.

2.2. Strategic forest carbon management: Balancing age structure for sustainable carbon sequestration

In the study of Braga et al. (2024), research findings indicate a significant correlation between human activities' intensity and fluctuations in carbon stocks. They reconstructed carbon stock dynamics over a forty-year period (1980–2022), revealing variations in carbon storage capacities associated with site-specific structural characteristics. The site with low intensity of silvicultural interventions exhibited the highest carbon stock across all carbon pools (378 tones C ha−1), more than double compared to the site without silvicultural interventions (134 tones C ha−1). This study highlights forest ecosystems' resilience to regenerate and maintain carbon sequestration capacities following harvesting, provided there is no alteration in forest land use.

In the same perspective, it is essential to improve the age structure by proper anthropogenic interventions to secure a sustainable carbon sink in forests (Böttcher et al., 2008; Colombo et al., 2012; Gonçalves, 2022; Gower et al., 1995; Ryan et al., 1997; Yu et al., 2021). Subsequently, if thinning to reduce the density of overstocked mature forests, along with using thicker trees for commercial use and replanting in their places to balance the age structure like in the figure 13 (Bae, 2009; Y.-H. Kim, 2016; W. Lee et al., 2022), the annual carbon sequestration transitions to an increasing trend after 2040, with a projected recovery of 2020 levels of growth by 2065 as shown in figure 14 (Y. Kim et al., 2022).

To apply these findings to the context of South Korea, KFS plans to use 41% of forest land area for replantation over the next 60 years until 2080, as shown in Figure 13 by Y. Kim et al. (2022). Using the 2020 forest land area statistics (6,298,134 hectares), I calculated the annual average harvested area. The 41% of forests will be divided by 60 years so that the annual ratio of harvest becomes 0.68%. This is equivalent to 42,827 hectares per year.

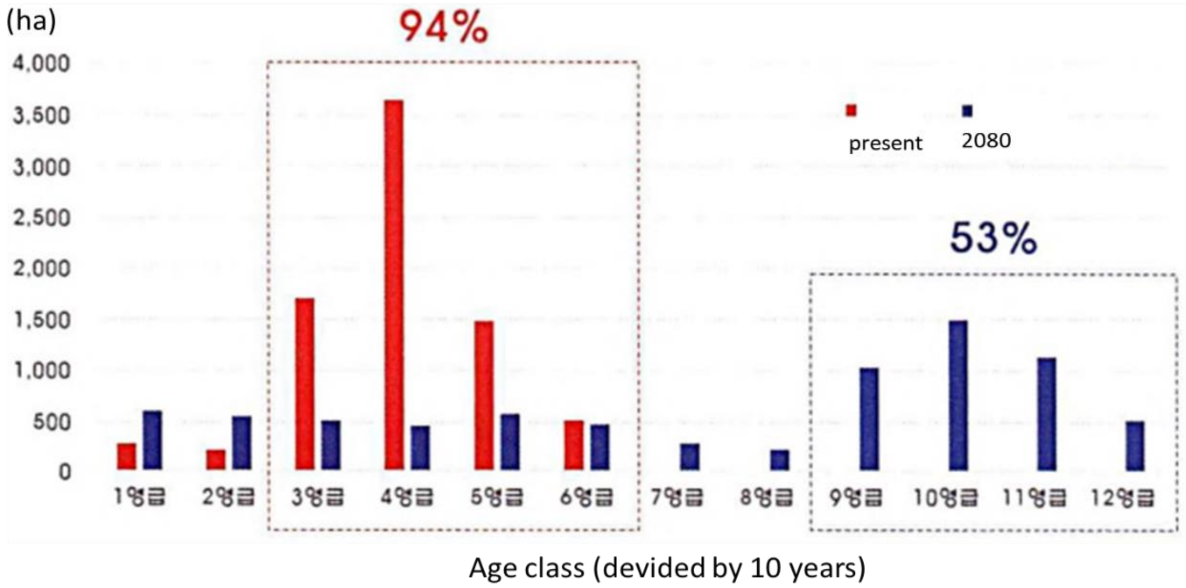

Figure 13. Age structure changed to more balanced ones in 2080 (blue bars) than now (red bars), if we implement forest carbon management policies. Originally published by Y. Kim et al. (2022).

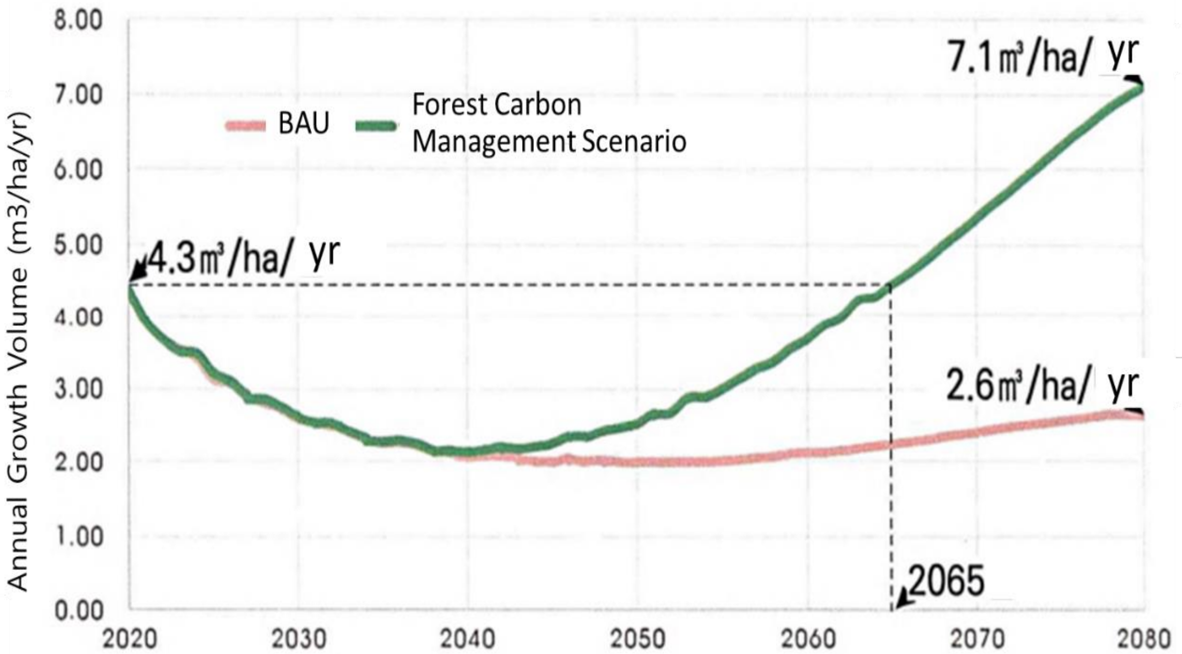

Figure 14. In the forest carbon management scenario, the annual growth volume will be recovered to the level of 2020 in 2065 and increase further in the future. Originally published by Y. Kim et al. (2022).

To get the value of forest use ratio on the Y. Kim et al. (2022)'s age restructuring plan, I assumed that the harvest targets are the large trees as the age class of 6 (50- to 59-year-old). In this way, the annual growing stock to be harvested is expected to remain close to the average over the next 60 years (2020-2080) as shown in the table 4. However, the practical reason for using the growing stock of the 6th age class (237.3 m^3ha^{-1}) is that it represents the maximum growing stock currently observable (Forest ICT Research Center & Korea Forestry Promotion Institute, 2021).

Table 4. The expected annual growing stock per hectare to be harvested, based on the data from Forest ICT Research Center & Korea Forestry Promotion Institute (2021).

2021-2040	2041-2060	2061-2080
< 237 $m^3ha^{-1}yr^{-1}$	≈ 237 $m^3ha^{-1} yr^{-1}$	> 237 $m^3ha^{-1} yr^{-1}$

Before calculating the total growing stock to be harvested on the annual average, I should set some more assumptions like in the table 5. It descripts context and clarification for the assumptions and factors, ensuring that the methodology for estimating the annual growing stock is clear and based on realistic forest management practices under the conditions that forest ecosystem resilience to be maintained and harvesting actions do not cause landslides or water pollution.

Table 5. Factors and assumptions to estimate annual growing stock. These conditions are made by the author to minimize the environmental impacts on forests by harvesting of woods, based on the realistic forest management practices and topographical conditions.

Factors	Assumptions and background
Growing stock ha^{-1}	1. 20- to 59-year-old trees in 2020 will be harvested during 2021 to 2080. Therefore, they will get older 80- to 119-year-old in 2080, being taken by gradual manner. 2. Mature trees will be harvested first. 3. The largest observable growing stock (237.3 m^3ha^{-1}) per age class is 6^{th} class (50- to 59-year-old) in 2020 will be used. Owing to lack of larger stock data, the 6^{th} class growing stock be used in the calculation.
Restructuring area yr^{-1}	1. The size of harvested area will be different on the conditions of forests and weathers. But the average area is 42,827 hectares per year. 2. There will be no large-scale clear-cutting. Harvest method will be selective cutting or small area cutting. Since 83% of Korean forests are in the steep slope with ≥20°slide, there is almost no clear-cutting practices to prevent land slide.

