Enhancing the provisioning of ecosystem services in South Korea under climate change: The benefits and pitfalls of current forest management strategies

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Abstract

We present a study about the integrated impact of adaptive management and climate change using spatially-explicit tools at first time for assessing changes in forest ecosystem services in South Korea. The aims of this study were to: (i) project potential changes among forest ecosystem services under various scenarios, (ii) assess the impact of forest management [Sc1: controlled, Sc2: business as usual, and Sc3: adaptive management] and climate change through comparison among them, and (iii) find insight for strategies to implementing both sustainable society and environment. For this purpose, the integrated tool was applied to analyze the changes in five ecosystem services: forest carbon storage, carbon sequestration, industrial wood production, freshwater supply, and forest recreation. The simulated results show that the ratio of these five ecosystem services of Sc3-to-Sc2 in the 2040s was estimated as 88.4%, 114.7%, 105.4%, 228.2%, and 86.5%, respectively. These results showed clear trade-offs between industrial wood production and freshwater supply on one side and forest recreation and forest carbon storage on the other side. In the case of carbon sequestration, the harvest activity might provide a negative effect in the short term, but it with a longer-term perspective could be positive through reforestation activity. In addition, this study showed that future climate change until 2050 in Korea could have a generally negative influence on forest carbon sequestration but that these negative effects could be partly offset through harvest management. Therefore, the plans of the spatial distribution of management activities for the equilibrium of demand and supply in ecosystem services should be required.

Keywords: *industrial wood production, carbon storage, recreation area, fresh water supply, carbon sequestration, forest harvest*

1. Introduction

Today, the value and usefulness of forests are increasing (Bonan 2008). Forest ecosystems are increasingly understood as multifunctional production systems that provide many products and services, such as timber, various non-wood products, recreational amenities, habitats, protected water resources, erosion control, and carbon sequestration (Pang et al. 2017). Forest ecosystem services are significantly affected by management activities such as afforestation, thinning, and harvest activities (Kim et al. 2019; Bugmann et al. 2017). Because ecosystem services are typically highly interlinked, optimizing one can affect others (Bennett et al. 2009); in other words, these interactions can lead to trade-offs (negatives interactions) or synergies (positives interactions). For example, afforestation reduces soil erosion (Vicente-Vicente et al. 2019) and increases carbon sequestration (Kim et al. 2016) and soil organic carbon (Vicente-Vicente et al. 2019); however, increased forestland might lead to reduced water yield, especially in semi-arid regions (Cao et al. 2010). Relationships among multiple ecosystem services can be analyzed and understood through trade-offs and synergies, which have become important topics in the study of ecosystem services at the global and regional scales (Ray et al. 2015).

Quantifying and exploring the spatiotemporal characteristics of ecosystem service trade-offs and synergies are beneficial to ecosystem management because they can mutate over time (Tilman 2000); some may appear immediately following ecosystem service changes (Kim et al. 2016), but some might take much longer to become apparent (Cao et al. 2010). Trade-offs arise when more of a particular ecosystem service is captured by one stakeholder at the expense of others, or when the provision of one ecosystem service is reduced as a consequence of increased use of another ecosystem service (Rodriguez et al. 2006). Such changes could be the result of explicit choices or arise without premeditation or awareness. Forests can be sensitive to climate change because the long life-spans of trees even though they have adaptive capacities such as high phenological plasticity to against future environmental changes (Seidl et al. 2017; Vitasse et al. 2010). Associated with climate change, factors that affect forest ecosystems can act independently or in combination (Lindner et al. 2014). Therefore, forestry researchers should know that ecological factors related to climate change as well as to manmade environmental changes can change the synergies and trade-offs among forest ecosystem services (Lindner et al. 2014; Rodriguez et al. 2006).

At present, one of the major management issues faced by the Korea Forest Service (KFS) and the country's forest sector is understanding the impacts of climate change and optimizing the use of forest resources to meet national Sustainable Development Goals (SDGs) (KFS 2017). Recently, the KFS lowered the legal final cutting age and is planning to increase the annual harvested area from 15,000 ha in the 2010s to 35,000 ha in the 2030s in order to increase timber production and improve the imbalance in forest age-class distribution (KFS 2017). Therefore, it is necessary to project corresponding changes in ecosystem services under alternative forest management scenarios to provide decision-making support regarding integrated sustainability assessment of policy and planning alternatives.

