Application of integrated Korean forest growth dynamics model to meet NDC target by considering forest management scenarios and budget

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Abstract
Background: Forests are atmospheric carbon sinks, whose natural growth can contribute to climate change mitigation. However, they are also affected by climate change and various other phenomena, for example, the low growth of coniferous forests currently reported globally, including in the Republic of Korea. In response to the implementation of the Paris Agreement, the Korean government has proposed 2030 greenhouse gas roadmap to achieve a Nationally Determined Contribution (NDC), and the forest sector set a sequestration target of 26 million tons by 2030. In this study, the Korean forest growth model (KO-G-Dynamic model) was used to analyze various climate change and forest management scenarios and their capacity to address the NDC targets. A 2050 climate change adaptation strategy is suggested based on forest growth and CO2 sequestration.

Results: Forest growth was predicted to gradually decline, and CO2 sequestration was predicted to reach 23 million tons per year in 2050 if current climate and conditions are maintained. According to the model, sequestrations of 33 million tCO2 year\(^{-1}\) in 2030 and 27 million tCO2 year\(^{-1}\) in 2050 can be achieved if ideal forest management is implemented. It was also estimated that the current forest management budget of 317 billion KRW (264 million USD) should be twice as large at 722 billion KRW (602 million USD) in the 2030s and 618 billion KRW (516 million USD) in the 2050s to achieve NDC targets.

Conclusions: The growth trend in Korea's forests transitions from young-matured stands to over-mature forests. The presented model-based forest management plans are an appropriate response and can increase the capacity of Korea to achieve its NDC targets. Such a modeling can help the forestry sector develop plans and policies for climate change adaptation.

Keywords: Forest growth model, Forest management, CO2 sequestration, NDC, Forest budget, Climate change

Background
Climate change is considered a global issue that affects our lives, surrounding environment, and socioeconomical sectors [1]. The Paris Agreement is proposed as a “new climate regime”, replacing the Kyoto Protocol that expired at the end of 2020 [2]. It includes long-term goals for greenhouse gas (GHG) reduction, introduction of
market mechanisms, climate change adaptations, implementation checks, and technology transfers [3]. The proposition of the "new climate regime" with the Paris Agreement will result in active international efforts to reduce GHG emissions [4]. After the adoption of the Paris Agreement, each country is expected to submit Nationally Determined Contributions (NDCs) and voluntarily set goals and plans that also address various cross-cutting issues [5]. Among them, the possibility of carbon emission reduction was reviewed sector-by-sector (e.g., industries, and energy), and the Paris Agreement emphasized the necessity of maintaining and promoting carbon sinks, including forests [6].

In response, the NDC submitted by each country should also include the utilization of carbon stocks and the sequestration functions of forests [7]. Accordingly, the Republic of Korea has increased its interest and investment in carbon reduction activities and is promoting carbon sequestration functions through forests, to achieve their NDC target in accordance with the 2030 Greenhouse Gas Roadmap [8]. According to the National Institute of Forest Science, current net amount of CO2 sequestration of the forest sector is estimated to be approximately 45 million tons per year but the expected amount of CO2 sequestration is 13 million tons per year in 2050 [9]. Therefore, the Korean government has set a CO2 sequestration target of 26 million tons by 2030 through the promotion of forest management and accelerated preparation [10], under the “2050 Carbon Sequestration and Long Term Strategy” [11]. The 2050 GHG reduction strategy is currently being reviewed and will upgrade the forest GHG inventory plans, including afforestation, reforestation, forest tending, roundwood production and supply expansion, and unused biomass [12].

Carbon sequestration will have to be expanded to meet the NDC for the forestry sector. This will also require enhancing the forest health, in accordance with proper forest management practices in changing climatic conditions. In addition to mitigating global warming, afforestation and efficient forest management will provide various public service functions, such as ecosystem conservation, water retention capacity, air purification, prevention of soil erosion, and provision of recreational functions [13]. In the Republic of Korea, forests comprise approximately 63% of the land, which can be considered a significant carbon sink [14–16]. Consequently, the Republic of Korea emphasizes the importance of forest management strategies [17]. This requires synthetic considerations that have not been considered in previous investigations [18]. Hence, this study sought to predict these synthetic considerations using a model [19].

Although Korea’s forest policy previously focused on the development of forest resources for erosion control and greening, it later changed to a systematic sustainable forest management objective [20]. Therefore, Korea’s forest management approach, from the past to the present, has primarily contributed to forestry governance and economic development, as it is implemented under state-based policies [21, 22]. In particular, the Korea Forest Service is responsible for forest GHG evaluation, and it executes the actual forest budget and establishes the forest unit price [23]. However, discussions regarding forest management measures that can promote carbon sinks are relatively inactive [24]. Furthermore, in previous studies, only thinning or cutting of forests was simulated, and dynamic growth was only modeled for individual tree species or the entire stand, depending on the future climate change scenario [25, 26]. It was previously difficult to understand which forest management strategies were advantageous and to identify the extent of management required to achieve the forest areas and yields set as policy targets. However, current modeling technologies can be used to address this problem by analyzing valid policy scenarios for NDC achievement.

Therefore, in this study, a spatiotemporal dynamic stand-growth model capable of reflecting forest growth mechanisms under climate change was used to analyze growth trends and determine the amount of CO2 sequestration for a range of forest management scenarios. This study will not only contribute to the achievement of the NDC, but also improve the effectiveness of the contribution through economic analysis.

**Methods**

**Study area**

The study area comprised the forest area in the Republic of Korea (longitude: 124° 54–131° 6 and latitude: 33° 9–38° 45). Korean forests include coniferous forests (mainly Pinus densiflora), deciduous broad-leaved forests (mainly Quercus spp.), and mixed forests, comprising approximately 37%, 32%, and 26%, respectively, of the total forest area in 2018 [27–29] (Fig. 1). They currently cover 62.6% (6.28 million ha) of Korean land; however, in the 1950s, they only covered 35% [30, 31]. They can be regarded as successful examples of forest restoration utilizing good management practices. However, the restored forests are currently experiencing management challenges [32]. As many stands in the Korean forests are becoming old, they suffer risks such as the decreasing growth of conifers due to climate change [33–35]. The government implements forest management policy through the 6th basic forest plan [36]. This study analyzed the ability of Korean forests to effectively cope with anticipated climate change.
NDC assessments in the forestry sector

Dynamic stand-growth model

In this study, the “KO-G-Dynamic model” a dynamic stand-growth model, was used to evaluate the CO₂ sequestration as aimed in the NDC [28] (Fig. 2). The KO-G-Dynamic model has previously helped enhance the forest growth model [37–40]. It can accurately predict the growth of temperate forests (which grow yearly), also considering the climatic impacts overlooked by traditional dynamic growth models [28, 41]. These climate factors affect diameter at breast height (DBH) and mortality [39, 40, 42]. This reduces the uncertainty in future growth estimates under climate change, facilitating the assessment of vulnerable forest areas according to Korea’s ecological and environmental characteristics [37, 40]. For this study, Korean forests were divided into seven major types: red pine (Pinus densiflora), Japanese larch (Larix kaempferi), Korean pine (Pinus koraiensis), cork oak (Quercus variabilis), Mongolian oak (Quercus mongolica), mixed forest A (Mixed-A: red pine and cork oak), and mixed forest B (Mixed-B: red pine and Mongolian oak), based on mapped forest type classification. These results can then be used to derive forest growing stock volume using information such as the diameter at breast height, tree height, and stand density (Eq. (1)).

\[
V_{ij} = a \cdot DBH_{ij}^b \cdot Hm_{ij}^c \times N_{ij}
\]

where \(i\) is the serial number for each stand, \(j\) is the year, DBH is the stand average diameter at breast height, \(Hm\) is the average tree height of the stand, and \(N\) is the stand density (trees/ha).