	3. High areas in mountain are hardly approachable and mostly conservation forests so that the work will be practiced in low area. 4. Most works will be done in the privately owned forest. Because private owners have 66% of forest areas where are relatively closer to roads and towns. National and municipal forests mostly act as conservation and recreation.

Under these assumptions, I calculated the harvested growing stock in total per year is as follows.

An estimation of maximum growing stock to be harvested from 2021 to 2080:

(a) 237.3 m^3ha^{-1} x (b) 42,827 ha yr^{-1} = (c) 10,162,847m^3yr^{-1}

(a) Average growing stock ha^{-1} to be harvested from 2021 to 2080

(b) Restructuring area yr^{-1} according to KFS Plan in the given years

(c) Estimated annual growing stock to be harvested in the given years

If we compare to total forest growing stock in 2020 (1,040,477,000 m^3), the use ratio accounts for 0.96%. However, we know the total growing stock of forests will increase each year until the year 2080, the projected forest utilization rate will get lower than 0.96% in the future. When thinking of the OECD data that the forest utilization rates for Germany and Sweden range about 0.9 (OECD, 2019) and they sustainably maintain annual increments in forest accumulation while ensuring consistent carbon sequestration levels (Böttcher et al., 2008; Ministry of the Environment Sweden, 2019), the forest utilization rate of 0.96% and lower is aligned with global standards and ensures that Korea's forests can continue to accumulate biomass and sequester carbon efficiently. By implementing selective cutting and avoiding large-scale clear-cutting, the plan also addresses ecological concerns such as preventing landslides and water pollution. The annual harvest projection reaffirms that well-managed forests, with a balanced age structure, not only enhance carbon sequestration but also preserve the ecological integrity of the forests, countering concerns about potential forest destruction.

2.3. Carbon absorption of forests in SK

General patterns of carbon dynamics

Since the initiation of the afforestation program in 1973, there has been a significant increase in stock volume of forest, which has been proportionally associated with an increase in carbon storage in biomass, as evidenced by numerous studies (A. Lee et al., 2009; J. Lee et al., 2014; X. Li et al., 2010). This increase encompasses carbon stock changes in deadwood, litter layer, and soil.

According to J. Lee et al. (2014) in figure 15 (a) based on analyzing the data of the 5th National Forest Inventory, Carbon stock in Biomass increased from 36.4 Tg in 1954 to 440.4 Tg in 2012. While carbon stock in Dead Organic Matter (DOM), which includes soil organic matter, dead woods, and litter, also increased from 386 Tg to 463 Tg during the same period. Dividing these for annual average growth of carbon, biomass increased by 7.0 Tg yr^{-1}, while DOM increased by 1.3 Tg yr^{-1}, indicating that DOM's annual carbon increase accounts for approximately 16% of the total increase. However, when examined on a yearly basis, the patterns of change in biomass and DOM exhibit different forms. In 1954, biomass was at a level that was only one-tenth of DOM, but by 2012, this ratio has almost equalized to 0.95:1.

(a) (b)

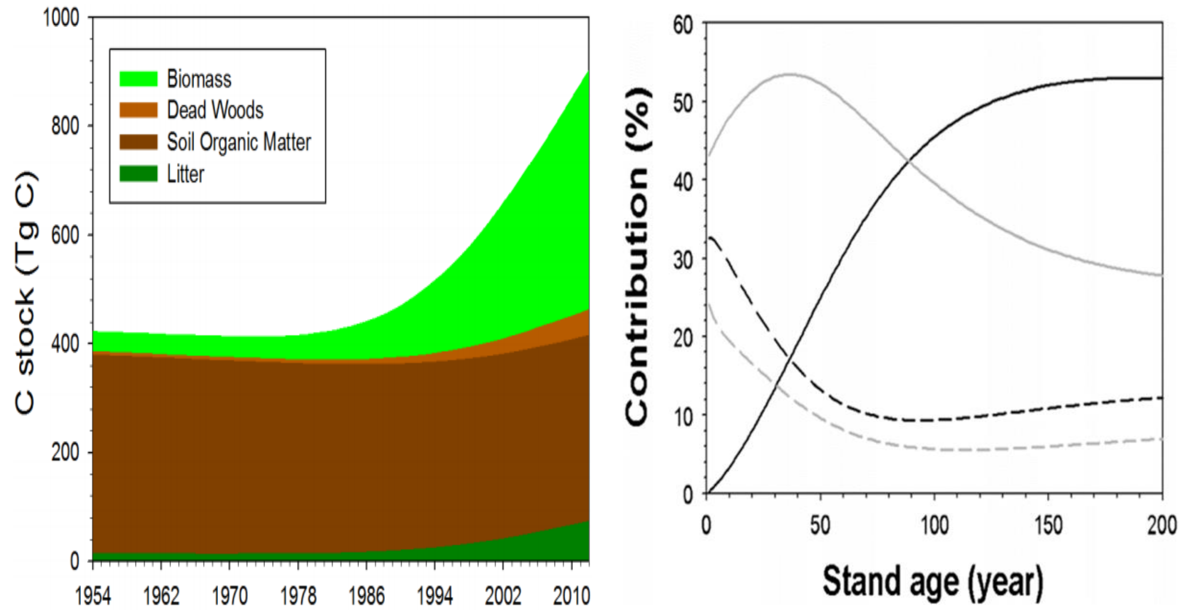

Figure 15. (a) Carbon dynamics of SK's Forest after Korean war indicates total carbon stocks were increased during the simulation period. Originally published by J. Lee et al. (2014). (b) Changes in carbon stock proportions by stand age of Scots pine forest in Turkey. Solid black line: biomass, Dashed black line: dead wood, Solid gray line: soil, Dashed gray line: litter. Originally published by J. Lee et al. (2016).

Until recent years, both biomass and DOM of forests have served as carbon absorbers. However, as it is observed in Turkish forest study of J. Lee et al. (2016) from figure 15 (b), the rate of increase in soil organic carbon will decrease soon and a period of soil carbon stabilization will come. From this point, biomass is expected to be the primary source of carbon sequestration in forests.

However, just as the stabilization period for DOM arrives, the increase in carbon stock by biomass cannot be sustained in the same rate. In temperate forests, tree growth rate is typically fast in the early stage and then begins to decelerate as the trees reach their 30s to 40s of age range (Lal & Lorenz, 2012). The large-scale afforestation efforts in Korea during the 1970s and 1980s have now entered this phase of reduced growth. This deceleration in growth rate is also reflected in the changes of annual carbon absorption during the recent 10 years (2010-2020) in the national greenhouse gas inventory. As shown in figure 16, carbon absorption of recent years in SK's forest land sector has been declining after experiencing the most active period from 1999 to 2009 (Greenhouse Gas Inventory & Research Center, 2022).