This study aimed to project potential changes among forest ecosystem services under various scenarios that were related to alternative forest management policies and climate change. Toward this aim, we simulated six scenarios based on three forest management strategies and two future climate conditions for the whole forest area in South Korea. In this study, we present models to assess the project potential changes among forest ecosystem services. We used five ecosystem services, C storage (CS), C sequestration (Cse), freshwater supply (WS), industrial wood production (IWP), and forest recreation (RE), to derive key indicators of trade-offs and synergies in forest ecosystem services. Our study can enhance the comprehension of complex interactions among multiple ecosystem services under different management and climate change scenarios.

2. Materials and methods

2.1. Study area and base map of Korean forests

South Korea is located at 124° 54′ – 131° 06′ E and 33° 09′ – 38° 45′ N (Fig. S1a). Forest area covers 63.7% (6,369,000 ha) of the total land area, and evergreen, deciduous broad-leaved, and mixed forests occupied approximately 40.5%, 27.0%, and 29.4% of the total forest area in 2018, respectively (KFS 2019 – Fig. S1c). We used the following spatial data sets in this study: Landsat TM and Spot remote-sensed forest cover data (KFS 2010; Kim et al. 2016); field data from the Korean National Forest Inventory (NFI) (National Institute of Forest Science, NIFoS 2011); topographic data; and data on restricted areas with impractical working conditions, protected areas, and areas of national interest for nature conservation (Kim et al. 2016); we spatially integrated these data sets with a 0.01° grid size (≈1 km). We also here account more detailed forest specific information, such as the distribution of stand age, tree species, site indices, and management types, in both this assessment and earlier reports (Kim et al. 2019) using downloaded the data from the Integrated Forest Growth Information System (http://map.forest.go.kr/).

2.2. Climate data

We also applied two climate data sets for assessing trade-offs and synergies among the ecosystem services. In the first data scenario, CC, climate conditions were assumed to repeat as current levels (2001–2010) by every ten years from 2011 to 2050 in South Korea, specifically, mean temperature and precipitation of 10.2 °C and 1,150 mm. The data for the second climate scenario were Representative Concentration Pathway 8.5 (RCP8.5). In the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC), RCP8.5 assumes that greenhouse gases (GHGs) will continue to be emitted at the current rates and the carbon dioxide concentration will reach 940 ppm; in this scenario, Korea's mean temperature and precipitation changed from 10.2 °C and 1,150 mm in 2010 to 12.9 °C and 1,802 mm in 2050, both respectively (Fig. S2). The Korea Meteorological Administration provided the high-resolution (1-km spatial resolution) raster-based monthly mean temperature and precipitation data (https://data.kma.go.kr/).

2.3. Forest management scenarios

To assess changes among different ecosystem services, we defined three forest management scenarios classified by annual harvest based on South Korean' forest management policies. Under the first scenario, Sc1, an overprotective forest area is managed with controlled management. For this scenario, we assumed that the total forest area was the defined protected area without harvest during study periods, and therefore, we estimated annual IWP by harvest activities as zero under Sc1.

For the second scenario, Sc2 [=business as usual (BAU)], we held the current harvest area at 15,000 ha per year; in this scenario, the KFS maintained annual harvest areas at 2010s levels. In the third scenario, Sc3 (=adaptive management), the harvest area increased to 35,000 ha per year based on the 6th Basic Forest Plan (KFS 2017); this scenario reflected harvest policies based on improved forest management strategies.

In this study, we divided the forest area into two types—manageable and restricted—based on previous studies (Kim et al. 2016). Based on forest legislation and geographic conditions, the forest area with harvest activities occupied approximately 3,138,000 ha, approximately 51.7% of the total forest area (Fig. S1d). The KFS's sustainable forest management law authorizes clear-cut harvest at the final age of maturity for each tree species only in managed areas, and forest managers oversee each stand according to the cycle of final felling and regeneration. We did not include natural disturbances and changes in land use/cover such as afforestation or deforestation in the simulations in this study, assuming, rather, that total forest area remained constant over time.