Coefficients (\(a, b,\) and \(c\), determined for each tree species (Table 1), were incorporated with the biomass allometric equation data developed by the National Institute of Forest Science (NIFoS) [43]. The DBH was estimated using the forest growth model (Eq. (2)), \(Hm\) was calculated using the site index and the age of stand, Age was calculated based on the age-class of the vector-based forest map which classified forest age by every 10 years, compared with the age data of the NFI. Therefore, raster data set had averaged data following previous studies [28], and Nha was analyzed using a tree mortality model.

\[
DBH = f(Age, SI, Nha)
\]
where SI is the site index, Nha is the stand density (trees/ha), and Age is the age of the stand.

The mortality rates of stands can be obtained using the relative density index, which is derived from the maximum stem number determined by Sterba (1987) [44]. The DBH development formula was used to derive an equation for the estimation of maximum stand density based on the mean of the dominant tree height and the mean of the DBH, Kim et al. [39] not only identified the relationship between the estimated maximum and actual stand density ratio, but also mathematically analyzed the relationship between maximum stand density reduction and the actual mortality (Eq. (3)).

\[
\left( \frac{\text{Mortality}_i}{N_{\text{max}i} - N_{\text{max}i+1}} \right) = a \cdot e^{b \left( \frac{N_{\text{ha}i}}{N_{\text{max}i}} \right)}
\]

\[
\text{Mortality}_i = a \cdot e^{b \left( \frac{N_{\text{ha}i}}{N_{\text{max}i}} \right)} \cdot (N_{\text{max}i} - N_{\text{max}i+1}) \quad (3)
\]

where \(\text{Mortality}_i\) is the actual mortality at stand age \(i\), \(N_{\text{ha}i}\) is the stand density at stand age \(i\), and \(N_{\text{max}i}\) is the maximum stand density at stand age \(i\).

For forest management assessment, the area of reforestation and the area of management with maximum forest growth were estimated in manageable areas [30]. It was assumed that the legal final cut would be performed among tree species as currently announced by the Korea Forest Service [45]. The forest management area was fixed for each scenario, and the stand with the highest stand age was cut first (Eq. (4)). If the forest physiognomy of the same age class is greater than the number of potential cutting areas within the size of the potential cutting area determined for each scenario, the forest growing stock volume is cut in order of highest to lowest. Crown thinning was implemented twice a year [46–48].

\[
PH_i = \sum \left[ \left( \text{Age}_{ki} \geq FA_j \right) \cap (\text{MA}) \right]
\]

(4)
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 where forest management is possible.

In the 5th national forest inventory, the site index for each stand was estimated and applied to the model based on the dominant tree height information from the enumeration districts. It was calibrated based on further data from the 6th national forest inventory. Using the above formulas, the accumulation and growth volumes of forests can be analyzed annually [28, 39].

**CO₂ sequestration in forests**

In this study, the amount of CO₂ sequestration was calculated for seven dominant forest types in Korea to determine the feasibility of sequestering 26 million tons by the 2030s, as proposed in the basic roadmap for GHG reduction.

For this calculation, the calculation method of CO₂ sequestration basically utilizes the IPCC 2006 guidance provisions method and follows the stock change method of the forest land part [49, 50]. The National Institute of Forest Science which analyzes forest carbon in South Korea also uses the methodology to calculate CO₂ sequestration [43]. At this time, it is estimated through sequestration factor for each tree species based on the growth according to the annual difference in stand volume. In this study, carbon stock (\( C \)) was calculated by using country-specific factors such as basic wood density (\( D \)), biomass expansion factor (\( BEF \)), and root/shoot ratio (\( RS \)) developed by the National Institute of Forest Science in the stand volume calculated through the growth model [28] (Table 2, Eq. 5). This estimated the annual change in carbon stock (\( CS \)) in remaining forest land (Eq. 6) and converted to CO₂ sequestration (Eq. 7).

\[
C_t = V_t \times D_j \times BEF_j \times (1 + RS_j) \times CF \tag{5}
\]

\[
\Delta CS_t = \frac{CS_{t+1} - CS_t}{t+1 - t_t} \tag{6}
\]

\[
\Delta CO_{2t} = \Delta CS_t \times \frac{44}{12} \tag{7}
\]

where \( C \) is carbon stock (tC/ha), \( V \) is the stand volume (m³/ha), \( D \) 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), \( t_t \) is the year, \( j \) is tree species, \( CS_t \) and \( CS_{t+1} \) are the annual change in carbon stock (tC/ha/year) calculated at \( t_t \) and \( t_{t+1} \) year, \( \Delta CO_{2t} \) is annual carbon dioxide sequestration (tCO₂/ha/year), and 44/12 is the stoichiometric ratio of CO₂ and C.

**Table 1** Coefficients used to calculate the forest growing stock volume by tree species (NiFoS, 2010)

| Coefficient | Pinus densiflora | Larix kaempferi | Pinus koraiensis | Quercus variabilis | Quercus mongolica |
|-------------|-----------------|-----------------|-----------------|-------------------|------------------|
| a           | 0.000201        | 0.000088        | 0.000015        | 0.000047          | 0.000344         |
| b           | 1.7593          | 1.7828          | 2.4239          | 1.8603            | 1.3639           |
| c           | 0.6583          | 0.9397          | 0.8651          | 1.0589            | 0.8793           |

**Table 2** Carbon emission factors for the major Korean tree species (NiFoS, 2014)

| Tree species              | Basic wood density | Biomass expansion factor | Root/Shoot ratio |
|---------------------------|--------------------|--------------------------|------------------|
| Pinus densiflora          | 0.472              | 1.413                    | 1.254            |
| Pinus koraiensis          | 0.408              | 1.812                    | 1.283            |
| Larix kaempferi           | 0.453              | 1.335                    | 1.291            |
| Quercus variabilis        | 0.721              | 1.338                    | 1.324            |
| Quercus mongolica         | 0.663              | 1.603                    | 1.388            |
| Mixed forest 1 (Pinus densiflora, Quercus variabilis) | 0.5965 | 1.375 | 1.289 |
| Mixed forest 2 (Pinus densiflora, Quercus mongolica) | 0.5675 | 1.508 | 1.321 |
Application scenario

In this study, three time periods were used: the current base period (2010–2015), 2030 (2026–2035), and 2050 (2046–2055). The analysis reflects the current transition in the forest physiognomy in Republic of Korea from young-matured stands to over-mature forests. Four scenarios were established individually according to the application of the variables which are climate change and forest management intensity in South Korea [41].

