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Realizing climate resilient development pathways in forestry: A focus on carbon management in Republic of Korea

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A R T I C L E I N F O

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A B S T R A C T

Overcoming the climate crisis and achieving the 1.5 °C target requires the exploration of climate-resilient development pathways (CRDPs), as emphasized in the intergovernmental panel on climate change (IPCC) AR6 report. Republic of Korea has aligned itself with the international context by setting nationally determined contributions (NDC) and long-term low greenhouse gas emission development strategies (LEDS) goals. In addition, the country has announced plans to enhance carbon sink in the forestry sector. This study explored the CRDP in the forestry sector using an advanced Korean forest dynamic growth model (AKO-G-Dynamic model) with refined management algorithms. We utilized this model and applied various options for forest management based on the available detailed data, including climate change scenarios and policies reflecting possible CRDPs in the Republic of Korea. As a result, CO_2 sequestration in the 2050s was predicted to be 23.08 million tCO_2 year^{-1} if climate change SSP 5–8.5 and the current forest management level are maintained and 28.49 million tCO_2 year^{-1} if climate change SSP 1–2.6 and resilient level of forest management are applied. Furthermore, from the perspective of the age class of the forest, the proportion of over-matured forests decreased, leading to an improvement in the imbalance of age classes as climate change mitigation and sustainable forest management were implemented. Therefore, this study demonstrated realizable CRDPs and their implementation in decision-making concerning the NDC and LEDS. This comprehensive analysis of climate change and forest management, exploring the CRDP from various perspectives, can contribute to the development of forest management policies for climate adaptation strategies and carbon sink enhancement, thereby influencing the allocation of the carbon budget.

1. Introduction

Since the Paris Agreement, each country has set nationally determined contributions (NDC) reduction targets for greenhouse gas emissions (UNFCCC, 2021a). Moreover, the recently published intergovernmental panel on climate change (IPCC) Sixth Assessment Report (AR6) and the 1.5 °C target have continued to emphasize the role of forests as sinks (IPCC, 2022). Efforts to reduce greenhouse gas (GHG) emissions and mitigate climate change using forests have been discussed in various ways centered on the United Nations Framework Convention on Climate Change (UNFCCC). In particular, the IPCC AR6 Impacts, Adaptation, and Vulnerability report emphasizes the direction of climate-resilient development pathways (CRDP) for forests. This indicates the need for a multidimensional analysis of greenhouse gas mitigation and adaptation processes based on various options, such as carbon sequestration, reforestation, and climate crisis reduction through future sustainable forest management (IPCC, 2023). As COP28 actively engaged in detailed discussions on halting deforestation, forest carbon capture technologies, climate change adaptation, and related issues, it underscored the necessity for diverse exploration and collaboration

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among countries to effectively explore the CRDP for forests (Korea Forest Service, 2021b).

The Republic of Korea also submitted '2030 NDC' and '2050 LEDS' to the UNFCCC in line with the international situation after the Paris Agreement and is making efforts to reduce greenhouse gases. Republic of Korea's first NDC submission suggested a 37 % greenhouse gas reduction target compared to business-as-usual (BAU) by 2030. However, this does not reflect a reduction in forestry and requires further investigation (UNFCCC, 2016). Since then, the reduction in the forestry sector was reflected in the revised NDC, which included 26.7 million tons of CO_2eq (25.5 million tons of CO_2eq for the forestry industry) and 33.5 million tons of CO_2eq from overseas reductions using sinks (UNFCCC, 2021b). Furthermore, the recently raised target is a 40 % reduction plan compared to 2018's emissions (KDI, 2021). A long-term plan for climate crisis mitigation has been formulated in the 2050 carbon neutrality promotion strategy, targeting a forest absorption capacity of 23.6 million tons (accounting for 93 % of the total absorption capacity of 25.3 million tons, with the forestry sector playing a crucial role) (Korea Ministry of Economy and Finance, 2022). As such, forestry reduction measures are becoming increasingly important in the Republic of Korea, and it is necessary to seek a CRDP that reflects Korea's forest characteristics.

Despite the success of the large-scale afforestation and conservation policies implemented in the 1970s and the 1980s, Republic of Korea currently face an urgent need to establish secondary forest growth. This is due to the imbalanced age distribution, with 30-and-40-year-old forests occupying two-thirds of the total forest area (Korea Forest Service, 2021d). In response, the government has presented policies such as new afforestation, sustainable forest management, planting of future-adapted tree species, and utilization of wood and forest biomass. However, substantive scientific evidence supporting these policies is lacking. Furthermore, previous research has been limited in actively exploring climate-resilient pathways for carbon sinks by incorporating both climate change and national forestry policies.

Accordingly, this study aimed to directly address the challenge of enhancing sustainable forest management in the Republic of Korea by linking greenhouse gas mitigation and adaptation options. Specifically, this research focuses on applying the IPCC AR6 CRDP concept (Reisinger et al., 2020) to the Republic of Korea's forests, with the objective of evaluating and comparing different carbon management strategies. We employed carbon management simulations based on domestic forest policies to develop and implement feasible adaptation options, distinguishing our study from previous conceptual research. This involved predicting trends in growth, carbon dioxide sequestration and storage, and harvesting based on scenarios involving climate and growth mechanisms, reflecting the CRDP concept. The primary goal of this study is to identify and explore CRDPs that accurately reflect the unique environmental and ecological characteristics of the Republic of Korea's forests. By doing so, we aim to enhance the value of carbon sink sources and provide optimal carbon management strategies that respond to dynamic forest changes. Through a comprehensive multidimensional analysis, this study seeks to contribute scientific evidence for policy decision-making, particularly in the context of extreme climate conditions and diverse forest management options.