2.4. Quantifying ecosystem services

Forest maturity and management activities affect forest-based ecosystem services (Bugmann et al. 2017; Fig. S3). For example, forest C stocks and recreation services increase with forest maturity (Norman et al. 2010), but Cse remains slow in the "stand imitation phase", becomes faster beyond that, and shoots up in "stem-exclusion phase" to "mature phase" until it reaches a peak, after which Cse declines (Oliver et al. 1996); harvesting produces timber and thus decreases Cse in the near term, but more C will be absorbed from the atmosphere in the future (Kim et al. 2017). For this study, we assessed the changes in forest ecosystem services under each scenario based on the impacts of maturity and harvest management on the services (Fig. S3 and S4).

We used the integrated tool based on models and methods for spatially explicit simulation to assess the corresponding changes in forest ecosystem services. This tool comprises three main modules: dynamic growth model for calculation of storage and yield, a water yield model for estimation of freshwater supply, and recreation service model for assessment of potential recreation value (Fig. S5). We used the tool to simulate forest growth and management under combinations of our three different management and two climate scenarios (Sc1-CC, Sc1-R85, Sc2-CC, Sc2-R85, Sc3-CC, and Sc3-R85) and assessed the impacts on the five ecosystem services. Specifically, we mapped, quantified, and compared the consequences for the ecosystem services under the different scenarios, which allowed us to compared the trade-offs and synergies among different ecosystem services and scenarios. We conducted all spatial analysis, buffer analysis, raster calculation, zonal statistics, and visualization of maps in ArcGIS 10.5 (ESRI 2015). A detailed description of the main models and all abbreviations for this study are presented in supplement materials (Table S1 and Fig. S4).

2.4.1. Simulating forest growth and management

In this study, for application of dynamic growth model, we constructed the forest stands in 1 km × 1 km grids and described the state of each grid with four variables with varying values: forest type [seven major forest 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), site index, stand age, and management type using the fifth NFI and the fifth Forest Cover Map (FCM). In addition, each grid was spatially linked to climatic and topographic conditions from digital elevation model data and climate data. A detailed description of the processes of data preparation is given in Kim et al. (2019). We first assigned values for each of the four variables to each grid point. To simulate the future forest development, we also projected the grids' future states based on the forest management treatments specified for individual grid, i.e., final felling or no action. Beginning with each grid's initial status in the 2010 year, CS, Cse, and IWP of each grid were simulated considering climate and management scenarios annually until the 2050 year using the dynamic growth model. In addition, some of the outputs from this simulation used as the input data for assessing

WS and RE value through the integration tool.

2.4.2. Forest biomass and C stocks

To simulate stem volume and carbon stock annually under climate change and management scenarios, we integrated four independent Korea-specific models: diameter at breast height (DBH) growth, tree mortality, growth modifier, and height growth as developed earlier (Kim et al. 2019). This model simulates forest volume and C stocks as follows: (1) estimated mean tree height growth based on stand age and site index of each stand using regression models, as suggested by the KFS (2009); (2) estimated stand density (trees per ha) change using a mortality model (Kim et al. 2017); (3) estimated stand mean DBH growth reflecting topographic and annual climatic conditions using regression models and a growth modifier developed by Piao et al. (2018) and Kim et al. (2019); and (4) estimated forest volume and carbon stocks using the outputs from the previous three steps, regression models, basic wood density, and biomass extension factors developed by NIFoS (2014; Table S2). Kim et al. (2019) described and validated the performances of this model, and Kim et al. (2019) give a detailed description of the integrated model.

2.4.3. Yield and IWP production

In this study, we considered only differences in rotation time for each stand according to tree species based on the legal final cutting age (Table S3). The state variable *x* represents the stand age on a 100-ha stand by each grid size in this study; there are 201 age classes and each age class represents one age, spanning tree ages from 0 to 200. The decision variable *d* is set to 0 for keeping the stand or 1 for fell the stand with the decision made at the start of the stage knowing the current age of trees in the stand; tree age is zero at the start of a stage if trees are felled at that time. We implemented a clear-cut harvest at the final age of maturity for each tree species (Table S3), and based on the management scenarios assumed in Sc2 and Sc3, the maximum annual harvest areas for the scenarios were, respectively, 15,000 ha and 35,000 ha. In the study, if more forest stands than the maximum reached final cutting age, we applied harvesting to the top 150 or 350 grids with the highest stand age and volume stocks by management scenario. The simulations in this study did not include any biomass loss in harvesting.