Under each scenario, the cost of adapting various management strategies to future climate change was estimated. Also, these scenarios can be analyzed chronologically. The four scenarios were finally summarized as follows (Table 3).

In Scenario 1, climate change was not considered, which means the current climate condition is maintained. Also, an overprotective forest was assumed that no forest management, such as harvest, is performed during study periods.

In scenarios 2, forest changes were predicted by applying the IPCC representative concentration pathway (RCP) scenario 8.5. RCP 8.5 is a scenario (business as usual BAU) in which greenhouse gases are emitted without reduction of greenhouse gases and is mainly used to predict changes in forests due to climate change. Therefore, scenario 2 reflected the climate change and the overprotective forest which is same as scenario 1.

In scenario 3, climate change was considered like scenario 2, but it includes climate change adaptation strategies. It applied the current forest management practices of clear-cut harvest, in accordance with the legal final cutting age, harvest by crown thinning, and reforestation. According to the statistics of the Korea Forest Service, current annual forest tending area is approximately 130,000 ha, of which the legal final cut is approximately 15,000 ha and thinning is 30%, which is conducted twice a year [51]. Therefore, it was set to implement thinning for 20 and 40 years of age, and density management by 30% crown thinning in the selected rank in order of highest to lowest according to the stand volume among the age [52]. Based on the Korean policy about the cutting age, the cutting ages of red Pine, Korean pine, Japanese larch, cork oak, Mongolian oak, mixed forest A, mixed forest B were 60, 60, 50, 60, 60, 60 and 60 respectively [53]. At this time, it was set that the major tree species which can properly grow according to climate change are planted during reforestation in the clear-cut area according to normal final age [42, 54]. These management level were continuously maintained under Scenario 3.

Scenario 4 was based on the premise that ideal forest management would be implemented, which would cover all the above scenarios; the area of clear-cut harvest was approximately 35,000 ha/yr using the legal final cutting age, harvesting by crown thinning, and the use of appropriate tree species for reforestation. Under the Korea Forest Service forest tending promotion plan (2018–2037), 200,000 ha of cutting (legal cut, thinning, etc.) is planned annually [55]. Therefore, in this study, the thinning intensity, the frequency of implementation for which the current state was maintained, and the addition of 35,000 ha of legal final cut to maximize forest growth were applied to Scenario 4 [41, 56].

In short, scenario 2, 3, and 4 modeled the impact of climate changes based on RCP 8.5 with different intensity of forest managements based on the adaptation strategies. When this study applied the forest management, the spatial area was classified into two types of management forest areas and restricted forest areas [39]. Based on forest regulations and spatial data, the harvest and management area of the forest occupied 3,178,900 ha, approximately 52.48% of the total forest. Furthermore, Korea Forest Services suggested and authorized clear-cut harvest for each year.

Table 3  Scenario classification for this study

| Scenario | Description |
|----------|-------------|
| 1        | Overprotection |
| 2        | Future climate change scenario RCP 8.5 |
| 3        | Future climate change scenario RCP 8.5 |
| 4        | Ideal level of forest management: |

| Scenario | Description |
|----------|-------------|
| 1        | Current climate maintenance (no climate change occurs) |
| 2        | Overprotection |
| 3        | Future climate change scenario RCP 8.5 |
| 4        | Ideal level of forest management: |

| Scenario | Description |
|----------|-------------|
| 1        | Current climate maintenance (no climate change occurs) |
| 2        | Overprotection |
| 3        | Future climate change scenario RCP 8.5 |
| 4        | Ideal level of forest management: |
tree species according to the final age of maturity [57]. Therefore, the cycle of final felling and regeneration is according to the tree species in the manageable area. In addition, we did not include any natural disturbances and changes in land cover such as afforestation or deforestation in the simulation periods.

Data preparation and modifications

To quantitatively understand the effects of climate change, a baseline climate scenario and climate change scenario were used in this investigation. For the current climate assessment, the average temperature data from 2000 to 2010 were considered as the fixed baseline climate. For future climate changes, the realistic climate scenario (Hadgem3ra–RCP8.5) was utilized, assuming business-as-usual and no reduction in global warming [58–62].

A forest-type map and Korean National Forest Inventory (NFI) program data were used to construct a basic dataset for model simulation. The dataset is based on spatial data of 1 km × 1 km grid cell, and it was constructed with the area of about 60,564 km² (6,056,400 ha) only for stocked forest land. The forest-type map provides information such as forest physiognomy, tree species, DBH class, age class, and crown density of the stand. These basic data were created using aerial photographs from 2009 to 2013 at a scale of 1:15,000 and was applied to the modeling at a scale of 1:5,000 [63]. The NFI includes circulating systematic sampling survey over five year periods, 20% each year (i.e., 800 plots from among 4000 permanent plots on a 4 km × 4 km grid) of all South Korean forests [64, 65]. Four circular sample plots were located at the intersections of 4 km × 4 km grid lines. Forest field survey provided data reflecting the characteristics of the forest. The measured forest dataset (DBH, height, age, tree species, and stand volume) allowed stand categorization, and this was combined with a site investigation dataset (coordinates, quality of locality, elevation, slope, and aspect) [66]. In this study, the 5th NFI (2006–2010) was the basis and was supplemented with 6th NFI (2011–2015) data [27]. The representative tree species and baseline stand volumes were established by combining the spatial and attribute data from the forest and site datasets [67, 68]. The site index of each stand was estimated by reviewing the reforestation budgets currently implemented in the Republic of Korea [52] (Table 4).

Results

Growth of forest trees

Using the KO-G-Dynamic model, an annual forest growing stock volume was estimated for each scenario, and the annual growth results were analyzed. The results were derived using different methods, depending on the scenario-specific options. The study focused on years 2030 and 2050 to match NDC milestones. In the 2030s, the annual growth rates under scenarios 1, 2, 3, and 4 were 2.98 m³ ha⁻¹, 2.88 m³ ha⁻¹, 2.88 m³ ha⁻¹, and 2.89 m³ ha⁻¹, respectively. The annual growth rates for scenarios 1, 2, 3, and 4 in the 2050s were 2.05 m³ ha⁻¹, 1.97 m³ ha⁻¹, 1.99 m³ ha⁻¹, and 2.30 m³ ha⁻¹, respectively (Fig. 3). Although the accumulation was higher in the 2050s than in the 2030s, annual growth relatively decreased. The processes of slashing, felling, cutting, and thinning decreased annual growth rates; however, growth thereafter significantly increased when compared to scenarios without management (Fig. 4).