2. Materials and methods

2.1. Study area

The study area consists of the forests in the Republic of Korea, located in East Asia, where 62.63 % (6,290,854 ha) of the land area is covered by forests (Fig. 1) (Korea Forest Service, 2023). Within the forested areas, coniferous forests occupy 27.8 %, broad-leaved forests 33.4 %, and mixed forests 38.8 % (Korea Forest Service, 2021c). The Republic of Korea is characterized by a warm monsoon climate, with hot summers and cold, dry winters, resulting in significant seasonal variations. Ecologically, the region is classified as part of the temperate broad-leaved deciduous forest zone (Walter, 1973). However, current forests, established primarily through attribute-oriented afforestation practices, are aging due to uneven stand structures. Moreover, coniferous tree species are becoming increasingly vulnerable to climate change (Byun et al., 2012; Kim et al., 2017a, 2017b; Yoo et al., 2020). In response, the government is implementing forest management policies, such as the Basic Forest Plan, Climate Change Adaptation Plan, and Carbon Neutrality Strategy Plan (Government of the Republic of Korea, 2021; Korea Forest Service, 2018b; Korea Ministry of Economy and Finance, 2022). To explore the impact of carbon management strategies aligned with national-level forest management policies, our study examined pathways to assess the feasibility of CRDP in the Republic of Korea.

2.2. Advanced Korean forest dynamic model

This study explored CRDP for enhancing carbon sinks in the forestry sector by utilizing the "KO-G-Dynamic model," a Korean dynamic stand-growth model. The forest management module within the model, designed using the existing model, was advanced (Eq. (1)) (Hong et al., 2022). This dynamic growth model can predict changes in forests based on changes in stand density. It not only allows the application of various forest management scenarios but also incorporates the impact of climate, which is often overlooked in traditional dynamic growth models. Thus, the model can accurately predict the growth, mortality,

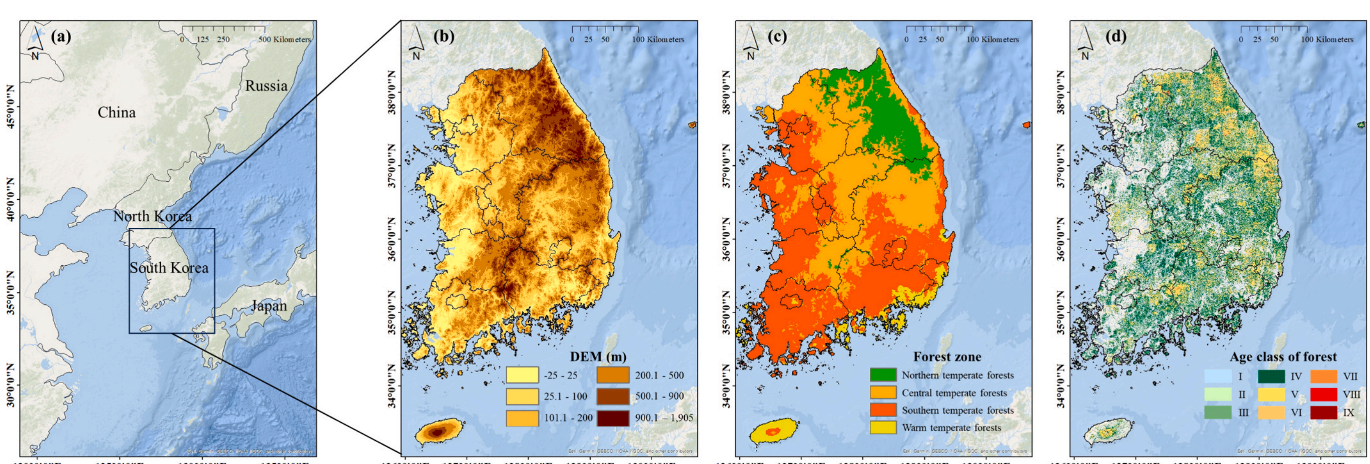

Fig. 1. (a) Study area and its (b) elevation map and, (c) forest zone map and (d)age class of forest map.

Table 1
Carbon emission factors for the major Korean tree species (NIFoS, 2021).

Tree species	Basic wood density	Biomass expansion factor	Root/Shoot ratio
Pinus densiflora	0.47	1.41	0.26
Pinus koraiensis	0.41	1.74	0.28
Larix kaempferi	0.45	1.34	0.29
Quercus variabilis	0.72	1.34	0.32
Quercus mongolica	0.66	1.60	0.39
Mixed forest 1 (*Pinus densiflora, Quercus variabilis*)	0.59	1.37	0.29
Mixed forest 2 (*Pinus densiflora, Quercus mongolica*)	0.56	1.51	0.32

and harvest of temperate forests that undergo annual growth cycles. This model established stand boundaries using forest-type maps and Korean National Forest Inventory (NFI) data in a 1 km × 1 km grid. It classifies factors such as stand age, site index, major tree species (seven main forest types: *Pinus densiflora, Pinus koraiensis, Larix kaempferi, Quercus variabilis, Quercus mongolica*, mixed forest A (Mixed-A*: Pinus densiflora* and *Quercus variabilis*), and mixed forest B (Mixed-B: *Pinus densiflora* and *Quercus mongolica*), and management types (protected and managed forests). Based on these factors, the model then calculates information such as tree height, diameter at breast height (DBH), and stand density. These data predict the growing stock by considering the environmental and ecological characteristics specific to Korea. The KO-G-Dynamic model was compared and calibrated using the 5th and 6th NFI data and verified using national forestry statistical data and other research (Kim et al., 2019).