$$H_t = \sum f(selection\ x_{it},\ x_{it} \geq FC),\ H_t \leq H_{max} \quad (1)$$

$$IWP_t = \sum f(biomass\ x_{it},\ x_{it} \in H_t) \quad (2)$$

where *i* is the identification number of a grid in this study; *f(selection)* is a logical function as the selection of harvest area which are the top 150 or 350 grids with the highest stand age and volume stocks among x_i in year *t*; H_t is the harvest area in year *t*; x_{it} is the stand age of grid *i* in year *t*; *FC* is the legal final cutting age of each tree species (Table S3); H_{max} is the maximum of annual harvest area for each scenario; *f(biomass)* is a logical function as return the stem biomass of x_i in year *t*; and IWP_t is the industrial wood production in year *t*.

2.4.4. Estimation of forest recreation service

Many researchers have linked forest maturity, accessibility, and diversity of structure with high RE value (Hörnsten and Fredman 2000; Nielsen et al. 2007; Zandersen and Tol 2009). In this study, we quantified RE of each grid annually based on functions using geographic and environmental factors (Eq. 2 and 3; Table S4). Firstly, we consider the recreational opportunities and accessibility to the forests to assess the potential RE based on a previous study (Pang et al. 2017). The grids within 2 km of housing area or within 300 m along each side of small roads are only considered to evaluate RE in this study. Secondly, we used the stand age and volume for considering the diversity of forest maturity. We determined that forests more than 70 years old or higher stand volume than the reference stand volume were valuable RE. The stand volume of applicable forest is divided by the reference stand volume in the assessing process of RE in order that forest quality should be reflected (Eq. 2). The reference stand volume for each forest type is calculated that the mean stand volume for the NFI plots that stand age is older than 70 stand age minus their one standard deviation (Table S5). In addition, to reflect the different preferences of visitors for forest types such as coniferous, broad-leaved, and mixed forest, R_p is multiplied by 0.75, 1, 1.25 for these forest types (Eq. 3). These values were computed based on the difference of willingness to pay from the analysis in the economic valuation of the recreational benefits (Nielsen et al. 2007). Although in that research, there is no specific value for the coniferous forest, we estimated the relative value for coniferous forest using the same ratio between the mixed forests and monoculture of broadleaves. Thirdly, we evaluated the visual diversity and spatial diversity of each grid in the assessment of RE. Each grid was computed a diversity index for the values within a specified neighborhood (3×3) for each input cell position. The grid with one, two, and three forest types in the neighborhood grids were valued as 0.75, 1.0, and 1.25, respectively. We used land cover data on residential areas and road systems together with stand age data from the forest cover map in the 5th NFI and the output from the dynamic forest growth model to identify potential recreation area. Based on these considerations, the RE value for each grid was computed as follow (Eq. 3):

$$R_{it} = f(Age_{it}\ or\ Volume_{it})/F_r \times f(Accessibility_i) \times T_i \times N_{it} \quad (3)$$

where $f(Age_i \text{ or } Volume_i)$ is a logical function as if stand age or stand volume (m^3 ha^{-1}) of *i* grid in year *t* is older than 70 years or higher volume than reference stand volume (m^3 ha^{-1}), stand volume of *i* grid in year *t* is returned, if it is not, the zero value is returned; F_r is reference stand volume for forest type; *f*(*Accessibility*) is a logical function that if *i* grid is within a 2 km radius of housing areas or linked to the areas within 300 m radius from a road network, the one value is returned, if it is not, the zero value is returned; T_i is preferences for forest type of *i* grid; N_{it} is a diversity index for *i* grid in year *t*; and *R* is estimated recreation service value. We considered that forest area, residential area, and road network were constant in the analysis.