Amount of CO₂ sequestration in the forests

The amount of CO₂ sequestration was calculated based on the forest growing stock volume calculated above. In 2030s, the amounts of CO₂ sequestration for scenarios 1, 2, 3, and 4 were estimated as 34,611,300 tCO₂ year⁻¹, 33,556,800 tCO₂ year⁻¹, 32,419,236 tCO₂ year⁻¹, and 33,598,573 tCO₂ year⁻¹, respectively. For 2050s, the amounts of CO₂ sequestration for scenarios 1, 2, 3, and 4 were 23,038,500 tCO₂ year⁻¹, 23,355,321 tCO₂ year⁻¹, 23,038,500 tCO₂ year⁻¹, 23,355,321 tCO₂ year⁻¹, and 27,001,520 tCO₂ year⁻¹ (Fig. 5), respectively. All scenarios had lower absorption levels in the 2050s than in the 2030s (Fig. 6). The forest management scenarios (3 and 4) absorbed more carbon than those without management. This is the result of improving South Korea’s unbalanced age class structure through forest management from a long-term perspective. The simulations in this study did not include CO₂ emissions losses during harvesting. The analysis of CO₂
sequestration levels exhibited variation according to tree species and forest growing stock volume.

Cost–benefit analysis of forest management
The costs and benefits of each scenario were then analyzed. In Korea, although the proportion of private forests is higher than that of national and public forests, the government emphasizes the value of forests as a public property and notifies forest owners about the government’s laws and policies as part of their governance [73]. Therefore, in this study, the costs were calculated according to the forestry unit price, which was estimated from the budget of the Korea Forest Service [74], and the benefits were estimated according to the transactional economic gains from log trading and CO₂ sequestration [75].

The annual costs for scenarios 1, 2, 3, and 4 in 2030 were 321 billion KRW (267 million USD), 418 billion KRW (348 million USD), 639 billion KRW (533 million USD), and 722 billion KRW (602 million USD), respectively, whereas those in 2050 were 321, 453, 506, and 618 billion KRW (267, 377, 421, and 516 million USD), respectively (Table 5). In Scenario 4, which had the most sustainable results, the cost of thinning, including other processes such as cleaning, cutting, mowing, and vine removal, was 521 billion KRW (434 million USD) per year in the 2030s. In the 2050s, the cost of thinning was 397 billion KRW (331 million USD) per year. The cost of the clear-cut harvest to the legal final cutting limit based on the spatial simulation of the unit price per tree species was estimated to be 1.1 billion KRW (0.9 million USD) in 2030 and 1.2 billion KRW (1 million USD) in 2050. According to Korean forestry statistics, the percentage

![Table 4 Forest sector budget unit prices (Korea Forest Service, 2018)](image)

| Division                  | Pinus densiflora | Pinus koraiensis | Larix kaempferi | Other coniferous forests | Other broad-leaved forests |
|---------------------------|------------------|------------------|-----------------|--------------------------|---------------------------|
| Felling and bucking cost  | 18,622 (16)      | 16,356 (14)      | 19,246 (16)     | 27,084 (23)              | 20,747 (17)               |
| (USD/m³)                  | (USD/m³)         | (USD/m³)         | (USD/m³)        | (USD/m³)                 | (USD/m³)                  |
| Primary transportation cost in mountainous | 21,939 (18) | 20,508 (17) | 20,508 (17) | 20,508 (17) | 21,939 (18) |
| (USD/m³)                  | (USD/m³)         | (USD/m³)         | (USD/m³)        | (USD/m³)                 | (USD/m³)                  |
| Reforestation unit price of major species of trees | | | | |
| Pinus densiflora | 6,176,827 (5147) | 6,474,693 (5396) | 6,072,753 (5061) | 6,288,078 (5240) | 7,269,601 (6058) |
| Pinus koraiensis | | | | | |
| Larix kaempferi | | | | | |
| Quercus variabilis | | | | | |
| Quercus mongolica | | | | | |
of collecting product by forest yarding, in forest tending work, is approximately 30% [76, 77]. Collecting products by forest yarding is the process of cutting, using forestry machines, and yarding and transporting both wood and any by-products that have value as biomass [24]. The estimated cost was therefore calculated by applying the above percentage of collected yarding product in the context of future environmental and policy situations. In the case of reforestation, the appropriate species were identified, recognizing the influence of climate change, and the unit cost for reforestation of that tree species was applied. According to the legal final cutting age, the cost of reforestation with suitable tree species, when considering climate change in the cut over area, was 192 billion KRW (160 million USD) in 2030 and 211 billion KRW (176 million USD) in 2050. Other costs, such as gas, oil, and personnel expenses, were applied to the area values for thinning and final cutting.

The estimated high forest management expenditure in 2030 reflects the high initial economic cost. However, forest growth is reduced by the degree of forest sensitivity to climate change, and the corresponding management area is decreased (Fig. 7).

The benefits of each scenario were estimated from the above in conjunction with the log trading price suggested by the Korea Forest Service and the carbon credit price (KOC: Korea Offset Credit) in 2019 [78]. The benefits for scenarios 1, 2, 3, and 4 in 2030 were 1,508 billion KRW (1,257 million USD), 1,275 billion KRW (1,063 million USD), 1,237 billion KRW (1,024 million USD), and 1,207 billion KRW (995 million USD), respectively, whereas those in 2050 were 1,508 billion KRW (1,257 million USD), 1,057 billion KRW (881 million USD), 1,040 billion KRW (855 million USD), and 1,088 billion KRW (890 million USD), respectively (Table 6). It has been shown that more
benefits are derived from a long-term than from a short-term perspective (Fig. 8).

**Discussion**

Using forests for CO₂ reduction has become a direct method in achieving the NDC. This study identified the latest forest policy trends, including the trading values of wood and carbon, and derived an optimal forest management plan. Scenario 1 was a hypothetical potential future without climate change and harvest, Scenario 2 incorporated climate change but overprotective forest, and scenarios 3 and 4 included climate change and management. Although the cost–benefit ratios for scenarios 2, 3, and 4 were similar, the carbon sequestration was considerably higher in the management scenarios. This indicates that it would be better to change the current policy from passive to more active forest management, as it will have the same cost–benefit ratio with more carbon sequestration, which is in line with the Paris Agreement.