In this advanced model, the climate change scenario was updated, and the forest age and accumulation mechanisms in the management module were considered, as well as the accessibility of the forest road, so that more practical management analysis could be performed. Therefore, the core system of the Advanced KO-G-Dynamic (AKO-G-Dynamic) model reflected the logical approach and equations of the previous model, but the model included additional components for forest road accessibility and modules for applying changed climate scenarios. Based on the accessibility of the forest road, the legal final cut and reforestation were implemented for the stand that reached the legal final cutting age for each species in the managed forest. This model was simulated using the R 4.0.4 software.

$$PH_i = \sum \left[\left(Age_{kij} \geq FA_j \right) \cap (MA) \cap (FR) \right] \quad (1)$$

Where PH_i is the potential cutting area for year i, Age_{kij} is the k stand, i is the year, j is the stand age for the tree species, FA_j is the legal final cutting age of tree species j, and MA is the area in which forest management is possible. FR is the accessibility from forest roads.

2.3. CO_2 stock and sequestration in forests

In this study, the stock and sequestration amounts for major tree species were calculated to explore the CRDP to improve carbon sink potential. It was estimated through the sequestration factor for each tree species based on growth according to the annual difference in stand volume (NIFoS, 2021). Carbon stock (C) was calculated using country-specific factors developed by the National Institute of Forest Science, such as basic wood density (D), biomass expansion factor (BEF), and root/shoot ratio (RS). These factors were applied to the stand volume calculated using the growth model (Table 1, Eq. (2)). This method estimated the annual change in carbon stock (CS) in the remaining forest land (Eq. (3)) and converted it to CO_2 sequestration (Eq. (4)) (IPCC, 2019; Penman et al., 2003).

$$C_{t_i} = V_{t_i} \times D_j \times BEF_j \times \left(1 + RS_j\right) \times CF \quad (2)$$

$$CS_{t_i} = \frac{CS_{t_{i+1}} - CS_{t_i}}{t_{i+1} - t_i} \quad (3)$$

$$\triangle CO_{2t_i} = \triangle CS_{t_i} \times \frac{44}{12} \quad (4)$$

where C is carbon stock (tC ha^{-1}); V is the stand volume (m^3 ha^{-1}); D is the basic density of the wood; BEF is called biomass expansion factor; RS is the root to shoot ratio; CF is the carbon fraction (biomass to carbon, IPCC default = 0.5); $\boldsymbol{t_i}$ is the year; j is tree species; $\boldsymbol{CS_{t_i}}$ and $\boldsymbol{CS_{t_{i+1}}}$ are the annual change in carbon stock (tC ha^{-1} year^{-1}) calculated at $\boldsymbol{t_i}$ and $\boldsymbol{t_{i+1}}$ year; $\triangle \boldsymbol{CO_{2t_i}}$ is annual carbon dioxide sequestration (tCO_2 ha^{-1} year^{-1}); and 44/12 is the stoichiometric ratio of CO_2 and C.

2.4. Simulating the CRDPs based on climate change and management scenarios

This study performed a long-term analysis considering the current (2000–2020) and the future forecast periods of 2030 (2021–2030), 2050 (2041–2050), 2080 (2071–2080), and 2100 (2091–2100). This analysis reflects the current transition in forest physiognomy in the Republic of Korea, from young-mature stands to over-mature forests. Thus, this study estimated forest changes from various perspectives using climate data and management options.

Current climate data were obtained from observational weather in the forest grid provided by the Korea Meteorological Administration (KMA). In terms of future climate change data, while existing studies predicted the future using climate change data that considered only the intensity of the radiative force under representative concentration pathways (RCP), this study utilized the shared socioeconomic pathways (SSP) to consider future socio-economic changes. The SSP scenario comprises five distinctive scenarios regarding future mitigation and adaptation efforts for climate change, including social factors and policies. For this model, 1 km × 1 km of detailed SSP climate data from the Republic of Korea were applied. The annual temperature and precipitation of the SSP 1–2.6 and SSP 5–8.5 scenarios were used in the 5ENSMN ensemble model (HadGEM3-RA, WRF, CCLM, GRIMs, RegCM4) (KMA, 2022).

Four scenarios were individually established based on the application of climate change and forest management intensity variables in Republic of Korea (Kim et al., 2021).

The CO_2 stock, sequestration, and age distribution of various climate-resilient development pathways under future climate change were estimated for each scenario. In addition, these scenarios were analyzed chronologically. The four scenarios are summarized as follows (Table 2).

Climate change in Scenario 1 was considered SSP 5–8.5; this implied a society and economy with intensive fossil fuel usage and expanding urban-oriented development. However, it also included climate change adaptation strategies. It applied the current forest management practices of clear-cut harvest following the legal final cutting age, harvest by crown thinning, reforestation, and forest roads. Based on statistics from

Table 2
Scenario classification for this study.

Scenario	Description
1	Future climate change scenario SSP 5–8.5 Current level forest management: • clear-cut harvest according to the legal final cutting age (~ 15,000 ha year^{-1}) • harvest by thinning (~ 30 %) • accessibility from forest road (~ 0.5 km) Reforestation
2	Future climate change scenario SSP 1–2.6 Current level forest management: • clear-cut harvest according to the legal final cutting age (~ 15,000 ha year^{-1}) • harvest by thinning (~ 30 %) • accessibility from forest road (~ 0.5 km) Reforestation
3	Future climate change scenario SSP 5–8.5 Resilient level of forest management: • clear-cut harvest according to the legal final cutting age (~ 35,000 ha year^{-1}) • harvest by thinning (~ 30 %) • accessibility from forest road (~ 1 km) Reforestation
4	Future climate change scenario SSP 1–2.6 Resilient level of forest management: • clear-cut harvest according to the legal final cutting age (~ 35,000 ha year^{-1}) • harvest by thinning (~ 30 %) • accessibility from forest road (~ 1 km) Reforestation

the Korea Forest Service, the current annual forest tending area is approximately 130,000 ha, with around 15,000 ha designated for the legal final cut. Thinning, which constitutes 30 %, is conducted twice a year (Korea Forest Service, 2013). Therefore, thinning was set to be implemented at ages 20 and 40, and density management by 30 % crown thinning was applied to the selected rank in order from highest to lowest according to stand volume among the age (Lee et al., 2020). Korean policy stipulates that the cutting ages of *Pinus densiflora, Pinus koraiensis, Larix kaempferi, Quercus variabilis, Quercus mongolica*, mixed forest A, and mixed forest B should be 60, 60, 50, 60, 60, 60, and 60 years, respectively (Korea Law Information Center, 2017). It was established that the major tree species that can properly grow with climate change are planted during reforestation in clear-cut areas, considering the normal final age (Choi et al., 2011; Ryu et al., 2016). Moreover, the management area was within 0.5 km of forest roads (Hwang et al., 2016), reflecting the current status in the Republic of Korea (Cha et al., 1998). This management level was maintained continuously under Scenario 1.