2.4.5. Estimation of fresh water supply

We calculated the WS based on the annual water yield after multiplying the above- and underground run-off coefficient by the annual precipitation in the spring season (March–May). To reflect age-dependence and management influences on WS from the forest, we applied the mathematical model described by Tian et al. (2008). They found that water distribution on forest floors in differently aged forest plantations was mainly influenced by human cultivation activities in young stands and by stand structure in mature stands. Thus, this method was well suited for modeling forest management activities such as harvest and reforestation, adapted to South Korea in this case, using the evapotranspiration (ET) coefficient of major tree species. However, it had a limitation that the research was only focused on one tree species as Chinese fir. Therefore, we applied the modifier function was developed by Kim (2018) to expand spatially from the plot-level methodology to the national level (Eq. 4). The freshwater supply model involves many factors, such as forest type, stand age, topography, monthly precipitation, and coefficients for estimation evapotranspiration. Tian et al. (2008) and

Kim (2018) give a detailed description of the analysis processes and coefficients for Eq. 4 and 5.

$$MD_i = \frac{1-ET_i}{1-ET_{CF}} \cdot \frac{C_i}{C_{25}} \tag{4}$$

$$WS_t = \sum P_{it} \cdot (b_{ijt0} + b_{ijt1} \cdot P + b_{ijt2} \cdot P^2 + \cdots\cdots + b_{ijtn} \cdot P^n) \cdot MD_i \tag{5}$$

where MD_i is the modifier at grid *I*; ET_{CF} is the evapotranspiration (ET) coefficient of Chinese fir (0.77); ET_k is the *ET* coefficient of each Korean major tree species (0.70, 0.77, 0.82, 0.60, and 0.69 for red pine, Japanese larch, Korean pine, oak, and mixed forest, respectively) at grid *i*; C_i is the runoff coefficient according to the slope at grid *i*; b_n are the coefficients for grid *i* with stand age *j* in year *t* (Tian et al. 2008); *n* represents the degree of a polynomial function; *P* is the precipitation at *i* grid during spring season in year *t*; and WS_t is the freshwater supply in *t* year.

3. Results and Discussion

3.1. Spatiotemporal distribution of ecosystem services

3.1.1. C storage

We estimated CS changes by forest factors such as forest rotation age and by climate change scenario (Fig. 1a). Total forest CS under Sc1-CC and Sc1-R85 increased, respectively, from 400.0 Tg C to 814.1 Tg C and 780.9 Tg C at the rates of 10.35 and 9.52 Tg C yr^{-1} during 2010–2050. Our results projected relatively high CS increases between the western and eastern parts of South Korea but not in the mountainous area (Fig. S6); one of the main reasons for these results is that the forests in this area are younger overall than the mountain forests (Kim et al. 2019). We tried to validate the model separately in this study by comparing estimated CS with the Statistical Yearbook of Forestry (KFS 2019). The CS for all South Korean forests increased from 405.7 to 493.8 Tg C between 2010 and 2017, and in simulation Sc2-CC, CS increased from 400.0 to 491.3 Tg C during that period. Therefore, it could be inferred that the model successfully reflected the change in volume and C trends of Korean forests by time series, although uncertainties remain for individual stands spatial consistency between observed data and model results.

The differences in the C stocks among the studied management scenarios are depicted in Fig. 1a and Fig. S7. Estimated CS in 2050 under scenarios Sc2-CC and Sc3-CC was 746.6 and 659.9 Tg C, respectively. Typically, CS varies based on growth and harvest activities (cutting by final maturity age) and considering climate change in Sc2-R85 and Sc3-R85, the projected CS values for 2050 were 718.6 and 648.1 Tg C, respectively. The estimated differences between their C stocks in 2050 shown by climate change were –27.9 and –11.8 Tg C, respectively. Our results showed that management activities might help lessen the negative impacts of climate change on forest growth and C stocks. Based on observation data, climate change impacts on tree growth of major temperate forests in South Korea are different depended on tree species and geographical conditions (Kim et al. 2019, 2020). Therefore, decision-makers in forest management have to need the insight to maximize the positive effects of climate change on the forest with a long-term perspective (Lindner et al. 2014).