The optimized forest management scenario, which encourages greater growth than current forest practices and which accommodated the changing climate, was advantageous in terms of the amount of CO₂ sequestered and economic feasibility [79]. In the 2030s, the optimal forest management scenario includes prevention of young-matured stands from becoming over-mature forest. However, in the short term, the estimated 2.89 m³ ha⁻¹ of forest growth is smaller than the forest growth of 2.98 m³ ha⁻¹ under current management. Contrastingly, in this scenario in the 2050s, the forest growth
under optimal management was on average 0.4 m$^3$ ha$^{-1}$ greater than that in the non-management climate change scenario, demonstrating the meaningful outcomes of continuous management practices. Previous investigations have also shown this to be a more effective long-term forest management strategy [80–82].

In many previous studies in South Korea, only one forest management method, such as cutting or thinning, was generally considered, and mixed forest management was rarely addressed. Moreover, studies on forest management have predominantly focused on specific tree species (e.g., *Pinus densiflora*, *Pinus koraiensis*, and *Larix kaempferi*), and studies on forest physiognomy as a whole are rare [47, 83–87]. Furthermore, there have been few studies on how forest management measures can increase adaptability to climate change [88, 89]. Therefore, this study not only reinforces our knowledge of adaptive capacity but also suggests the necessary budget for appropriate forest management measures, based on the mechanisms of forest physiognomy that are increasingly sensitive to climate change. However, the study did not consider dead organic matter, soil carbon pools, and harvested wood product, which Korea considers in reporting NIR (National Inventory Report) currently [90]. In addition, the actual natural (disease and insect pests, wind damage, landslide) and anthropogenic (forest fires, illegal activities, land cover change) disturbances that occur every year should be more considered to develop further forest modeling. In future research, it is necessary to find advanced strategies in conjunction with domestic dead organic matter, soil carbon pools and global forest management models reflecting the actual dynamic of forestland [16, 52, 91, 92].

Sequestration based on forest growth according to the improvement of the age class structure through forest management is a key contributor in achieving NDC [93]. Therefore, in this study, a forest growth model was used to analyze whether sequestration based on growth could contribute to the achievement of the NDC. Evidently, under climate change, the Republic of Korea’s forest sector could achieve its NDC target of 26 million tons of CO$_2$ sequestration by 2030. Indeed, it is estimated
Table 5 Cost analysis for forest scenarios 1–4 (in units of 100 million KRW, in units of million USD). Sustainable scenarios add forest management prescriptions and budget requirements

| Classification | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|----------------|------------|------------|------------|------------|
|                | 2030       | 2050       | 2030       | 2050       |
|                | (15 years cumulative) | (35 years cumulative) | (15 years cumulative) | (35 years cumulative) |
| (A) FMOACB KRW/year (USD/year) | 2,090 (174) | 2,090 (174) | 2,090 (174) | 2,090 (174) |
| (B) REFACB KRW/year (USD/year) | 1,122 (93) | 1,122 (93) | 1,122 (93) | 1,122 (93) |
| Total cost of forest resources management KRW/year (USD/year) | 3,212 (267) | 3,212 (267) | 3,212 (267) | 3,212 (267) |
| (C) Vulnerability cumulative area VCuA (ha) | 6,637,600 | 21,154,400 | 225,000 | 525,000 |
| (D) AvCPVM KRW/year (USD/year) | 0.0021 (0.000182) | 0.0021 (0.000182) | 0.0021 (0.000182) | 0.0021 (0.000182) |
| (E) CVMAP KRW/year (USD/year) | 968.6 (80.7) | 1,323 (110) | 150.67 | 147.30 |
| Total annual cost due to harvest by thinning KRW/year (USD/year) | 5,217 (434) | 3,979 (331) | 5,217 (434) | 3,979 (331) |
| (F) CC.GS.LEFA.SP KRW/year (USD/year) | 4.472 (0.372) | 4.430 (0.369) | 11.03 (0.919) | 12.91 (1.076) |
| (G) Av.OE.LOG KRW/year/ha (USD/year/ha) | 0.0021 (0.000015) | 0.0021 (0.000015) | 0.0021 (0.000015) | 0.0021 (0.000015) |
| (H) C.LOG.AP KRW/year (USD/year) | 32.83 (2.736) | 32.83 (2.736) | 65.14 (5.428) | 71.69 (5.974) |
| Total annual cost due to harvest by thinning KRW/year (USD/year) | 5,217 (434) | 3,979 (331) | 5,217 (434) | 3,979 (331) |
that up to 30 million tons could be absorbed if the forest growth sector was managed well. These results demonstrate that forest management is more important for the promotion of CO₂ sequestration than other management measures, especially when considering the forest growth due to climate change. Moreover, the analysis results of the sensitive areas, where forest growth may decrease with climate change, showed that forest management reduces the sensitive area by approximately 1,500,000 ha compared to climate change scenarios without such management.

According to the Korea Forest Service budget, the annual cost of forest tending works is 209 billion KRW (174 million USD), and the cost of reforestation is 112.2 billion KRW (93 million USD) [94]. Furthermore, only 5% of the deforestation amount was applied in collecting products [95]. However, this budget might be insufficient when considering climate adaptation, promotion of forest health, and reduction of disaster risk in conditions of extreme climate changes. Therefore, sustainable forest management plans, developed using the KO-G-Dynamic model, should be implemented for areas where forest growth can decrease the risk imposed by climate change. In this way, policymakers can better understand the future of forest area in terms of time and space.

Furthermore, forest tending works and reforestation unit costs per species can be estimated. At this time, the required forest management costs, for the recommended forest tending and reforestation, are approximately triple the current budget [96]. Therefore, the development and application of appropriate modeling can help in the assessment of current sensitivity and provide direction for achieving the NDC.

The present results also contribute to national sustainable development goals (SDGs). In the Republic of Korea, the forest sector plays an important part in achieving national SDGs, especially in aspects of Goal 15 and with close links to Goal 13 when considering NDCs [97]. As this study indicates, forest management is the key to GHG reduction, and application of an integrated forest model allows the quantification of diverse goals. This is important in understanding how the forest ecosystem is affected by climate change and how social, environmental, and economic factors can be changed by related adaptive policy instruments [98, 99].

The quantified results from the KO-G-Dynamic model can be used by decision makers to promote future policy assessments and by forest landowners who face climate change [100]. Candidate policies can be tested prior to forest activities and plans can be developed to help maximize carbon
sequestration, as well as income [101]. Such future blueprints can be created using integrated modeling and provide policy-oriented solutions focusing on the NDCs and SDGs in South Korea [102].