In Scenario 2, forest changes were predicted by applying SSP 1–2.6. SSP 1–2.6 reflected sustainable economic growth in an environmentally friendly way with minimal use of fossil fuels owing to the development of renewable energy technology. Scenario 2 had the same forest management as Scenario 1; however, it reflected differences according to climate change scenarios.

In Scenario 3, climate change was similar to that in Scenario 1 but included climate-resilient development pathways. The area of the clear-cut harvest was approximately 35,000 ha year^{-1} using the legal final cutting age, harvesting was through crown thinning, and appropriate tree species were used for reforestation. Under the Korea Forest Service, a forest tending promotion plan (2018–2037), 200,000 ha of annual cutting (e.g., legal cutting and thinning) is planned (Korea Forest Service, 2018b). Therefore, in this study, the thinning intensity, frequency of implementation for which the current state was maintained, and addition of 35,000 ha of legal final cutting to maximize forest growth were applied to scenario 3 (Hong et al., 2022; Korea Forest Service, 2018a). In addition, according to the 5th National Forest Road Master Plan (Korea Forest Service, 2020a, 2021a), the scenario was established to implement management at the priority level for stands within 1 km of forest roads (Hwang et al., 2016).

Scenario 4 was based on the premise that ideal forest management of the CRDP would be implemented, covering all the above management scenarios and SSP 1–2.6.

'Scenarios 1 and 2' and 'Scenarios 3 and 4' analyzed the adaptation strategies using various forest management intensities. They also modeled the effects of climate change in relation to SSP 1–2.6 and SSP 5–8.5 from multiple angles. When applying forest management, spatial area are classified into two types: managed and restricted forest areas (Kim et al., 2017a, 2017b). Based on forest regulations and spatial data, the managed harvest area spans 3,178,900 ha, representing about 52.48 % of the total forest area. The density of forest roads is 3.5 m ha^{-1}. The density and facility expansion of forest road standards were analyzed based on accessibility, referring to previous studies. This study prioritizes the implementation of forest road-focused forest management. Furthermore, the Korea Forest Service has suggested an authorized clear-cut harvest for each tree species according to the final age of maturity (Korea Forest Service, 2020b). Therefore, the cycle of final felling and regeneration depends on the tree species in the management area. In addition, this study did not include any natural disturbances or changes in land cover, such as afforestation or deforestation, during the simulation periods.

2.5. Data preparation and modification

In this study, a basic data-set for model simulation was constructed using forest type maps and NFI to analyze CRDP. A data set was constructed with a spatial resolution of 1 km. The forest type maps utilized data from 2019 (Hong et al., 2023). Information on tree species, forest physiognomy, stand age class, DBH class, stand density, protection, and management type were used for the model simulations. For the NFI data, attributes within the basic spatial dataset were supplemented based on field-measured data. Estimating the site index of stands from measured dominant tree heights was incorporated into the model. Furthermore, to simulate the management module, the 2019 forest road data provided by the Korea Forest Service were gridded for accessibility. For managed areas, the legal final cut, thinning, and reforestation area were applied based on the 6th Basic Forest Plan and 4th Forest Tending Promotion Plan. For the selection of managed areas, the criteria were based on the legal final cutting age, and an algorithm was devised for selection based on stand age and stand volume. Thinning intensity was established to be approximately 30 %, conducted twice a year for stands aged 20 or 40 years. The accessibility of forest roads was determined based on previous literature and the 5th Forest Road Plan (2021–2030) by applying either a 0.5 km or 1 km radius.

For climate data, we used meteorological observations from the KMA and monthly average temperature and cumulative precipitation data with a 1 km resolution from the detailed Republic of Korea's SSP climate change scenarios (2021−2100). Current climate data were obtained from an automated synoptic observation system of 73 weather stations (2000–2020). In the case of climate change data, in order to compare the potential future of nature or humans in terms of CRDP and the scenario of desirable social goals in terms of carbon neutral management on a BAU basis, SSP1–2.6 (minimization of fossil fuel use through development of renewable energy technology, sustainable Economic growth assumption) and SSP5–8.5 (assumption of high fossil fuel use and indiscriminate expansion of development) were applied. A detailed description of the data preparation process is provided by Kim et al. in 2019 (Kim et al., 2019).

3. Results

3.1. The changes in growth of forest

This study analyzed annual growth using an integrated forest growth model, weather data reflecting society and economy, and advanced management options. The growth results varied according to the scenarios, and the results were derived by year or period to consider dynamic changes in forests.

In the 2030s, Scenarios 1 and 2 show an annual growth of 2.88 m^3 ha^{-1} $year^{-1}$, while Scenario 3 is slightly higher at 2.89 m^3 ha^{-1} $year^{-1}$, and Scenario 4 is lower at 2.57 m^3 ha^{-1} $year^{-1}$. By the 2050s, Scenario 4 has the highest growth rate at 2.39 m^3 ha^{-1} $year^{-1}$, and Scenario 1 has the lowest at 1.97 m^3 ha^{-1} $year^{-1}$. In the 2080s, Scenario 4 again leads with 2.40 m^3 ha^{-1} $year^{-1}$, while Scenario 1 is the lowest at 1.83 m^3 ha^{-1} $year^{-1}$. In the 2100 s, Scenario 4 shows the highest predicted growth rate of 3.16 m^3 ha^{-1} $year^{-1}$ (Fig. 2).