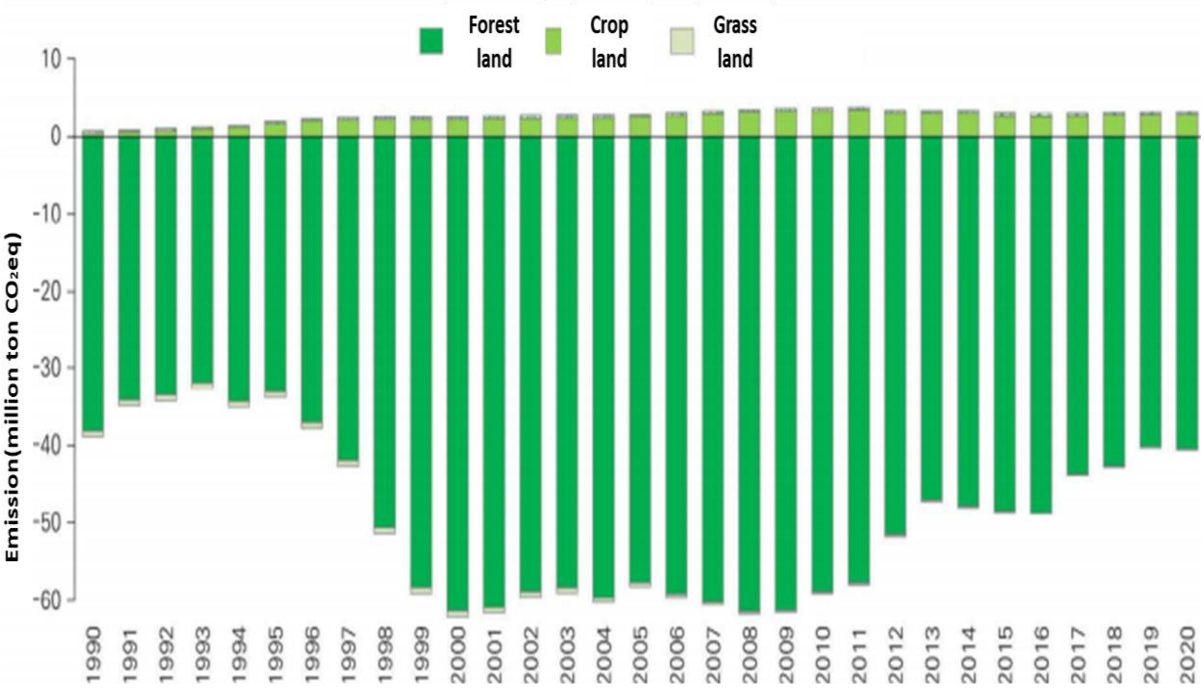

Figure 16. Emissions and removals by sector in the Land Use, and Land Use Change in Forests. The amount of negative CO_2 Emission peaked between the years of 1999 to 2009 with about minus 60-million-ton $CO_{2eq}yr^{-1}$ and it starts to show the gradual diminish to 2020 in carbon removal amounts. Originally published by Greenhouse Gas Inventory & Research (2022).

Carbon removal contribution factors according to 2006 IPCC Guideline

The Paris Agreement establishes a long-term goal and encourages parties to United Nations Framework Convention on Climate Change (UNFCCC) to include their best achievable targets in their NDCs. The implementation status of NDC is shared through national GHG inventory reports. Specific details of the reports, such as scope, standard and quantification of emissions and removals of greenhouse gas, are to follow the 2006 IPCC guideline (United Nations, 2015). Calculating and reporting the carbon sequestration capacity of forest land must adhere to this IPCC guideline, and it is a crucial consideration in formulating policies for offsetting GHG emissions to achieve SK's 2030 NDC and 2050 Carbon Neutrality target.

Volume 4 of IPCC guideline provides guidance for preparing annual GHG inventories in the Agriculture, Forestry and Other Land Use (AFOLU) Sector. SK applies Tier 2-level national-specific coefficients to calculate the carbon stock of biomass and harvested wood products (HWP), while reporting no change for DOM using Tier 1-level using default methods and global common coefficients. Forest areas in the land use category should be the areas which have been forest for at least the past 20 years (IPCC, 2006). In other words, there should be a consistent, comparable, and reliable data built over at least 20 years.

The data for biomass is based on the Forestry Statistics Yearbook, which has been surveyed since 1990, however the calculation of carbon in DOM has been surveyed since the 5th Forest Resource Survey in 2006, so it will be possible to apply national-specific coefficients of DOM once the data has been established for over 20 years. This implies that a carbon-neutrality implementations, internationally recognized, could experience discrepancies between actual forest carbon flows and those accounted for if scientific and administrative preparations are inadequate.

Looking at the estimation of carbon stock change of SK forest until 2050, as follows in figure 17, it is beneficial to have inventory report of DOM. Soil carbon stock, which had been declining at a slow pace during the 1970s and 1980s when reforestation efforts were just beginning, began to slowly recover after the 1990s and it is expected that this recovery will continue steadily over the next 30 years. This increasing trend is more obvious for the carbon stock of deadwood which changes alongside with biomass (Son et al., 2017).

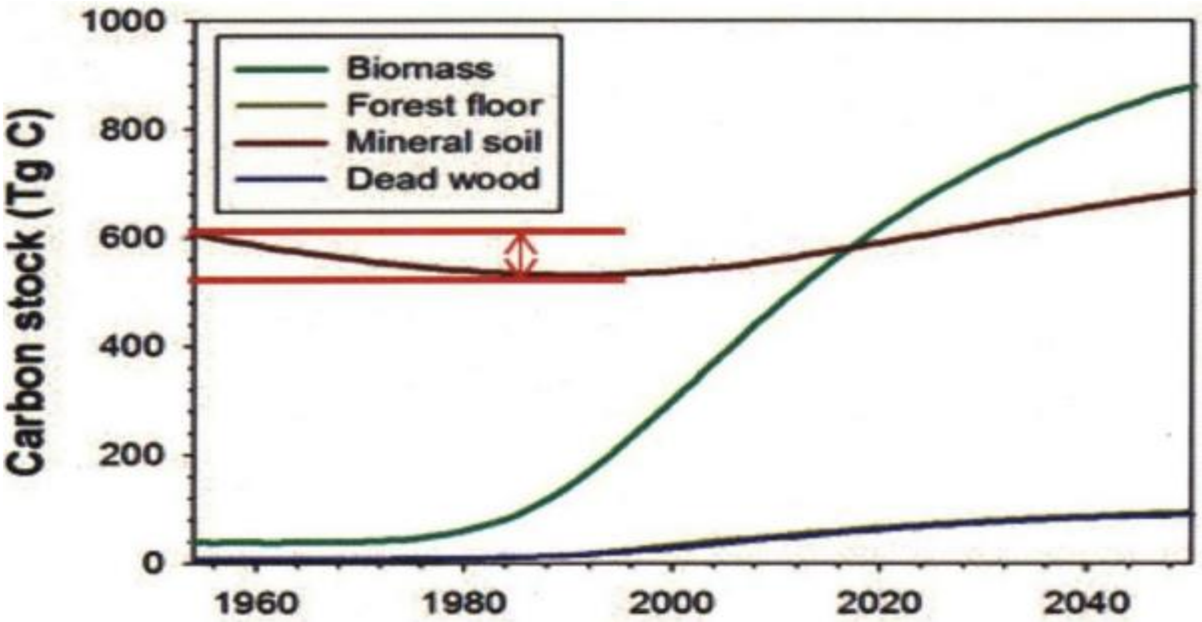

Figure 17. Carbon stock increases are estimated for Mineral soil, Dead wood, and Biomass in the future 30 years. Originally published by Son et al. (2017).

When comparing the average of annual growth in carbon stock between biomass and DOM, as shown in Table 6, the importance of DOM inclusion is more prominent in the coming years. Because the annual increases of biomass carbon stock will get slowed down with aging of forests while the effects of aging will be less on DOM.

Table 6. DOM contribution to carbon sequestration in forests were less in the past years (1954 to 2012). However, it is predictable that its annual average carbon uptake contribution will increase significantly, accounting for up to 35% of the total every year between the year 2015 to 2050.

Year	Biomass	DOM	source
1954 (a)	36.4 Tg	386 Tg	(J. Lee et al., 2014)
2012 (b)	440.4 Tg	463 Tg	

Average of annual C growth (b-a)/duration of years	7 $Tgyr^{-1}$	1.3 $Tgyr^{-1}$	
Ratio in Total annual growth	84%	16%	
2015 (c)	552 Tg	688 Tg	
2050 (d)	880 Tg	869 Tg	
Average of annual C growth (d-c)/duration of years	9.4 $Tgyr^{-1}$	5.2 $Tgyr^{-1}$	(Son et al., 2017)
Ratio in Total annual growth	65%	35%	

Although the reported removal amount of $CO_{2eq}yr^{-1}$ is very small as 0.5-million ton in 2020 (Greenhouse Gas Inventory & Research Center, 2022), HWP is the sector with the greatest expansion potential. In the AFOLU sector of 2020 GHG inventory report of SK, HWP is the second source of GHG removal and entirely associated with forest activities. According to the IPCC Guideline, carbon stored in trees is released through logging and then reabsorbed through the production of wood products. The calculation of HWP in SK follows production approach, which calculates the carbon storage of wood products produced domestically. Wood products imported from foreign countries are excluded. This approach is highly disadvantageous for importing countries of timber and wood products but is in line with efforts to activate regional carbon cycling system (Sato & Nojiri, 2019). There is another limiting factor to count HWP as removal source. If land-use change, such as deforestation, occurred in the production site of wood, the logged trees are immediately treated as oxidation and not included in the HWP carbon accounts. Therefore, the production should be within the area of managed forests (IPCC, 2019). Knowing this basic premise that HWP sector only counts 'wood produced from domestic forests with no conversion of land use' helps alleviate environmental conservation concerns about other countries forest destruction and pretext for domestic forest land conversion.

However, in 2022, Korea's total wood utilization was about 30-million m^3 with 25.7-million m^3 imported as logs or wood products. Figure 18 illustrates the scale and domestic material utilization ratios of eight major wood product categories which have over 1-million m^3 yr^{-1} (based on industrial purchases). The No 1. amount of usage, pulp, relies entirely on import with particle board and plywood doing the same. Wood pellets, which is experiencing rapid growth alongside with the expansion of biomass power generation, has low domestic material utilization ratio of 12.5%. Sawn wood has the longest half-life of 35 years among all product types but only 12.2% are produced domestically. Only fiberboard and wood chips have relatively high ratios of 87% and 44.2% respectively (Korea Forest Service, 2023b).