**Conclusions**

In this study, the KO-G-Dynamic model, a spatiotemporal forest growth model, was used to analyze forest management strategies, including costs and benefits, in response to climate change and commitments to GHG reductions. A number of forest management scenarios were simulated using a KO-G-Dynamic model, based on forest growth and the role of forests as a carbon sink, and an optimal management scenario was identified. Increased forest growth leads to an increase in CO₂ sequestration, contributing in the achievement of the NDC, and is also linked to the SDGs. In the long-term assessment, climate change increased the likelihood of reduced forest growth and required increased budgets as the areas of vulnerability increased. The forest sector’s NDC target for South Korea, which was considered a difficult goal, was possible if appropriate forest management practices were implemented. With the arrival of the “new climate change regime,” the nation’s forest management policy needs to operate with clear goals and directions. Therefore, it is important to quantify the GHG contributions of forests under sustainable management practices and accordingly tailor an appropriate budget. However, it is also essential to establish and improve laws and systems such as the Carbon Absorption Promotion Act and the Greenhouse Gas Reduction Act, as they can be used to manage and implement appropriate practices.
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Author contributions
Conceptualization, MH, CS, MK, and WKL; Data curation, JK, SL, CS, and CHL; Formal analysis, MH; Methodology, MH, MK, and WKL; Supervision, CS and MK; Validation, CS and MK; Visualization, MH, CHL, and WKL; Writing—original draft, MH; Writing—review & editing, CS, MK, KC, YS, and WKL.

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Availability of data and materials
Forest data are available online through the Forest Big Data Exchange of the South Korea website (https://www.bigdata-forest.kr/). Climate data were obtained from the Korea Meteorological Administration (http://www.climate.go.kr/home/CCS/contents_new/35_download.php). The estimation of forest growth in units of 1 km, according to climate change using the KO-G-Dynamic model, can be downloaded from the Korea Adaptation Center for Climate Change (http://motive.kei.re.kr/).

Declarations
Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no conflicts of interest.

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| Classification | Scenario 1 | | | Scenario 2 | | | Scenario 3 | | | Scenario 4 | | |
|----------------|------------|----|----|------------|----|----|------------|----|----|------------|----|
|                 | 2030 (15 years cumulative) | 2050 (35 years cumulative) | 2030 (15 years cumulative) | 2050 (35 years cumulative) | 2030 (15 years cumulative) | 2050 (35 years cumulative) | 2030 (15 years cumulative) | 2050 (35 years cumulative) |
| Carbon trading revenue from forest CO2 sequestration KRW/year (USD/year) | 15,085 (1257) | 15,085 (1257) | 12,759 (1063) | 10,577 (881) | 12,288 (1024) | 10,262 (855) | 11,945 (995) | 10,686 (890) |
| Log trading revenue from tree trimming KRW/year (USD/year) | 87 (7) | 143 (11) | 131 (10) | 200 (16) |
| Total potential benefit KRW/year (USD/year) | 15,085 (1257) | 15,085 (1257) | 12,759 (1063) | 10,577 (881) | 12,376 (1031) | 10,406 (867) | 12,077 (1006) | 10,887 (907) |

Fig. 8 Cost–benefit analysis. Estimation of the benefits relative to the costs by scenario. Trend analysis of the estimated cost-benefits for different forest types. Scenario 1 exhibits a trend in which the cost–benefit value is maintained as it is based on the current climate and no forest management; scenarios 2–4 assume climate (Hadem3ra–RCP8.5) variability and different degrees of forest management. The tendencies of scenarios 2–4 was estimated through trend lines.
References