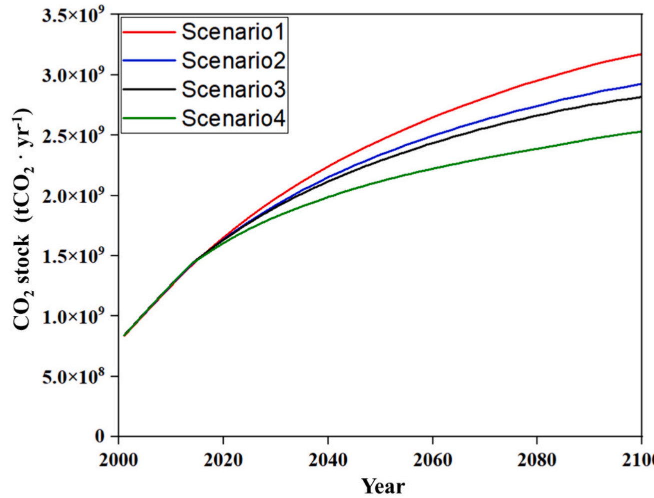

Fig. 3. The changes in annual CO_2 stock under climate change and management scenarios.

Although the overall growth was estimated to decrease until 2050 owing to climate change, the estimated growth by climate zone would increase along with the reforestation of species suitable for climate change following harvest. In addition, the estimated growth was lower than that in the scenario in which forest tending was slightly reduced according to the growth of the young forest owing to the reforestation of appropriate tree species due to climate change in the early stage of the expansion of forest management. However, it has increased significantly over the long term.

3.2. The change in CO_2 stocks

The model analyzed the growing stock-based CO_2 stocks in forests. In the 2030s, CO_2 stocks were 1.97 billion tCO_2 $year^{-1}$ for Scenario 1, 1.92 billion tCO_2 $year^{-1}$ for Scenario 2, 1.90 billion tCO_2 $year^{-1}$ for Scenario 3, and 1.82 billion tCO_2 $year^{-1}$ for Scenario 4. In the 2050s, Scenario 1 had the highest stocks at 2.45 billion tCO_2 $year^{-1}$, while Scenario 4 had the lowest at 2.11 billion tCO_2 $year^{-1}$. By the 2080s, Scenario 1 again had the highest stocks at 2.95 billion tCO_2 $year^{-1}$, with Scenario 4

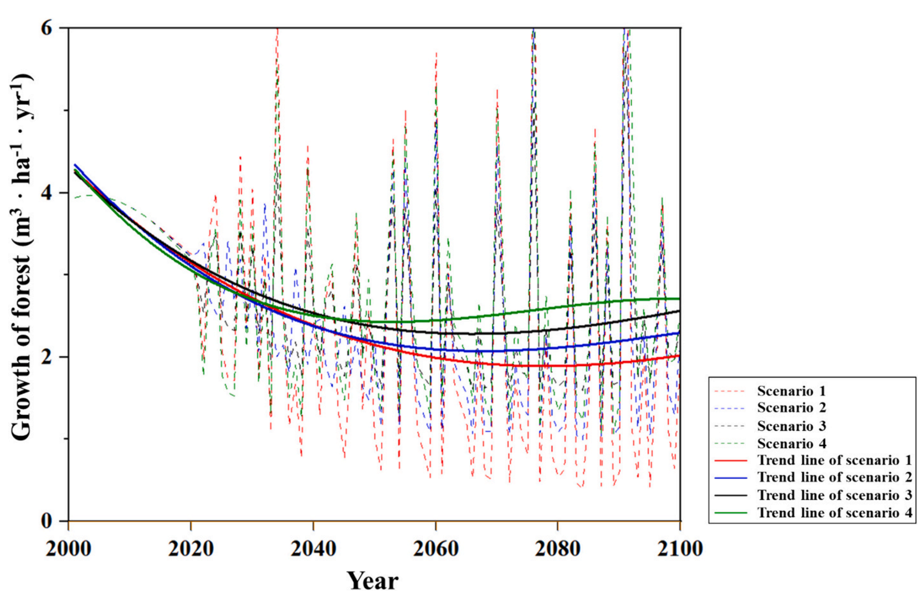

Fig. 2. The estimated growth of the forest according to the scenarios (Scenario 1: SSP 5–8.5 + Current forest management level, Scenario 2: SSP 1–2.6 + Current forest management level, Scenario 3: SSP 5–8.5 + Resilient forest management level, Scenario 4: SSP 1–2.6 + Resilient forest management level).

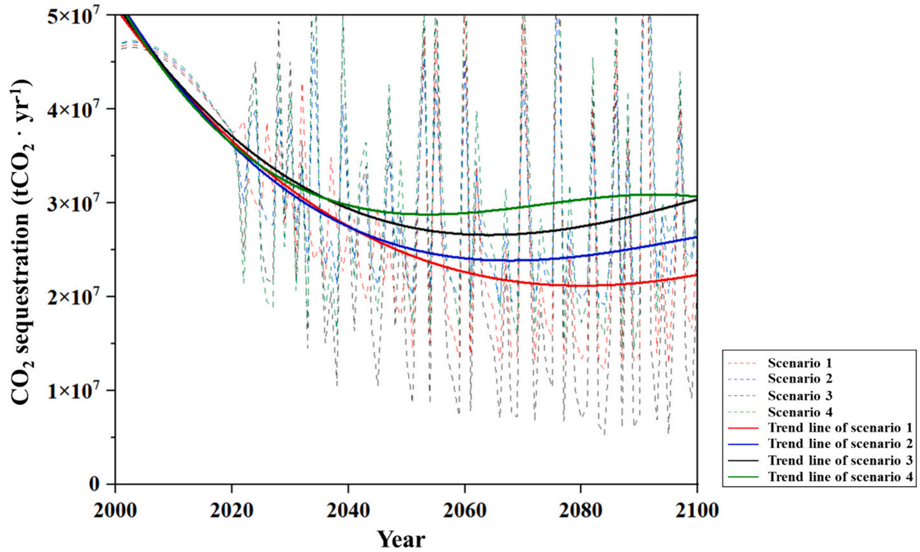

Fig. 4. Estimated result of time series CO_2 sequestration.