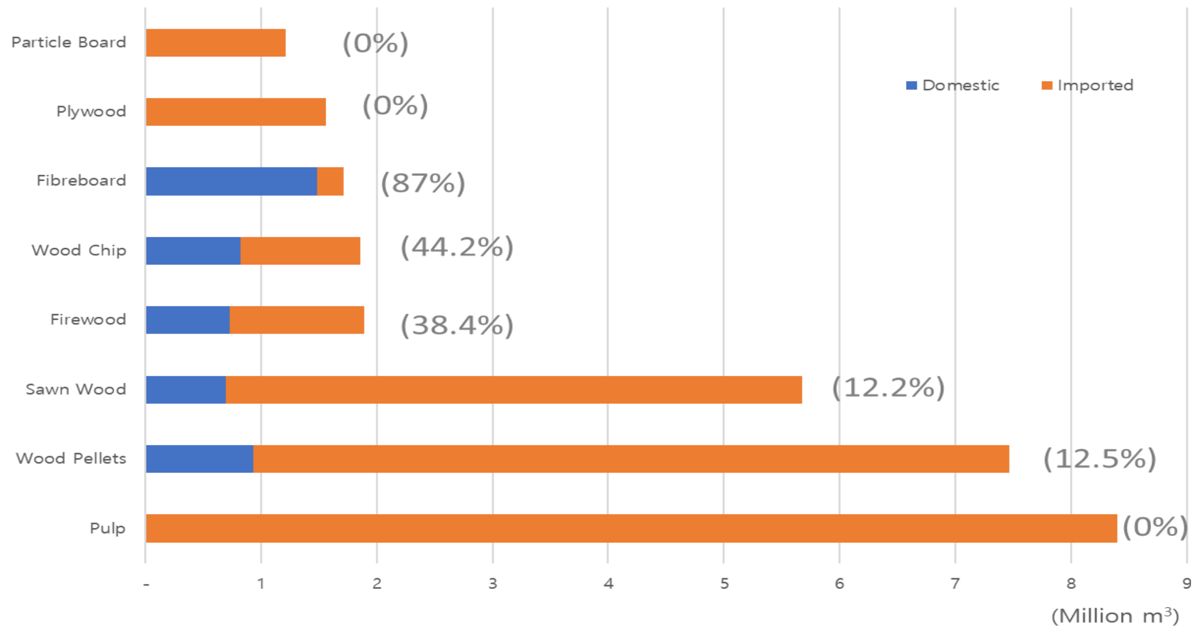

Figure 18. The bar graphs indicate the amount of usage per wood products of SK in 2022 while blue bar and the percentage values in parentheses shows the domestic ratio in total. The graph is made by the author using the data from Korea Forest Service (2023b).

To enhance HWP's carbon storage capacity, production volume, carbon conversion factor, and decay rate of wood products are the keys. Wood products that utilize domestically sourced wood with higher carbon conversion and longer use periods can sequester more carbon in the longer term, referring to the default conversion factors for HWP in table 7 (IPCC, 2019; IPCC, 2006).

Table 7. Default conversion factors for HWP. The table is made by the author, using the data from IPCC (2019) and IPCC (2006).

Factors	Sawn Wood	Wood-based Panels	Paper
Density (Mg/m^3)	0.458	0.595	0.9 (Mg/Mg)
Carbon Fraction (Mg C/Mg)	0.5	0.454	-
Carbon Conversion Factor ($Mg\ C/m^3$)	0.229	0.269	0.386
Half-life (yr)	35	25	2
Decay Constant (k)	0.02	0.03	0.35

Chang et al. (2022) estimated that annual carbon stock change in total HWP will decrease from 0.7-million-ton $CO_{2eq}yr^{-1}$ in 2020 to 0.6-million-ton $CO_{2eq}yr^{-1}$ in 2050, if Business-As-Usual (BAU) of 4.9 million m^3 domestic woods are produced every year. If the production volume of wood products remains unchanged, the carbon previously stored in wood products would reach the end of its lifespan and be released back into the atmosphere, resulting in a decrease in annual carbon sequestration.

In To-Be scenario, Chang et al. (2022) set gradual increase of production volume in wood products to 8-million m^3 by 2050, while expanding the use of structural sawn wood to 1.26-million m^3 and reducing the input of domestic timber for paper and other products by 25% as usual. As a result, the annual carbon stock change in HWP is projected to reach 2.14-million-ton $CO_{2eq}yr^{-1}$ in 2050. This represents 3.5-fold increase compared to the BAU scenario as shown in figure 19 (a) and 19 (b). This suggests that focusing the increased volume of domestically sourced timber harvest on the production of long-lived wood products would be more beneficial for achieving carbon neutrality, compared to utilizing the timber for short-lived products with low production as BAU.

(a) BAU Scenario (b) To-Be Scenario

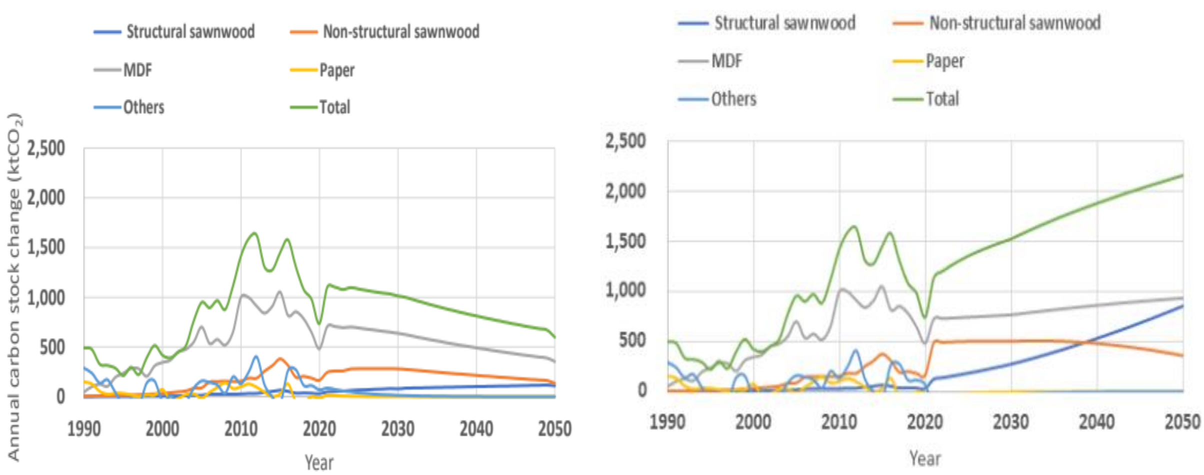

Figure 19. (a) Changes in carbon accumulation in HWP shows slow decrease with the BAU of domestic wood production volume. Originally published by Chang et al. (2022). (b) The annual accumulation increases with the larger usage of sawn wood. Originally published by Chang et al. (2022).

The IPCC (2006) includes not only the carbon storage in biomass but also all processes in the forest ecosystem cycle in its carbon accounting. More comprehensive approach ensures sustained carbon sequestration for SK by balancing biomass growth, DOM contributions, and HWP carbon storages.

4. Results

Before addressing the research questions in detail, it is important to synthesize and contextualize the findings of this study. One key aspect that emerged from the analysis is the identification of limiting factors affecting tree volume growth in South Korea's forests. Understanding these factors is crucial for developing effective forest management strategies that can enhance carbon sequestration and support sustainable forestry practices. The table 8 summarizes the main limiting factors identified in this study.

Table 8. Limiting factors to the tree volume growth

Factor	Main reasons
Forest-aging	Productivity peaks in the age around 20s in temperate forests. 75% of SK forest trees belong to 30 to 49 of age range as of 2020.
Density	$RD_{pinus\ densiflora}$ =1.17 The most dominant species in SK showed over-population than proper RD level (< 0.7).
Crown-closure	Measurements during 2006 to 2010 showed 44% of forests in the highest level of crown closure (76% - 100%).

These limiting factors highlight the challenges that SK's forests face in terms of maintaining and enhancing their productivity and carbon sequestration potential. Addressing issues related to forest aging, species density, and crown closure through restructuring the age structure can help mitigate these challenges and improve forest health and resilience.

The proposed restructuring plan includes using 41% of the total forest land area for replantation over the next 60 years until 2080. This involves an average annual restructuring of 42,827 hectares, focusing on the harvest of trees in the 50-59 age class with a growing stock of 237.3 m^3/ha, the maximum currently observable. The forest utilization rate under this plan is projected to be 0.96%, aligning with global standards observed in countries like Germany and Sweden. This strategic approach ensures that Korea's forests can continue to accumulate biomass while annual biomass growth also be ensured.