1. Caney S. Cosmopolitan justice, responsibility, and global climate change. Leiden J Int Law. 2005;18(4):747–75.
2. Falkner R. The Paris Agreement and the new logic of international climate politics. Int Aff. 2016;92(5):1107–25.
3. Bodansky D. The legal character of the Paris Agreement. Rev Eur Comp Int Environ Law. 2016;25:142–50.
4. United Nations. Paris Agreement. 2015.
5. Rogelj J, Den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature. 2016;534:631–9.
6. Min K, Lee YH, Seok HD, Koo JC, Kim ME, Park SH. Preliminary study for establishing a forest carbon sink enhancement plan. Naju, 2013.
7. Yim JS, Lee D. The 23rd united nations framework convention on climate change negotiation trends and prospects for forest sector in the conference of parties. Seoul; 2018.
8. Yim JS, Han H, Lee D. The implementation of greenhouse gas reduction road map for new climate change regime. Seoul; 2020.
9. Han H, Bae JS, Kim YH, Shin JH. Forest carbon market trends and prospects. Seoul, 2020.
10. UNFCCC. Submission under the Paris Agreement the Republic of Korea’s enhanced update of its first nationally determined contribution. All NDC; 2021.
11. Korea Greenhouse Gas Inventory and Research Center. National greenhouse gas inventory report. Seoul; 2019.
12. Lee W-K. 2050 Strategies for the transition of low carbon society in the forest sector. Korea Environ Inst. Sejong; 2020.
13. Choi SI, Joo RW, Kim KD, Kim JS, Jeon HS. Study on policies and actions associated with promotion of social and environmental benefits of forest. J Korean For Soc. 2010;99:75–84.
14. Kim YH. Trends and policy tasks of domestic and foreign forest carbon market due to climate change. Seoul. 2016;93:43–50.
15. Climate Focus. Forests and land use in the Paris agreement. 2015;1:5–7
16. Kim M, Lee WK, Kurz WA, Kwak DA, Morken S, Smyth CE. Estimating carbon dynamics in forest carbon pools under IPCC standards in South Korea using CBM-CFS3. Forest. 2017;10(1):83–92.
17. Bae JS, Seol A. Forest sink contribution to NDC and new opportunities for forest management. Seoul, 2019.
18. Kurz WA, Dymond CC, White TM, Stinson G, Shaw CH, Rampley GJ, et al. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol Modell. 2009;220:480–504.
19. Ham B, Song C, Park E, Choi S-E, Lee W-K. Development of forest activity data and forest management rate for national greenhouse gas inventory in the forest sector. J Chim Chang Res. 2020;11(1):53–63.
20. Lee JY. Evaluation of the historical development of forest administration paradigm changes. J Korean Policy Stud. 2013;13(3):261–79.
21. Bae JS, Joo RW, Kim Y-S. Forest transition in South Korea: reality, path and drivers. Land Use Policy. 2012;29(1):198–207.
22. Lee DK, Kwon KC, Kang K-S. Contribution of tree plantation, tree breeding and soil erosion control techniques during Saemaul Undong periods to the successful forest rehabilitation in the Republic of Korea. J Korean For Soc. 2017;106:371–9.
23. Bae JS, Son Y-M, Yim JS. Unit cost estimation of forest offset program reflecting greenhouse gas emissions from deforestation. J Rural Dev. 2014;37:165–83.
24. Lee SM, Kim KD, Song SH. The roles of forest and optimal forest management schemes under the Convention of Climate Change. Naju, 2010.
25. Kwon K, Han H, Seol A, Chung H, Chung J. Analyzing thinning effects on growth and carbon absorption for Cryptomeria japonica stands using distance-independent growth simulations. J Korean For Soc. 2016;105(1):132–8.
26. Lee SJ, Kim SY, Lee BD, Lee YJ. Estimation of canopy fuel characteristics for Pinus densiflora Stands using diameter distribution models: forest managed stands and unmanaged stands. J Korean Soc Sci. 2018;107:412–21.
27. Kim M, Lee W-K, Son Y, Yoo S, Choi GM, Chung DJ. Assessing the impacts of topographic and climatic factors on radial growth of major forest forming tree species of South Korea. For Ecol Manage. 2017;404:269–79.
28. Kim M, Kraxner F, Son Y, Jeon SW, Shvidenko A, Schepaschenko D, Ham BY, Lim GH, Song C, Hong M. Quantifying impacts of national-scale afforestation on carbon budgets in South Korea from 1961 to 2014. Forests. 2019;10(7):1–18.
29. Korea Forest Service. Statistical yearbook of forestry 2018. Daejeon; 2018.
30. Korea Forest Service. Statistical yearbook of forestry 2019. Daejeon; 2020.
31. FAO. Global forest resources assessment 2020 Report : Republic of Korea. Rome; 2020.
32. Park MS, Youn YC. Reforestation policy integration by the multiple sectors toward forest transition in the Republic of Korea. For Policy Econ. 2017;76:45–55.
33. Lim JH, Chun JH, Park KE, Shin MY. Effect of climate change on the tree-ring growth of Pinus koraiensis in Korea. J Korean For Soc. 2016;105(3):351–9.
34. Wang X, Pederson N, Chen Z, Lawton K, Zhu C, Han S. Recent rising temperatures drive younger and southern Korean pine growth decline. Sci Total Environ. 2019;649:105–16.
35. Yoo S, Lim C-H, Kim M, Song C, Kim SJ, Lee W-K. Potential distribution of endangered coniferous tree species under climate change. J Clim Chang Res. 2020;11(4):215–26.
36. Korea Environment Institute. Development of integrated model for climate change impact and vulnerability assessment : forest, agriculture. 2018;2–94.
37. Byun JG, Lee W-K, Kim M, Kwak DA, Kwak H, Park T, Byun WH, Son Y, Choi JK. Radial growth response of Pinus densiflora and Quercus spp. to topographic and climatic factors in South Korea. J Plant Ecol. 2013;6(5):380–92.
38. Nam K, Lee W-K, Kim M, Kwak DA, Byun WH, Yu H, Kwak H, Kwon T, Sung J, Chung DJ. Spatio-temporal change in forest cover and carbon storage considering actual and potential forest cover in South Korea. Sci China Life Sci. 2015;58(7):713–23.
39. Kim M, Lee W-K, Choi GM, Song C, Lim CH, Moon J, Piao D, Kraxner F, Shvidenko A, Forssell N. Modeling stand-level mortality based on maximum stem number and seasonal temperature. For Ecol Manage. 2017;386:37–50.
40. Piao D, Kim M, Choi GM, Moon J, Yu H, Lee W-K, Wang S, Jeon SW, Son YM. Development of an integrated DBH estimation model based on stand and climatic conditions. Forests. 2018;9(3):155.
41. Kim M, Kraxner F, Forssell N, Song C, Lee W-K. Enhancing the provisioning of ecosystem services in South Korea under climate change: the benefits and pitfalls of current forest management strategies. Reg Environ Chang. 2021;21:1.
42. Korea Environment Institute. Development of integrated model for climate change impact and vulnerability assessment : forest, agriculture. Sejong; 2021.
43. Son YM, Lee GH, Kim R, Pyo JK, Park IH, Son YW, Kim C. Carbon emission factors by major tree species for forest greenhouse gas inventory. Seoul, 2010.
44. Sterba H. Estimating potential density from thinning experiments and inventory data. For Sci. 1987;33(4):1022–34.
45. Ryu D, Song C, Lim C-H, Lee S-G, Piao D, Lee W-K. Assessing effects of shortening final cutting age on future CO2 absorption of forest in Korea. J Clim Chang Res. 2016;7:157–67.
46. Ahn B, Lee K, Kim C, Lee J. Estimation of forest biomass arising from forest management operation II—estimation based on the projection of forest areas. J Korea TAPPI. 2009;41(4):25–32.
47. Park J, Kim SK, Lee SJ, Lee K, Kim H. Thinning effect on vegetation structure and stand characteristics of oak Stands. J Agric Life Sci. 2013;47(6):81–9.
48. Dobner M, Niccolletti MF, Arce JE. Influence of crown thinning on radial growth pattern of Pinus taeda in southern Brazil. New For. 2019;50(3):437–54.
49. IPCC. 2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change. Japan, 2019.

50. Penna J, Gyftokos M, Taka H, Thelma K, Dina R, Leandro B, Kyoko M, Todd N, Kyoto T. Good practice guidance for land use, land-use change and forestry. IAEA. 2003.

51. Korea Forest Service. The 3rd stage forest tending 5-year promotion plan 2012–2018. Daejeon, 2013.

52. Lee J, Kim H, Song C, Kim GS, Lee WK, Son Y. Determining economically viable forest management option with consideration of ecosystem services in Korea: a strategy after successful national forestation. Ecosyst Serv. 2020;41:101053.

53. Korea Law Information Center. Enforcement rules of the act on the creation and management of forest resources. Korea Law Inf Cent. Sejong, 2017.

54. Choi S, Lee W-K, Kwak D-A, Lee S, Son Y, Lim J-H, Saborowski J. Predicting forest cover changes in future climate using hydrological and thermal indices in South Korea. Clim Res. 2011;49:229–45.

55. Korea Forest Service. The 6th basic forest plan 2018–2037. Daejeon, 2018.

56. Korea Forest Service. The 4th stage forest tending 5-year promotion plan 2019–2023. Daejeon, 2018.

57. Korea Forest Service. Sustainable forest resource management guidelines. Daejeon, 2020.

58. Hausfather Z. Explainer: How “shared socioeconomic pathways” explore future climate change [Internet]. CarbonBrief. 2018. https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change.

59. Kim JU, Kwon WT, Byun YH. Monthly changes in temperature extremes over South Korea based on observations and RCP8.5 scenario. J Clim Chang Res. 2015;6(2):261.

60. Leary N, Kulkarni J. Climate change vulnerability and adaptation in developing country regions. Draft Final Report of the AIACC Project, UNEP, Nairobi, 2007;1–208.

61. Lee C, Boo KO, Hong J, Seong H, Heo T, Seol KH, Lee J, Cho C. Future changes in global terrestrial carbon cycle under RCP scenarios. Atmosphere (Basel). 2014;24:363–15.

62. Cha W, Choi J, Lee O, Kim S. Probabilistic analysis of sea level rise in Korea. J Korean Soc For. 2020;103:30–6.

63. Kim KM, Kim CM, Jun EJ. Study on the standard for a 1:25,000 scale digital forest type map production in Korea. J Korean Soc Geogr Inf Stud. 2009;151:143–51.