3.1.2. C sequestration

As shown in Fig. 1b, the annual Cse in South Korean forests tended to decrease gradually from 2010 to 2050, unlike the results for CS; this is because the annual forest growth and Cse were related to stand age in our approach. In most cases, the age response of a C sink to a new steady state consists of a rapid initial increase followed by a gradual decline (Hudiburg et al. 2009). Changes in annual Cse are also affected by forest management activities. Within the three management scenarios without climate change, i.e., Sc1-CC, Sc2-CC, and Sc3-CC, the annual Cse tended to increase in the presence of forest management activities (Fig. 1b), and without these activities, decreased from 11.58 Tg C yr^{-1} in 2010 to 5.74, 6.28 and 6.80 Tg C yr^{-1} in 2050, respectively, during the study period. In our simulation, the harvested forest area in *i* year would be reforested automatically with one-year-old stand age in *i+1* year. Therefore, the over matured forests with low Cse capacity could be changed to young forests with high Cse capacity by harvest management. These results indicate that the harvest activity could help improve the Cse and imbalanced age structure of Korean forests in the long-term perspective. Approximately 67% of Korean forests had trees between 40 and 50 years old (KFS 2016) in the 2015 year and thus will require infrastructure and systems for larger future harvesting areas than after the 2010s, as provided by the forest management practice guide in South Korea.

3.1.3. Freshwater supply

The estimates of spring WS in the next four decades clearly showed gradual decreases over time (Fig. 1c). In scenario Sc1-CC, the WS was 4.53 billion m^3 $year^{-1}$ in 2010 and 4.15 billion m^3 $year^{-1}$ in 2050; this decline is linked to changes in forest structure over time considered in the simulation of water supply model. In the water supply model used in this study, the WS to precipitation ratio (%) in a forest area decreased steadily with forest aging, and other researchers have shown obvious declines in water supply as forests aged and cover and canopy increased (Cademus et al. 2014). The reduced water yields following canopy expansion derive from the changes in the balance between rainfall, evaporation, and system runoff response (Ilstedt et al. 2016); higher evapotranspiration, reduced water availability in soils and groundwater, and changes in energy fluxes (e.g., albedo, sensible, and latent heat) are some of the main mechanisms driving these changes (Ellison et al. 2017). In addition, these changes can be explained by the substantial decrease in rainfall amount and intensity that reaches the forest floor as the stand structure develops.

However, WS in scenarios Sc2-CC and Sc3-CC were projected to start to increasing gradually before stabilizing in accumulated harvested areas during the period from the 2030s to the 2040s. The simulation results showed that the 2050 WS estimates under Sc2-CC and Sc3-CC were 4.32 and 4.50 billion m^3 $year^{-1}$, respectively, accounting for 95.3% and 99.4% of the freshwater supplies in 2010. These results are closely linked to ecological mechanisms that the changes in forest structures caused by aging or disturbances could influence on runoff characteristics in forests (Ellison et al. 2017; Tian et al. 2008). In addition, based on several articles from the past decade, impact of afforestation or reforestation on water yield is negative such as reduction of downstream water availability, while forest clearing results in increased streamflow (Farley et al. 2005). Our results suggest that forest regeneration might help improve the national water cycle and reduce the damage from spring droughts.

Although the forest WS estimates of this study showed a broadly similar pattern with previous researches (Jung et al. 2009; Kim et al. 2010; Kim et al. 2017), there are some differences in the results of each study. There were two possible reasons for this. As shown in Table S6, each study used different models and methodologies to estimate forest WS. This probably contributes to making a difference in the estimated forest WS. The other possible reason was a difference in the research year and periods. As noted earlier, the amount of forest WS is greatly influenced by precipitation patterns. Therefore, our results for WS could be considered reliable even though it is based on indirect validation.

3.1.4. Industrial wood production

IWP differences in each scenario are illustrated in Fig. 1d; the results show that yields were higher in Sc3 than in Sc2. The annual mean IWP under Sc2-CC increased from 2.46 million m^3 in the 2010s to 3.36 million m^3 in the 2040s, and in comparison, the annual mean IWP under Sc3-CC in the 2040s was 7.67 million m^3, 228.2% higher than that under Sc2-CC. This was because the annual harvest area in Sc3 was larger than that in Sc2 in our assumption. According to the national forestry report, the total IWP from South Korean forests increased from 1.14 to 2.29 million m^3 between 2010 and 2017 (KFS 2019), and in simulation Sc2-CC, it increased from 0.67 to 3.04 million m^3 during that period. There are two possible reasons for these differences. First, they could be attributable to our method for selecting the target harvest areas; in our simulations, harvest management was prioritized based on stand age and stem volume, and therefore, the mean stem volume of forest areas selected for harvest in the model could be higher than that of actual harvest areas. The other possible reason could be related to the biomass loss rate in actual harvest activity. In our simulation, we did not consider biomass loss in harvest management.