To integrate this circular management policy into carbon perspective, general carbon dynamics and carbon accounting methodologies of SK were studied. The carbon absorption capacity in the national GHG inventory report can change according to the management practices as well as reporting methodologies. Different reporting methodologies, such as the inclusion or exclusion of specific carbon pools like DOM, and the application of Tier 1 versus Tier 2 level national-specific coefficients, can significantly affect the reported carbon sequestration values. Improving domestic production of timer for long-lived wood products will contribute to the national carbon accounting while protect the forests of other countries.

To simply compare the overall flow of carbon absorption capacity, table 9 utilizes the estimated annual carbon increment from the DOM section by Son et al. (2017). The carbon amount is converted to CO_2 using the ratio of 12:44. Additionally, the amount of GHG removal by biomass in 2015 from National GHG inventory and the results predicted by KFS before and after forest structure improvement in this thesis paper are introduced. The table 9 illustrates how the annual GHG removal by forests and forestry can be changed by the suggested means of improvement.

Table 9. To improve the future GHG removal by forests, systematic preparation and changes in forest managements are needed. 1) 2015 value (Greenhouse Gas Inventory & Research Center, 2022) 2) projected values (National Institute of Forest Science, 2022) 3) average annual value for DOM(Son et al., 2017) 4) HWP values (Chang et al., 2022)

Source	annual of GHG removal (unit : million-ton $CO_{2eq}yr^{-1}$)	Means of Improve

	Current NIR	2050 BAU	2050 To-Be	
Biomass (2015-2050)	47[1)]	15[2)]	24[2)]	Restructuring the forests
DOM (2015-2050)	-	-	19[3)]	20-year survey data preparation and include in the NIR
HWP (2020-2050)	0.7[4)]	0.6[4)]	2.14[4)]	Expanding wood production

To summarize, predicting future carbon absorption by South Korean forestry requires a comprehensive understanding of the past and present state of forests, including their history and cultural background. Amidst contradicting arguments, it is essential that policies remain focused and driven by scientific evidence. By addressing the research questions posed at the beginning of this study, I will draw on the insights gained from data analysis and contextualize them within the framework of Korean forestry

3.1. What is the past and present status of forest and forestry in South Korea (SK)?

SK's forests cover 62.7% (6,298,134 hectares) of the total land area. 72billion trees are growing with the average stock of 165 m^3ha^{-1}. Most areas belong to temperate zone, but southern and coastal regions are transitioning into a subtropical zone in the global warming condition. As evidence, coniferous trees, once occupied 51% in 1960s, decreased to 37% in 2020 with deciduous trees expanding from 17% to 32%. Owing to the historical tragedies of Japanese colonization and Korean war, forests were completely devastated. Forest lands were mostly replanted from 1973 to 1987 with 1st and 2nd Forestation Projects. Although the projects were unprecedentedly successful, the tree species were limited to few kinds of fast-growing ones to stabilize land-slide. SK's forests exhibit unique age structures in that 75% of trees are between the age 30 to 49 in 2020. The relevant authorities in 1960s and 1970s set the logging limit at 15% of annual growth and imported large number of timbers to protect forests. As a result of that time, the forest resource utilization rate is still around 20% and domestic wood utilization rate is sticking to 15% until now.

Main owners of forests are privates who want to have family burial places in mountain due to its cultural background. Although they occupied 66% of forests, the average ownership size is very small as 1.9 hectares. Furthermore, many of these small-scale forest owners reside away from their forest land and have little interest in forest management. Along with ownership of forests, forest product industry has similar issues of being small-scale. The forest policies over the past 50 years have focused on restoration efforts over utilization so that timber industry foundation has been weakened.

3.2. Which argument about effect of forest aging is right? How does forest density and structure influence the growth of forest?

Environmental NGOs argue that older trees absorb more carbon, whereas the KFS presents the opposite view. The discourse is underpinned by empirical evidence indicating that carbon sequestration escalates concomitantly with tree volume increments. Nevertheless, current trends reveal a deceleration in growth rates as the majority of SK's forests approach maturity.

Critically, Hong (2022) challenges the KFS's methodological framework for excluding understory vegetation in carbon accumulation assessments and restricted observational data in longitudinal studies of Korea (limited to 60 years), advocating that this leads to a systematic underestimation of total forest biomass. Conversely, findings from Yuan et al (2016) suggest that minor diameter classes contribute insignificantly to overall biomass, thereby supporting exclusion practices observed in numerous national forest inventories. Pregitzer & Euskirchen (2004), Böttcher et al. (2008), Colombo et al. (2012), and Yu et al. (2021) substantiated the efficacy of younger forests in sequestering carbon more efficiently.

Apart from their claims, another limiting factor to forest growing stock is density. Excessive stand density instigates self-thinning and high mortality rates, subsequently attenuates growth rates. When using the most dominant species (*pinus densiflora*) in Korea for calculation of forest density, the RD of 1.17 exceeds the proper RD level (< 0.7) in the pine forests. These dense forests of pine trees are an example that illustrate the typical state of SK's forests. Another indicator of forest density is crown closure. Almost half-area of the total forests ranks the highest closure level of 76% to 100%. This limits the growth of forests because the forest reaches a maximum leaf area, photosynthesis and dry-matter production will decline without proper management.

3.3. What would be the appropriate strategy to have circular management for SK's forests?

SK's forest management strategy includes thinning and harvesting trees in the 41% of total forest land area in Korea from until the year 2080. And then, they will replant to make circular system for carbon sequestration. On average, 42,827 hectares will be restructured every year and harvest around 10-million $m^3yr^{-1.}$ Comparing this amount to current total growing stock, the forest utilization rate is estimated at 0.96%, which is much higher than the current use ratio of 0.2%. However, the ratio of 0.96% is like that of German and Sweden (0.8% to 1.1 interannually), where they gradually accumulate total growing stock of forests and already have sustained carbon sequestration levels.

Using the strategy, the annual carbon sequestration transitions to an increasing trend after 2040, with a projected recovery of 2020 levels of growth by 2065 according to KFS.

3.4. How much GHG do SK's forests currently absorb and how is this absorption rate changing in BAU and To-Be scenario?

When combining the contributions of biomass, DOM, and HWP, the total annual GHG removal in the To-Be scenario by 2050 can reach 45.14 million-ton-$CO2_{eq}yr^{-1}$, compared to the 15.6 million-ton-$CO2_{eq}yr^{-1}$ in the BAU scenario. The value in the To-Be scenario is almost reaching to the current level of 47.7 million-ton-$CO2_{eq}yr^{-1}$, counterbalancing the decreasing factors.

Currently, SK's forests show significant increases in biomass and DOM carbon stocks. The BAU scenario predicts a decrease in annual GHG removal by 2050, while the To-Be scenario, with improved forest management and increased domestic timber production, projects higher GHG removal. Including DOM and enhancing HWP production are critical for future carbon sequestration.

5. Discussions

This study explored the relationship between forest management and carbon sequestration in South Korean forests, shedding light on the dynamic interactions between forest policies, aging forest ecosystems, and their carbon absorption capacities. By examining both historical and current forest management practices and implications on carbon neutrality, policy makers will get insights into the effectiveness of SK's forestry strategies under the growing pressures of climate change.

Particularly, the debates over the carbon offset effects of large-scale afforestation and the ecological impacts of managing aged forests highlight the importance of grounding policy decisions in robust scientific evidence and fostering a well-informed public discourse. Special efforts were made to gather and compare scattered administrative and research data to verify the adequacy of the initial goal set by the KFS 'to plant 3billion trees by 2050, aiming to reduce carbon emissions by 24-million- ton $CO_{2eq}yr^{-1}$ in forest sector'. By calculating and estimating the amount of GHG removals by improving the each managing strategies, one can easily understand how the final goal be approached. It also explained that the historical evolution of forest composition and contemporary management strategies have contributed to forest aging and overcrowding. The introduction of new management objectives and the estimation of annual utilization rate have served to address concerns regarding excessive forest exploitation.

Main thing to study further is climate factors. Climate differences can alter the potential amount and age-related dynamics of forest carbon sequestration (T. Li et al., 2015). This study focuses on the temperate forests of South Korean region but did not deal with the carbon responses of climate changes in the future. Sub-tropical transition is already ongoing from the southern part of the country so that the study about age-related carbon dynamics in the warming situation will give additional insights into the proper management of forests.

Distributions of organic carbon accumulated to wood, leaf, soil parts are different according to their ecosystem environments. In the study of Tatuo & Tsunahide (1967), 63% of organic carbon was stored in soil and litter in the subalpine spruce forest at 1,650m above sea level in central Honsyu area while tropical rain forest and warm temperate forest shows the largest distribution of organic carbon (70%-80%) in living biomass parts. Considering the topography of SK with rugged mountains, studies of the relationship between carbon and Mountain environments will deepen the knowledge about Korean carbon dynamics.