64. Tomppo E, Gschwandtner T, Lawrence M, McRoberts RE. National forest inventories: Pathways for common reporting. National Forest Inventories–Pathways Common Report. 2010.

65. Yim JS, Kim ES, Kim CM, Son Y-M. Assessment of forest resources change using permanent plot data in national forest inventory. J Korean For Soc. 2013;104(2):239–47.

66. Korea Forest Research Institute. 5th National Forest Inventory Report. Korea Forest Research Institute Seoul, 2013.

67. Kim ES, Kim KM, Kim CC, Lee SH, Kim SH. Estimating the spatial distribution of forest stand volume in Gyeonggi Province using national forest inventory data and forest type map. J Korean For Soc. 2010;99:827–35.

68. Choi K. Estimating radial growth response of major tree species using climatic and topographic condition in South Korea. J Clim Chang Res. 2014;5(2):127–37.

69. Kim H, Jeong S-H, Kim D-G, Kim H-J, Choi S-M, Lee MB, Bae SW, Lim JH, Lee S-H. Developing a site index model considering soil characteristics for Pinus thunbergii stands grown on the west coast of Korea. J Korean Soc Appl Biol Chem. 2013;56(2):173–80.

70. Kim H-J, Kim H-S, Park S-J, Park H-J, Lee S-H. Development of site index curves and height–DBH growth model of Larix kaempferi for Deogyu mountain in South Korea. Forest Sci Technol. 2018;14(3):145–50.

71. Korea Forest Service. Public announcement of the legal final cutting age standard. Daejeon, 2017.

72. Son Y-M, Hwang J-S, Park H, Lee S-T, Kang JT. Thinning and target forest type. Seoul, 2015.

73. Kim NK. Korea forest policies. Seoul, 2020.

74. Korea Forest Service. Standard estimating of mountains and forests business. Daejeon, 2018.

75. Jung H, Jeon SW, Lee W-K. Development of natural resources valuation assessment for decision-making process. 2015.

76. Korea Forest Service. Performance analysis of forest cutting target area and collection yarding productivity. Daejeon, 2020.

77. Kim J-H, Park S-J. An analysis of the yielding productivity and cost in forest tending operation. J Korean For Soc. 2010;99:625–32.

78. Korea Forest Service. Analysis of projects in the field of forest resource development and re-establishment of policy direction. Daejeon; 2019.

79. Battaglia M, Sands Pj. Process-based forest productivity models and their application in forest management. For Ecol Manage. 1998;102(1):13–32.

80. Cherubini F, Striemman AH, Hertwich E. Effects of boreal forest management practices on the climate impact of CO2 emissions from bioenergy. Ecol Model. 2011;223(1):59–66.

81. Lippke B, Oneil E, Harrison R, Skog K, Gustavsson L, Sathre R. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. Carbon Manag. 2011;2(3):303–33.

82. Keenan RJ. Climate change impacts and adaptation in forest management: a review. Ann For Sci. 2015;72(2):145–67.

83. Kim Y, You J, Yim J, Lee S, Park J. Analysis of forest resources and timber production potential of Larix kaempferi in South Korea. J Korean Soc For Sci. 2020;109:454–60.

84. Kim JH, Kang SK. The developmental pattern of succeeding regeneration after the application of shelter-forestry system in a shrub-stage Pinus koraiensis plantation. J Korean For Soc. 2008;97:597–600.

85. Bae S, HWang J, Lee S, Kim H, Jeong J. Changes in soil temperature, moisture content, light availability and diameter growth after thinning in Korea (Pinus koraiensis) Plantation. J Korean For Soc. 2010;99:397–403.

86. Kim Y, Kim T, Won H, Lee K, Shin MY. Estimation of timber production by thinning scenarios using a forest stand yield model. J Korean For Soc. 2012;101(4):592–8.

87. Ko S, Son Y, Noh NJ, Yoon TK, Kim C, Bae SW, Hwang J, Lee ST, Kim HS. Thinning intensity effects on carbon storage of soil, forest floor and coarse woody debris in Pinus densiflora Stands. Forest Sci Technol. 2014;103:30–6.

88. Naudts K, Chen Y, McGrath MJ, Ryder J, Valade A, Luysaart S. Europe’s forest management did not mitigate climate warming. Science. 2016;351(6273):597–600.

89. Han H, Kim YH, Bae JS, Shin JH. Analyzing the effects of species conversion projects on CO2 absorption enhancement in poorly stocked forest stands. J Clim Chang Res. 2020;11:197–202.

90. Korea Greenhouse Gas Inventory and Research Center. National greenhouse gas inventory report of Korea 2020. Seoul, 2021.

91. Lee SJ, Yim JS, Son YM, Son Y, Kim R. Estimation of forest carbon stocks for national greenhouse gas inventory reporting in South Korea. Forests. 2018;9(10):625.

92. Lee J, Yoon TK, Han S, Kim S, Yi MJ, Park GS, et al. Estimating the carbon dynamics of South Korean forests from 1954 to 2012. Biogeosciences. 2011;8:4637–50.

93. Antwi-Agyei P, Dougill AJ, Agyekum TP, Stringer LC. Alignment between nationally determined contributions and the sustainable development goals for West Africa. Clim Policy. 2018;18(10):1296–312.

94. Korea Forest Service. Forest service budget settlement in 2018. Daejeon, 2018.

95. Korea Forest Service. Deforestation area and collection volume. Daejeon, 2019.

96. Lee W-K, Song C, Hong M. Strategies for the adaptation of forest and forestry by climate change. Forestlookout of Korea; 2019.

97. Jung TY. Sustainable development goals in the Republic of Korea. Routledge. 2018.

98. Nielsen AB, Olsen SB, Lundhede T. An economic valuation of the recreational benefits associated with nature-based forest management practices. Landsc Urban Plan. 2007;80(1–2):63–71.

99. Ellison D, Lundblad M, Petersson H. Carbon accounting and the climate politics of forestry. Environ Sci Policy. 2011;14(8):1062–78.

100. Kim M, Ham BY, Kraner F, Shvidenko A, Schepaschenko D, Krasovskii A, Park T, Lee W-K. Species- and elevation-dependent productivity changes in East Asian temperate forests. Environ Res Lett. 2020;15(3):034012.
101. Wang W, Peng C, Kneeshaw DD, Larocque GR, Lei X, Zhu Q, Song X, Tong Q. Modeling the effects of varied forest management regimes on carbon dynamics in jack pine stands under climate change. Can J For Res. 2013;43(5):469–79.

102. Janetschek H, Brandl C, Dzebo A, Hackmann B. The 2030 Agenda and the Paris Agreement: voluntary contributions towards thematic policy coherence. Clim Policy. 2020;20(4):430–42.

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