showing the lowest at 2.38 billion tCO_2 $year^{-1}$. In the 2100 s, Scenario 1 is predicted to have the highest CO_2 stocks at 3.17 billion tCO_2 $year^{-1}$ (Fig. 3).

Despite the overall trend of increasing forest stocks, management has been associated with decreased forest stocks. This contributed to the prevention of carbon emissions due to climate change-induced tree death and enhanced the utilization of carbon capture in harvested wood products (HWP) after logging.

3.3. The changes in annual CO_2 sequestration

The model analyzed growth-based CO_2 sequestration according to climate change scenarios and management options. CO_2 sequestration was derived as a result of the value in the model by year and was shown by period from a long-term perspective.

In the 2030, CO_2 sequestration was 33.56 million tCO_2 $year^{-1}$ for Scenario 1, 33.42 million tCO_2 $year^{-1}$ for Scenario 2, 33.60 million tCO_2 $year^{-1}$ for Scenario 3, and 30.94 million tCO_2 $year^{-1}$ for Scenario 4. By the 2050s, sequestration was highest in Scenario 4 at 28.49 million tCO_2 $year^{-1}$ and lowest in Scenario 1 at 23.04 million tCO_2 $year^{-1}$. In the 2080s, Scenario 4 had the highest sequestration at 28.48 million tCO_2 $year^{-1}$, while Scenario 1 had the lowest at 20.71 million tCO_2 $year^{-1}$. In the 2100 s, Scenario 4 is predicted to have the highest sequestration at 35.24 million tCO_2 $year^{-1}$ (Fig. 4).

CO_2 sequestration showed a similar pattern to that of growth. However, the values were somewhat different, depending on the carbon

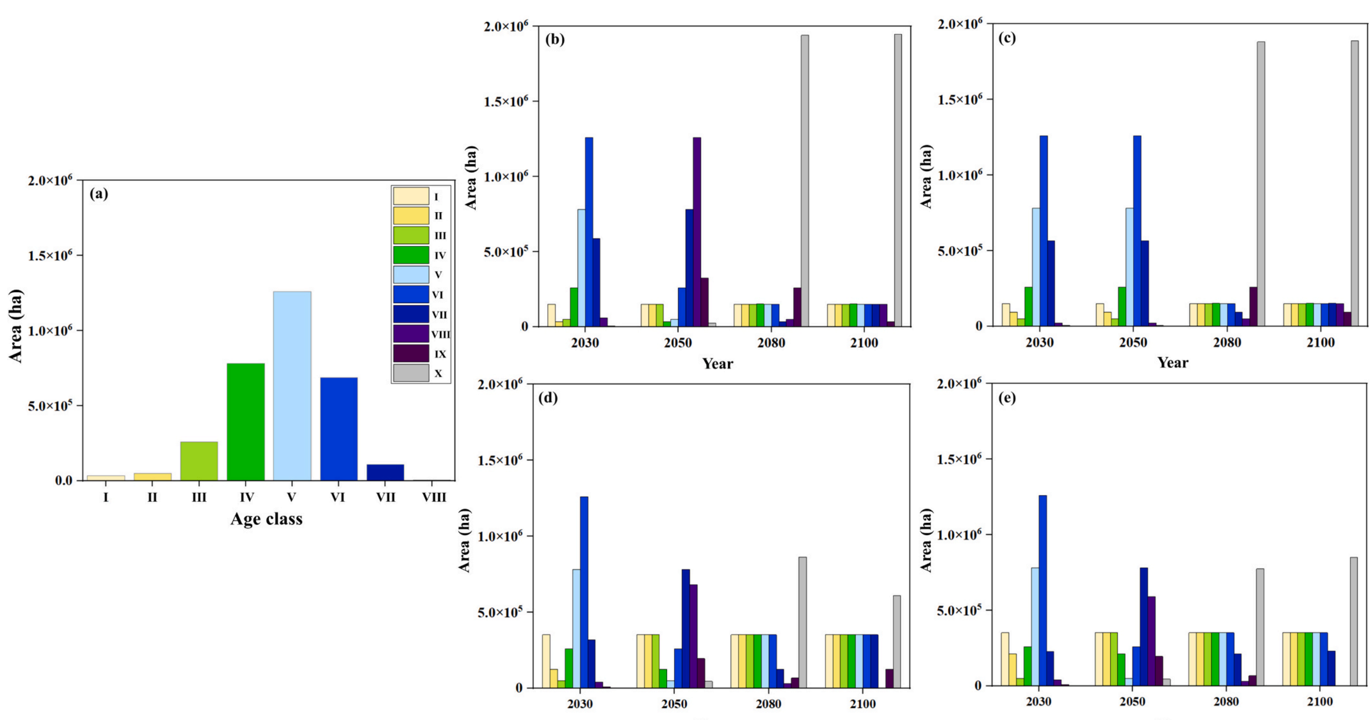

Fig. 5. The changes in age distribution within Republic of Korea's managed forests under different climate change and management scenarios (a: current age class distribution, b: Scenario 1, c: Scenario 2, d: Scenario 3, e: Scenario 4).