However, in this study, various papers and international cases were cited to quantify the potential carbon removal contributions of forest managements. While these estimations provide a rough gauge and trend, they may not precisely represent the actual reduction amounts.

Especially, when comparing the carbon dynamic data of past (1964-2012) to present and future (2015-2050), the carbon stock differences between 2012 of J. Lee et al. (2014) and 2015 of Son et al. (2017) were relatively big to fill up the 3-year gap. Variations in data collection methods, study scopes, and estimation techniques contribute to discrepancies in reported values. These variations should be considered when interpreting the data.

Discrepancies can also occur from omissions of relatively small amounts of contributions. For example, there would be some temporary impacts on carbon sequestration in DOM by harvesting, but it is omitted on the consideration that regrowth of forests after restoration will soon recover the impacts. To figure out the exact carbon effects according to management policies, the inter-annual negative effects of harvest on DOM carbon stock should also be analyzed.

Another example is the understory vegetation. Although they give unstable and small amount in carbon sequestration, it would be better to include the small absorption sources to the inventory system via developing the standard national value. In the same respect, the effects of wild fire, insects were not dealt in this paper.

To develop the holistic view of forestry in carbon neutrality, the substitution effects of forest by-products, such as biomass power generation, should be included. Although it is not included in the inventory report according to IPCC guideline, forest by-products contribute to mitigate carbon emissions by substituting fossil-based materials. Direct comparisons between wood and fossil products for the same functional unit are necessary to formulate adequate policies.

Additionally, the study of carbon footprints for wood products during their whole life cycle in the Korea's socio-economic environments and technologies would be useful to understand the whole contribution of forests in the nation. Caused by the small-scale forest industry structure and mountainous forests, comparatively high costs will be needed. To perform an accurate LCA (Life Cycle Assessment) for wood products, it is essential to develop carbon footprints specific to Korean wood products and simultaneously strive to reduce these footprints.

Consequently, continuous monitoring and longitudinal research will be crucial for further development of the evaluating system for carbon sequestration by forest management.

6. Conclusions

The strategic management of SK's forests to enhance carbon sequestration amidst the challenges of climate change, aging forests, and socio-economic constraints demands an integrated approach that combines scientific understanding with practical forestry management practices.

SK's forests currently hold growing stock levels exceeding the OECD average, a result of rapid greening efforts have led to an over-concentration of trees within the same age group, with a significantly small proportion of young trees, complicating sustainable carbon cycle management. Furthermore, long-standing forest conservation policies have resulted in one of the lowest forest utilization rates globally, significantly weakening the related timber industries and leading to an overreliance on timber imports, which in turn contributes negatively to global climate warming. Due to the structure of forest ownership, where 66% are privately owned and most managed forests are small holdings, active participation from these owners is essential. Yet, many of these small-scale forest owners, possessing less than 10 hectares and often residing away from their property, neglect proper management, leading to further forest degradation.

This thesis has scrutinized the historical and current management states of Korean forests through carbon dynamics. The carbon storage in the biomass has risen dramatically from 36.4 Tg in 1954 to 440 Tg in 2012, following extensive planting that began in 1973. Carbon storage in DOM, including soil, deadwood and litter, has also increased, although it has not been consistently documented for 20 years as required by IPCC guidelines, not yet contributing to annual carbon absorption figures. The HWP sector also predicts a decrease due to poor domestic production. With the biomass portion expected to gradually decrease, establishing a forest circular management system, including DOM in carbon accounting, and expanding domestic production of HWPs are necessary to improve annual carbon absorption rates.

Recently, KFS has been losing momentum in promoting forest carbon management due to repeated controversies challenging the basis of their policies. Forest carbon storage increases proportionally with growing stock. Opponents argue that KFS has understated the growing stock of understory vegetation and older trees to exaggerate the stock of middle-aged trees, based on only 60-year of observational data from SK's relatively young forests. However, studies like Yuan et al. (2016) found that biomass accumulation in small trees with a DBH ≤10cm accounted for only 0.6% of the total forest aboveground biomass in the forest near Baekdu Mountain. Moreover, research by Pregitzer &Euskirchen (2004) on trees up to 200 years old found that productivity peaks between 11-30 years, aligning with the KSF's claims.

Structural Issues also arise from the concentration of tree ages. Calculations of the relative density of *Pinus densiflora*, a representative species in Korean forests, show RD of 1.17, indicating that the forests are densely packed beyond the self-thinning threshold, necessitating management interventions. Crown closure surveys in 2011 showed that nearly half of the forests were at the highest closure level (76%-100%), also indicating the need for artificial management.

KFS plans by 2080 to harvest about 41% of the total forest area, translating to an annual harvest of 0.68% (42,827 hectares) of the forest area. Even calculating using the maximum growing stock of observable age class, the 6th class, this equates to an annual production of 10-million m^3. When compared to the total growing stock, the forest utilization rate is 0.96%, similar to the practices of leading carbon cycle management countries like German and Sweden, where forest utilization of less than 1% does not harm the overall stock increasing trend.

As SK continues to advance towards its 2050 Net-Zero goals, the role of forests as carbon sinks will undoubtedly be a cornerstone of national climate strategy. The path forward for Korean forest management is one that requires a balanced approach, integrating scientific research, practical management strategies, and stakeholder engagement to optimize carbon sequestration while ensuring the sustainability and resilience of forest ecosystems.

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References

1. Ali, A. (2019). Forest stand structure and functioning: Current knowledge and future challenges. *Ecological Indicators*, *98*, 665–677. https://doi.org/10.1016/j.ecolind.2018.11.017

2. Allen, C. D., Macalady, A. K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D. D., Hogg, E. H. (Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J. H., Allard, G., Running, S. W., Semerci, A., & Cobb, N. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, *259*(4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

3. An, H., Seok, H. D., Lee, S. M., & Choi, J. (2019). Forest management practice for enhancing carbon sequestration in national forests of Korea. *Forest Science and Technology*, *15*(2), 80–91. https://doi.org/10.1080/21580103.2019.1596843

4. Bae, J.-S. (2009). Assessments of Negotiation Options Regarding Post-2012 Rules for Land Use, Land-Use Change and Forestry (LULUCF) 1-with a Focus on the Forest Management Activities under the Kyoto Protocol. *Journal of Korean Society of Forest Science*, *98*(1), 55–65.

5. Beringer, J., Chapin, F. S., Thompson, C. C., & McGuire, A. D. (2005). Surface energy exchanges along a tundra-forest transition and feedbacks to climate. *Agricultural and Forest Meteorology*, *131*(3–4), 143–161. https://doi.org/10.1016/j.agrformet.2005.05.006

6. Berndes, G., Abt, B., Asikainen, A., Cowie, A., Dale, V., Egnell, G., Lindner, M., Marelli, L., Paré, D., Pingoud, K., & Yeh, S. (2016). Forest biomass, carbon neutrality and climate change mitigation. *From Science to Policy*, *3*.

7. Böttcher, H., Kurz, W. A., & Freibauer, A. (2008). Accounting of forest carbon sinks and sources under a future climate protocol-factoring out past disturbance and management effects on age-class structure. *Environmental Science and Policy*, *11*(8), 669–686. https://doi.org/10.1016/j.envsci.2008.08.005

8. Braga, C. I., Petrea, S., Radu, G. R., Cucu, A. B., Serban, T., Zaharia, A., & Leca, S. (2024). Carbon Sequestration Dynamics in Peri-Urban Forests: Comparing Secondary Succession and Mature Stands under Varied Forest Management Practices. *Land*, *13*(4). https://doi.org/10.3390/land13040492

9. Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P., & Federici, S. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories PRODUCTS*.