3.1.5. Forest recreation

We observed the total RE value in every scenario tended to increase gradually from 2010 to 2050. The potential recreation area and total RE value in Sc1-CC were estimated to be 689,400 ha and 0.75 million in 2010, and it increased to 3,431,100 ha and 5.15 million in 2050. Our estimated RE value in the 2010s was very low because stand age and volume are considered one of the main factors in assessing RE. Korea’s forests have spatial heterogeneity in stand age caused by profound historical deforestation before the 1960s and national plantation programs after the 1970s (Kim et al. 2019). In the NFI data, the accessible lowland forests are on average 10 years younger than mountainous forests that are distant from main residential areas (NIFoS 2011). As shown in Fig. 1e, changes in RE are also affected by forest management activities. The simulation results showed that estimated RE value under Sc2-CC and Sc3-CC in 2050 were 4.95 and 4.18 million, respectively, accounting for 93.3% and 81.2% of the RE under Sc1-CC in 2050. Owing to the larger areas of final felling and, thus of younger, less mature trees, the RE value in Sc3 was much smaller than that in Sc2 (Fig. 1e).

Difference patterns between the climate scenarios in the estimated RE value are shown (Fig. 1e). In simulation periods, the overall results show that the total RE value under Sc2 and Sc3 were higher in CC than in R85. However, the total RE value in Sc1-CC is estimated as slightly lower than in Sc1-R85. This was because each grid of forest area is given different weight depending on stand volume, dominant tree species, and diversity of species composition with the neighbor area (diversity index in Eq. 3) in the process of estimation RE value. In our simulation results, the overall growth of broad-leaved forests with higher weight values for RE than coniferous forests were positive effected by climate change according to R85 (Fig. 1e). In addition, the overall diversity index was estimated to increase gradually from 2010 to 2050 due to without harvest activity in Sc1-R85. In Sc2-R85 and Sc3-R85, the climate change impacts on forests were the same as in Sc3-R85, but the diversity index and potential recreation areas were lower, due to harvest management than in Sc1-R85. Consequently, these negative effects on RE from the harvest in Sc2-R85 and Sc3-R85 were estimated higher than the positive impact of climate change.

3.2. Variations in trade-offs and synergies

We compared the projections for the five ecosystem services in the 2040s with the situation in the 2010s (2010–2017), the base period for assessment, and the differences are shown in Fig. S6. We identified the trade-offs and synergies among multiple services by forest aging by comparing the conditions in 2015 with those in the 2040s under Sc1-CC; as expected, we observed clear synergy between CS and RE in this study. The scenarios further showed trade-offs between CS and RE and IWP on one side and between Cse, IWP, and, to some extent, WS on the other. In the 2040s under Sc1-CC, Cse decreased by approximately 43% compared with the base year, thus negatively affecting South Korea's achieving its nationally determined contributions. South Korea's NDCs include the target of reducing GHG emissions, excluding land use, land-use change, and forestry, by 37% below the business-as-usual emission (850.6 MtCO2eq) by 2030.

Fig. S6 presents the temporal variations in the trade-offs and synergies among multiple ecosystem services by climate change from the 2020s to the 2040s. WS correlated strongly with precipitation levels. For instance, in the RCP8.5 scenarios, spring precipitation in South Korea was considerably higher in the 2020s than in the 2010s, but projected WS decreased to nearly the same level as for the 2010s during the period from the 2020s to the 2040s. Other ecosystem services except RE were estimated to decrease gradually over time because of climate change. Estimated average CS, Cse, and IWP under Sc2-R85 in the 2040s were 30.7 Tg C, 6.51 Tg C yr^{-1} and 3.11 million m^3, and they decreased by 3.3%, 2.7%, and 7.3% compared with Sc2-CM in the 2040s, respectively.