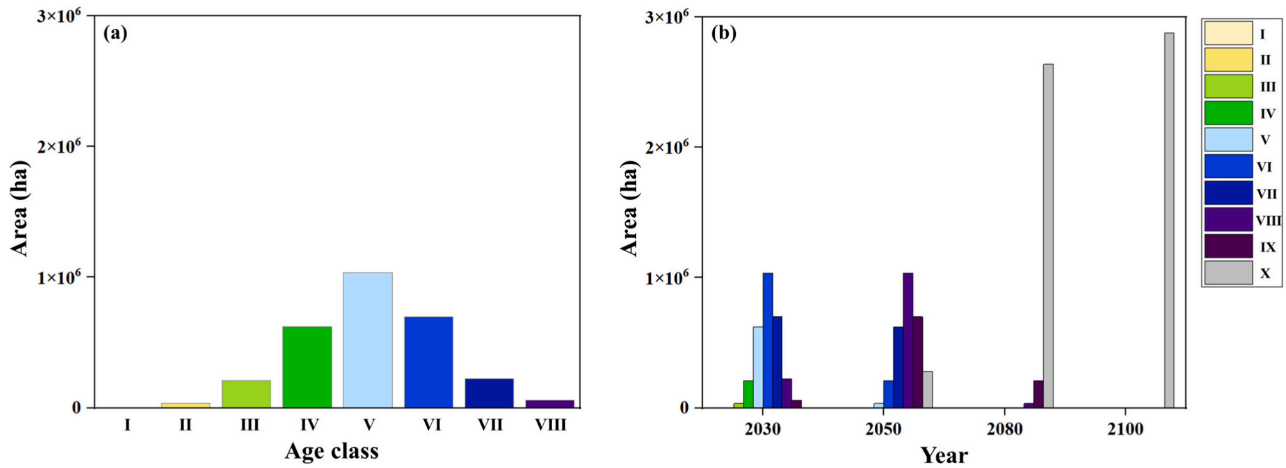

Fig. 6. The (a) distribution state of the current age class and (b) future age class distribution prediction in the protected forest.

emission coefficient for each tree species, and the replanting of appropriate tree species for climate change. In addition, the higher the management level, the higher the CO_2 sequestration.

3.4. The age distribution

Forest management for climate change mitigation and adaptation improved the unbalanced age-class structure in the Republic of Korea's forests and slowed the process of forest over-maturing. Age class III or above currently accounts for approximately 98 % of base stands.

When applying the scenarios, the proportion of forests reaching age class III or above in the 2030s was high across all scenarios, with Scenarios 1 and 2 maintaining around 95 % or more. However, a more pronounced difference was estimated in managed and protected forests by the 2100 s.

This was analyzed separately for protected and managed forestlands. In the managed forests, the proportion of age class III was approximately 94 % in Scenario 1, approximately 92 % in Scenario 2, approximately 85 % in Scenario 3, and approximately 82 % in Scenario 4 in the 2030s. In the 2100 s, Scenarios 1 and 2 accounted for approximately 90 %, and scenarios 3 and 4 accounted for approximately 77 % (Fig. 5). The total area of protected forest was age class III or higher from 2030 onward (Fig. 6). Therefore, a high legally harvested area was associated with a high degree of improvement, and the advanced climate change scenario facilitated the speed of improvement.

4. Discussion and policy implications

While various plans and concepts for the CRDP have been intricately designed and discussed in terms of concepts, guidelines, and frameworks, studies that analyzed or deliberated their directionality are lacking (IPCC, 2023). Accordingly, this study conducted a multifaceted analysis of optimal forest carbon management strategies based on greenhouse gas reduction to explore feasible CRDPs in the Republic of Korea based on the scenario approach. Scenario 1 assumed that greenhouse gas reduction fails and that forest management is in its current state. Scenario 2 assumed that greenhouse gas reduction is successful but that forest operations are in their current state. Scenario 3 assumed failed greenhouse gas reduction, but the forests are optimally managed based on policies. Scenario 4 assumed successful greenhouse gas reduction and optimal forest management. Therefore, this study is significant in that it analyzed dynamic changes by considering not only the

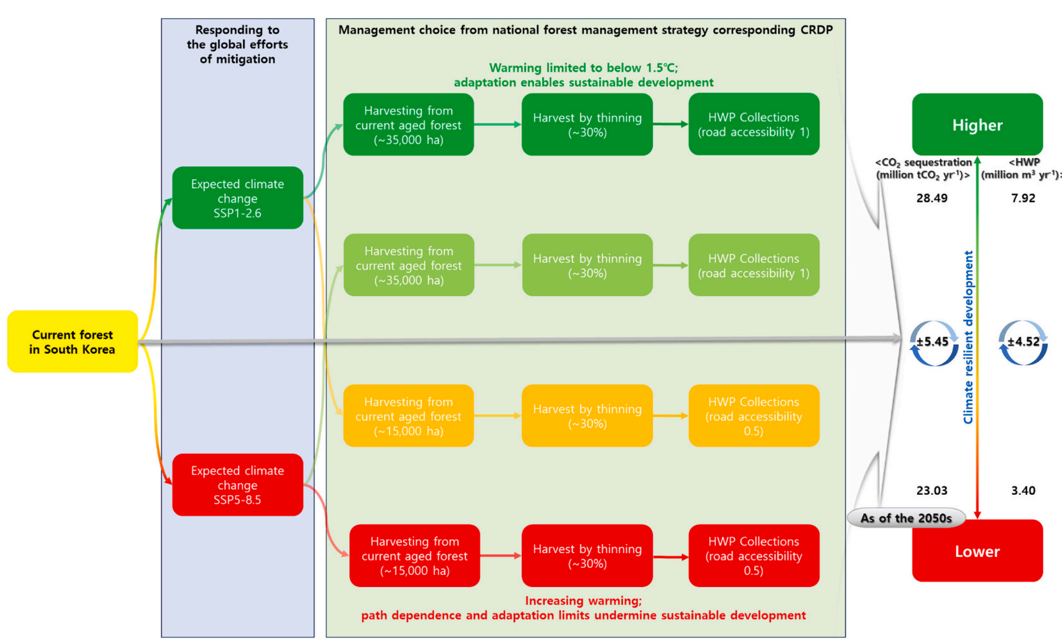

Fig. 7. Flowchart for exploring CRDP for GHG mitigation and adaptation efforts in the Republic of Korea.

intensity of the existing radiative forcing but also socioeconomic changes and the degree of forest management (Fig. 7).