10. Cao, J., Liu, H., Zhao, B., Li, Z., Liang, B., Shi, L., Wu, L., Cressey, E. L., & Quine, T. A. (2021). High forest stand density exacerbates growth decline of conifers driven by warming but not broad-leaved trees in temperate mixed forest in northeast Asia. *Science of The Total*

Environment, *795*, 148875. https://doi.org/10.1016/j.scitotenv.2021.148875

11. Chang, Y. S., Shin, J. H., & Kim, Y. H. (2022). Evaluation of Carbon Storage Enhancement Effect by Activating Utilization of Structural Sawnwood. *Journal of Climate Change Research*, *13*(6), 869–876. https://doi.org/10.15531/ksccr.2022.13.6.869

12. Chivhenge, E., Ray, D. G., Weiskittel, A. R., Woodall, C. W., & D'Amato, A. W. (2024). Evaluating the Development and Application of Stand Density Index for the Management of Complex and Adaptive Forests. *Current Forestry Reports*, *10*(2), 133–152. https://doi.org/10.1007/s40725-024-00212-w

13. Cintas, O., Berndes, G., Hansson, J., Poudel, B. C., Bergh, J., Börjesson, P., Egnell, G., Lundmark, T., & Nordin, A. (2017). The potential role of forest management in Swedish scenarios towards climate neutrality by mid century. *Forest Ecology and Management*, *383*, 73–84. https://doi.org/10.1016/j.foreco.2016.07.015

14. Colombo, S. J., Chen, J., Ter-Mikaelian, M. T., McKechnie, J., Elkie, P. C., MacLean, H. L., & Heath, L. S. (2012). Forest protection and forest harvest as strategies for ecological sustainability and climate change mitigation. *Forest Ecology and Management*, *281*, 140–151. https://doi.org/10.1016/j.foreco.2012.06.016

15. Environmental Movement Union of Korea. (2021). *The Korea Forest Service's carbon neutrality plan includes large-scale logging projects, destroying forest ecosystems*. https://kfem.or.kr/ecologicalpreservation/?idx=17919225&bmode=view

16. FAO. (n.d.). *Global Forest Resources Assessment 2020*. Food and Agriculture Organization of the United Nations. Retrieved April 20, 2024, from https://fra-data.fao.org/

17. Forest ICT Research Center, & Korea Forestry Promotion Institute. (2021). 2020 Forest Resources of Korea. *Korea Forest Research Report*, *976*.

18. Franklin, O., Aoki, K., & Seidl, R. (2009). A generic model of thinning and stand density effects on forest growth, mortality and net increment. *Annals of Forest Science*, *66*(8), 815–815. https://doi.org/10.1051/forest/2009073

19. Gonçalves, A. C. (2022). Influence of stand structure on forest biomass sustainability. In *Natural Resources Conservation and Advances for Sustainability* (pp. 327–352). Elsevier. https://doi.org/10.1016/B978-0-12-822976-7.00007-7

20. Government of Korea. (2023). *National Strategy of Carbon Neutrality and the 1st National Plan*.

21. Government of Republic of Korea. (2023). *National Strategy for Carbon Neutrality and Green Growth*.

22. Gower, S. T., Isebrands, J. G., & Sheriff, D. W. (1995). Carbon Allocation and Accumulation in Conifers. In *Resource Physiology of Conifers* (pp. 217–254). Elsevier. https://doi.org/10.1016/B978-0-08-092591-2.50012-1

23. Green Alliance of Korea. (2021). *The carbon absorption function of forests must coexist with biodiversity*. https://www.greenkorea.org/activity/weather-change/climatechangeacction-climate-change/87457/

24. Greenhouse Gas Inventory & Research Center. (2022). *2022 National Greenhouse Gas Inventory Report*. 259–300.

25. Gustavsson, L., Haus, S., Lundblad, M., Lundström, A., Ortiz, C. A., Sathre, R., Truong, N. Le, & Wikberg, P. E. (2017). Climate change effects of forestry and substitution of carbon-intensive materials and fossil fuels. In *Renewable and Sustainable Energy Reviews* (Vol. 67, pp. 612–624). Elsevier Ltd. https://doi.org/10.1016/j.rser.2016.09.056

26. Hong, S.-H. (2022). Problems of Forest Management from a Carbon Neutral Perspective and Nature Based Solutions. *Environmental Law and Policy*, *29*, 21–48. https://doi.org/10.18215/elvlp.29..202206.21

27. International Centre for Sustainable Carbon. (2022). *AS BIOMASS BURNING SURGES IN JAPAN AND SOUTH KOREA, WHERE WILL ASIA GET ITS WOOD?* https://www.sustainable-carbon.org/as-biomass-burning-surges-in-japan-and-south-korea-where-will-asia-get-its-wood/

28. IPCC. (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Eggleston H.S., Buendia L., Miwa K., Ngara T., & Tanabe K., Eds.; Vol. 4). IGES, Japan.

29. Jandl, R., Bauhus, J., Bolte, A., Schindlbacher, A., & Schüler, S. (2015). Effect of climate-adapted forest management on carbon pools and greenhouse gas emissions. *Current Forestry Reports*, *1*(1), 1–7. https://doi.org/10.1007/s40725-015-0006-8

30. Jandl, R., Vesterdal, L., Olsson, M., Bens, O., Badeck, F., & Roc, J. (2007). Carbon sequestration and forest management. *CABI Reviews*. https://doi.org/10.1079/PAVSNNR20072017

31. Jangtae Mountain Recreational Forest. (2021). *Resting in a Metasequoia forest makes one with nature*. https://www.jangtaesan.or.kr:454/index.asp

32. Kim, H., McJeon, H., Jung, D., Lee, H., Bergero, C., & Eom, J. (2022). Integrated Assessment Modeling of Korea's 2050 Carbon Neutrality Technology Pathways. *Energy and Climate Change*, *3*. https://doi.org/10.1016/j.egycc.2022.100075

33. Kim, Y. (2015). Estimation of Secondary Emissions from Forest Carbon Offset Projects. *Journal of Climate Change Research*, *6*(4), 257. https://doi.org/10.15531/ksccr.2015.6.4.257

34. Kim, Y. (2017). Analysis of Forest Carbon Offset Credits from Forest Management Project based on to the Korean Forest Carbon Offset Standard and the VCS Methodology - Case Study on the Methodology for Forest Management through Extension of Rotation Age -. *Journal of Climate Change Research*, *8*(4), 369–375. https://doi.org/10.15531/ksccr.2017.8.4.369

35. Kim, Y., Lim, J., Han, H., Jang, Y., Kim, R., Lee, S., Shin, J., & Yu, J. (2022). *Research on forestry sector response measures to achieve national greenhouse gas reduction goals (NDC)*. National Institute of Forest Science, Korea.

36. Kim, Y.-H. (2016). Developing a Large-scale Carbon Offset Project Based on Forest Management - In Case of Jin-An Leading Forest Management Zone -. *Journal of Climate*

Change Research, *7*(2), 137. https://doi.org/10.15531/ksccr.2016.7.2.134

37. Koea Forest Service. (1979). *The 2nd Forestation Project*.

38. Korea Forest Research Institute. (2011). The 5th National Forest Inventory Report of Korea. *Korea Forest Research Report*, *440*.

39. Korea Forest Service. (2021). *Planting 3 billion trees by 2050 reduces carbon emissions by 34 million tons*. https://www.forest.go.kr/kfsweb/cop/bbs/selectBoardArticle.do?bbsId=BBSMSTR_1036&mn=NKFS_04_02_01&nttId=3154431

40. Korea Forest Service. (2023a). *2022 Forest industry survey*.

41. Korea Forest Service. (2023b). *2022 Wood Usage Survey*. www.forest.go.kr

42. Korea Forest Service. (2023c). *The 3rd National Plan of Carbon absorption promotion*.

43. Korea Forest Service. (2023d). *The Timber Utilization Survey Report for the Year 2022*.

44. Lal, R., & Lorenz, K. (2012). Carbon Sequestration in Temperate Forests. In *Recarbonization of the Biosphere* (pp. 187–201). Springer Netherlands. https://doi.org/10.1007/978-94-007-4159-1_9

45. Leading Forest Management Complex. (2022). *Going to the leading forest management areas where the future of forest management*. www.sundofm.or.kr

46. Lee, A., Noh, N., Yoon, T., Lee, S., Seo, K., Lee, W., Cho, Y., & Son, Y. (2009). Estimation of Forest Soil Carbon Stocks with Yasso using a Dendrochronological Approach. *Journal of Korean Forest Society*, 791–798.

47. Lee, D., & Choi, J. (2019). Evaluating maximum stand density and size–density relationships based on the Competition Density Rule in Korean pines and Japanese larch. *Forest Ecology and Management*, *446*, 204–213. https://doi.org/10.1016/j.foreco.2019.05.017

48. Lee, D., & Choi, J. (2020). Stocking Diagrams for Silvicultural Guideline in Korean Pines and Japanese Larch. *Forests*, *11*(8), 833. https://doi.org/10.3390/f11080833

49. Lee, J., Tolunay, D., Makineci, E., Çömez, A., Son, Y. M., Kim, R., & Son, Y. (2016). Estimating the age-dependent changes in carbon stocks of Scots pine (Pinus sylvestris L.) stands in Turkey. *Annals of Forest Science*, *73*(2), 523–531. https://doi.org/10.1007/s13595-016-0546-5

50. Lee, J., Yoon, T. K., Han, S., Kim, S., Yi, M. J., Park, G. S., Kim, C., Son, Y. M., Kim, R., & Son, Y. (2014). Estimating the carbon dynamics of South Korean forests from 1954 to 2012. *Biogeosciences*, *11*(17), 4637–4650. https://doi.org/10.5194/bg-11-4637-2014

51. Lee, S.-T., Park, J.-H., Chung, S.-H., & Kim, H.-H. (2021). The Estimation of the Potential Yield by Site Index for Pinus Densiflora Forests. *Journal of Agriculture & Life Science*, *55*(6), 31–38. https://doi.org/10.14397/jals.2021.55.6.31

52. Lee, W., Kim, Y., Min, G., Park, J., Seo, J., Son, Y., Woo, S., Lee, K., Lee, C., Choi, S., &

Choi, J. (2022). *The scientific Basis of Forest Carbon Management* (M. Lee, Ed.). Jieul books.

53. Lewis, S. L., Mitchard, E. T. A., & Koch, A. (2019). Restoring natural forests is the best way to remove atmospheric carbon. *Nature*, *568*, 25–28. go.nature.com/2hxnjkw
54. Li, Q., Liu, Z., & Jin, G. (2022). Impacts of stand density on tree crown structure and biomass: A global meta-analysis. *Agricultural and Forest Meteorology*, *326*, 109181. https://doi.org/10.1016/j.agrformet.2022.109181
55. Li, T., Ren, B., Wang, D., & Liu, G. (2015). Spatial Variation in the Storages and Age-Related Dynamics of Forest Carbon Sequestration in Different Climate Zones—Evidence from Black Locust Plantations on the Loess Plateau of China. *PLOS ONE*, *10*(3), e0121862. https://doi.org/10.1371/journal.pone.0121862
56. Li, X., Yi, M. J., Son, Y., Jin, G., & Han, S. S. (2010). Forest biomass carbon accumulation in Korea from 1954 to 2007. *Scandinavian Journal of Forest Research*, *25*(6), 554–563. https://doi.org/10.1080/02827581.2010.524892
57. Lidskog, R., & Sjödin, D. (2016). Extreme events and climate change: the post-disaster dynamics of forest fires and forest storms in Sweden. *Scandinavian Journal of Forest Research*, *31*(2), 148–155. https://doi.org/10.1080/02827581.2015.1113308
58. Long', J. N. (1985). A Practical Approach to Density Management. *The Forestry Chronicle*, 23–27.
59. Martes, L., & Köhl, M. (2022). Improving the Contribution of Forests to Carbon Neutrality under Different Policies—A Case Study from the Hamburg Metropolitan Area. *Sustainability (Switzerland)*, *14*(4). https://doi.org/10.3390/su14042088
60. Marzano, M., Quine, C. P., & Dandy, N. (2014). *Forests for All? Considering the Conservation Implications of Human-Species Interactions in the Context of Multifunctional Forestry* (pp. 55–69). https://doi.org/10.1007/978-94-007-7076-8_4
61. McNeely, J. A. (2003). Conserving forest biodiversity in times of violent conflict. *Oryx*, *37*(2), 142–152. https://doi.org/10.1017/S0030605303000334
62. Ministry of Interior. (1973). *10-year Project of National Land Afforestation*.
63. Ministry of the Environment Sweden. (2019). *Sweden's fourth Biennial Report under the UNFCCC*.
64. National Archives of Korea. (n.d.). *National Archives of Korea*. Retrieved April 16, 2024, from https://theme.archives.go.kr/next/forest/outline/greenKept.do
65. National Institute of Forest Science. (2022). *Study on Forest Sector Strategies for Achieving National Greenhouse Gas Reduction Targets*.
66. National Institute of Forest Science. (2023). *The 1st Comprehensive Report on Climate Change Impact Assessment in the Forest and Forestry Sector*.
67. National Mountain Museum. (n.d.). *Denuated forest picture in 1954*. Retrieved April 30, 2024, from

http://www.forest.go.kr/newkfsweb/kfs/idx/SubIndex.do?orgId=nmm&mn=KFS_37

68. Noble, I. R., & Dirzo, R. (1997). Forests as Human-Dominated Ecosystems. *Science*, *277*(5325), 522–525. https://doi.org/10.1126/science.277.5325.522
69. OECD. (2019). *Depletion and growth of forest resources*. https://doi.org/10.1787/2546ca0a-en
70. Peckham, S. D., Gower, S. T., & Buongiorno, J. (2012). Estimating the carbon budget and maximizing future carbon uptake for a temperate forest region in the U.S. *Carbon Balance and Management*, *7*. https://doi.org/10.1186/1750-0680-7-6
71. Peng, L., Searchinger, T. D., Zionts, J., & Waite, R. (2023). The carbon costs of global wood harvests. *Nature*, *620*(7972), 110–115. https://doi.org/10.1038/s41586-023-06187-1
72. Pregitzer, K. S., & Euskirchen, E. S. (2004). Carbon cycling and storage in world forests: biome patterns related to forest age. *Global Change Biology*, *10*(12), 2052–2077. https://doi.org/10.1111/j.1365-2486.2004.00866.x
73. Reineke, L. H. (1933). PERFECTING A STAND-DENSITY INDEX FOR EVEN-AGED FORESTS 1. *Journal of Agricultural Research*, *46*(No.7), 627–638.
74. Repo, A., Ahtikoski, A., & Liski, J. (2015). Cost of turning forest residue bioenergy to carbon neutral. *Forest Policy and Economics*, *57*, 12–21. https://doi.org/10.1016/j.forpol.2015.04.005
75. Ryan, M. G., Binkley, D., & Fownes, J. H. (1997). *Age-Related Decline in Forest Productivity: Pattern and Process* (pp. 213–262). https://doi.org/10.1016/S0065-2504(08)60009-4
76. Ryu, D.-H., Lee, W.-K., Song, C.-H., Lim, C.-H., Lee, S.-G., & Piao, D.-F. (2016). Assessing Effects of Shortening Final Cutting Age on Future CO_2 Absorption of Forest in Korea. *Journal of Climate Change Research*, *7*(2), 157. https://doi.org/10.15531/ksccr.2016.7.2.157
77. Sato, A., & Nojiri, Y. (2019). Assessing the contribution of harvested wood products under greenhouse gas estimation: Accounting under the Paris Agreement and the potential for double-counting among the choice of approaches. *Carbon Balance and Management*, *14*(1). https://doi.org/10.1186/s13021-019-0129-5
78. Shaw, J. D., & Long, J. N. (2007). A Density Management Diagram for Longleaf Pine Stands with Application to Red-Cockaded Woodpecker Habitat. *Southern Journal of Applied Forestry*, *31*(1), 28–38. https://doi.org/10.1093/sjaf/31.1.28
79. Son, Y., Son, Y., Lee, M., Park, K., Kim, C., Kim, L., Lim, J., Lee, J., & Lee, S. (2017). *Development and Utilization of Forest Soil Carbon Models*. National Institue of Forest Science.
80. Soo Bae, J., & Kim, E.-S. (2019). Understanding Forest Status of the Korean Peninsula in 1910: A Focus on Digitization of Joseonimyabunpodo (The Korean Peninsula Forest Distribution Map). *J. Korean Soc. For. Sci*, *108*(3), 418–428. https://doi.org/10.14578/jkfs.2019.108.3.418

81. Swedish Ministry for the Environment. (2019). *Revised National forestry accounting plan for Sweden Ministry for the Environment*.

82. Tak, K., Chun, Y., & Wood, P. M. (2007). The South Korean forest dilemma. *International Forestry Review* , *9*(1), 548–557. https://about.jstor.org/terms

83. Tatuo, K., & Tsunahide, S. (1967). PRIMARY PRODUCTION AND TURNOVER OF ORGANIC MATTER IN DIFFERENT FOREST ECOSYSTEMS OF THE WESTERN PACIFIC. *Jounal of Ecology in Japan*, *17*(2), 70–87. https://doi.org/https://doi.org/10.18960/seitai.17.2_70

84. United Nations. (2015). *Paris Agreement*.

85. Vidal, C., Alberdi, I., Hernández, L., & Redmond, J. (2016). *National Forest Inventories* (C. Vidal, I. A. Alberdi, L. Hernández Mateo, & J. J. Redmond, Eds.). Springer International Publishing. https://doi.org/10.1007/978-3-319-44015-6

86. Yu, Z., You, W., Agathokleous, E., Zhou, G., & Liu, S. (2021). Forest management required for consistent carbon sink in China's forest plantations. *Forest Ecosystems*, *8*(1), 54. https://doi.org/10.1186/s40663-021-00335-7

87. Yuan, Z., Gazol, A., Wang, X., Lin, F., Ye, J., Zhang, Z., Suo, Y. Y., Kuang, X., Wang, Y., Jia, S., & Hao, Z. (2016). Pattern and dynamics of biomass stock in old growth forests: The role of habitat and tree size. *Acta Oecologica*, *75*, 15–23. https://doi.org/10.1016/j.actao.2016.06.007

Annex. List of Figures & Tables

Figures

Tables