We compared extreme climate and sustainable climate scenarios against the BAU baseline to explore feasible national-level carbon management pathways to align with global responses. Overall, it was found that when SSP 1–2.6 was applied to the scenario rather than SSP 5–8.5, and management based on the forest plan rather than the current operation was implemented, the age class of the forest came out to be more balanced. For example, in Scenario 4, the growth and CO_2 sequestration in 2030 were lower than those in other scenarios because the degree of greenhouse gases and forest management was high. This was because replanting tree species suitable for climate change after cutting increased the distribution area of young forests compared to other scenarios (Ryu et al., 2016). Subsequently, the age class balance began in 2050, and the growth and sequestration of replanted species adapted to climate change increased. Thus, this study reveals an effective long-term forest management strategy.

In addition, regarding stocks, the higher the level of management, the lower the storage amount. However, this has contributed to the utilization of HWP by carbon capture following harvest (Jandl et al., 2018). The Republic of Korea has 804 million tons of biomass resources, and according to current forest trends, it has been predicted that the amount of forest biomass resources that can be supplied to the market per year is approximately 1300 thousand tons (Son et al., 2014). According to the simulations, the impact of each scenario on stem biomass, as calculated from cutting, varied substantially by the 2030s. Scenario 1 produced approximately 1749 thousand tons of biomass annually. This figure increased significantly under Scenario 2, reaching about 2036 thousand tons. However, the most notable increases were observed in Scenarios 3 and 4, with annual outputs escalating to 3539 thousand tons and 4313 thousand tons, respectively. This suggested that further expansion of forest management plans could increase carbon sinks and resource circulation (Domke et al., 2020). In particular, the HWP analysis should consider the accessibility of forest roads and biomass management after harvest. This study made this possible by improving the existing model with the AKO-G-Dynamic model. The strength of this model lies in its capability to conduct analyses considering these factors, enabling more effective policy design in response to climate change.

Most existing studies in the Republic of Korea have primarily focused on individual tree species or management strategies, such as thinning and deforestation, to analyze dynamic changes in forests (Bae et al., 2010; Kim and Kang, 2008). Furthermore, most climate change studies have applied the representative concentration pathway (RCP) scenario (Kim et al., 2012; Lee et al., 2014). In this study, we applied socioeconomic-based climate scenarios and enhanced the model by comprehensively considering the spatial and temporal aspects of forest management factors. It proposed strengthened adaptation strategies from a feasible process perspective.

Nevertheless, this study did not reflect the natural disturbances or changes in land cover, such as afforestation or deforestation, during the simulation periods, nor did it include carbon capture using wood products, which should be addressed in future studies (Rüter et al., 2016). The analysis conducted in the formation of the CRDP focused primarily on policy implications at the national level, and thus, an in-depth analysis of biodiversity and other related factors was not carried out (Pettorelli et al., 2021; Rudel et al., 2020). Although there was some consideration of species renewal, a review of the qualitative aspects of forests will be necessary in the future (Otero et al., 2020). Additionally, as global discussions on climate change and biodiversity progress, there is a need for further improvement in research that has focused on climate change and carbon. Therefore, current KO-G or AKO-G Dynamics model need to be developed considering these issues.

This study analyzed the development path through carbon management for climate mitigation based on Korea's national strategic plan to present a feasible way despite the difficulties in seeking a national CRDP to solve global climate problems. Therefore, utilizing the most recently available data, various pathways for CRDP were explored, considering extreme situations of climate change and forestry management stages. Consequently, scientific evidence can be provided incrementally for policy decision-making based on each step. It also plays a crucial role in climate change resilience and adaptation. In particular, through detailed management scenarios and quantitative figures, the extent of greenhouse gas reduction can be analyzed (Lundmark et al., 2014). These can play a role in the global achievement of the NDC and LEDS and serve as the basis for national forestry master plans and local government forest plans (Janetschek et al., 2020).

5. Conclusion

This study analyzed the multiple linkages between socioeconomic-based climate change data and forest management, including forest tending and forest roads, by advancing the existing integrated forest growth models. The results demonstrated that adopting climate resilient forests based on climate scenarios and forest management plans reflecting socio-economic change efforts for greenhouse gas reduction enhanced the forest's age-class balance and its role as a sink. In particular, it was confirmed that legal cuts, reforestation with species suitable for climate change, and accessibility based on forest road density are essential for adaptation to climate change.

Furthermore, the results can contribute to the efficient utilization of HWP if trees that are vulnerable to growth owing to climate change are harvested through resilient forest management. This suggests that the HWP can be used for carbon capture and storage. Therefore, Korea must prepare an adaptation strategy that reflects the characteristics of the forest, increase its budget, and improve the system to secure sinks. This suggests that the Republic of Korea can achieve CRDP and contribute to carbon neutrality.

CRediT authorship contribution statement

Mina Hong: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Cholho Song:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Moonil Kim:** Writing – review & editing, Supervision, Methodology. **Florian Kraxner:** Writing – review & editing, Supervision, Methodology. **Youngjin Ko:** Writing – review & editing, Supervision, Methodology. **Jiwon Son:** Writing – review & editing, Supervision, Methodology. **Woo-Kyun Lee:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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