In Sc2-CC and Sc3-CC in the 2040s, Cse improved by approximately 6.6% and 24.0% and WS by approximately 4.0% and 8.4%, respectively, compared with in Sc1-CC in the same decade. In addition, the ratio of CS, Cse, WS, IWP, and RE of Sc3-to-Sc2 in the 2040s was estimated as 88.4%, 114.7%, 105.4%, 228.2%, and 86.5%, respectively. These results showed the intensified harvest activity might provide a negative effect on Cse in the short term, but the long-term effect could be positive. These results also implied that sustainable forest harvesting could help in maintaining ecosystem services such as Cse and WS.

In this research, we tried to handle trade-offs and synergies among fives forest ecosystem services by aging, management, and climate change using various models. This is necessary for the integrated assessment of change in forest ecosystem services and providing a revealing insight into the policymakers. In addition, although this research focused on Korean forests, the results of the changing trend among forest ecosystem services are similar to other previous research for temperate forests (Bugmann et al. 2017; Pang et al. 2017). Therefore, our results cannot be only helpful for Korean forests but also temperate forests in the world. However, this strong point of our research could lead to a bit of complicated to describe the interactions between the different ecosystem services. Therefore, this limitation should be solved and improved in further research.

3.3. Implications for forest management

In order to measure the function of a forest as a carbon sink, we used biomass expansion factors to estimate the carbon content of a whole tree using stem volume as input data. Thus, in this study, we assessed only CS and Cse in the tree layer; the total forest carbon stock would have been considerably higher if we had included soil carbon, litter carbon, and ground vegetation (Kim et al. 2016). Moreover, considering carbon stored in wood products and substitution effects (such as forest regeneration) from using forest biomass as raw material instead of fossil fuels would have affected the carbon balance (Kallio et al. 2013).

This study simulated RE that were driven mainly by the forest's structures. In case of the RE, the provisioning potential could rely on forest's structure resulting from the dynamics by climate change, but the consumer's perceptions of ecosystem services can be enlarged by various climate resilience management and policies such as application of forest therapy, increasing forest education, investment of forest village, and forest tourism management

(Nielsen et al. 2007). Therefore, further research on the recreational values of Korean forests associated with identifying and assessing public preferences is suggested.

In this study, we assessed only IWP from stem volume, but final felling also produces harvest residues, i.e., tops, branches, and foliage. These have diverse uses such as for producing bioenergy, bio-compost, sawdust, and wood chips. Forest bioenergy is generally considered renewable, carbon-neutral energy, which means that forest bioenergy could mitigate climate change due to the neutrality of GHG emissions in the whole harvest and regeneration cycle. Our results indicate that given the abundant forest cover in South Korea, there is a substantial potential for bioenergy production, which could not only reduce fossil fuel emissions but also contribute to meeting any targets agreed to under potential climate change mitigation agreements.

However, increased extraction of harvest residues can be expected to have environmental impacts. For example, these could affect soil acidification, causing the decline of forest productivity (de Jong et al. 2017). In addition, residues contribute to the supply of deadwood, an important forest biodiversity component (Sullivan et al. 2011). In addition, increased surface fuel and a homogenized forest structure resulting from management practices such as timber harvest could lead to the accumulation of forest fuels that are playing a major role in increasing wildfire size and severity in many semiarid forest types (Allen et al. 2002). Therefore, future harvest policies should consider the balance between the extraction targets, such as commercial targets to produce IWP and fuel reduction targets to reduce wildfire hazards, and residue retention targets to maintain habitat and other forest functions.

Although we focused on only one type of forest management in this study, it is necessary to consider the correlation of other management practices and changes in ecosystem services additionally for improving or maintaining the resilience of the forest ecosystem.

Timber production by thinning and reforestation with trees of different species could help to lessen the negative effects of biomass production by improving the soil biota diversity (Vicente-Vicente et al. 2019). In addition, the techniques and systems for forest management are also important to maintain timber production while minimizing the negative effects on ecosystem services. According to previous research, improved timber harvesting could have relatively benefits to reduce logging emissions (Ellis et al. 2019), biodiversity (Bicknell et al. 2014), and soil erosion (Vicente-Vicente et al. 2019). Therefore, management-types and -related techniques should comprehensively consider in further study or actual actions for assessment of change in forest ecosystem services.

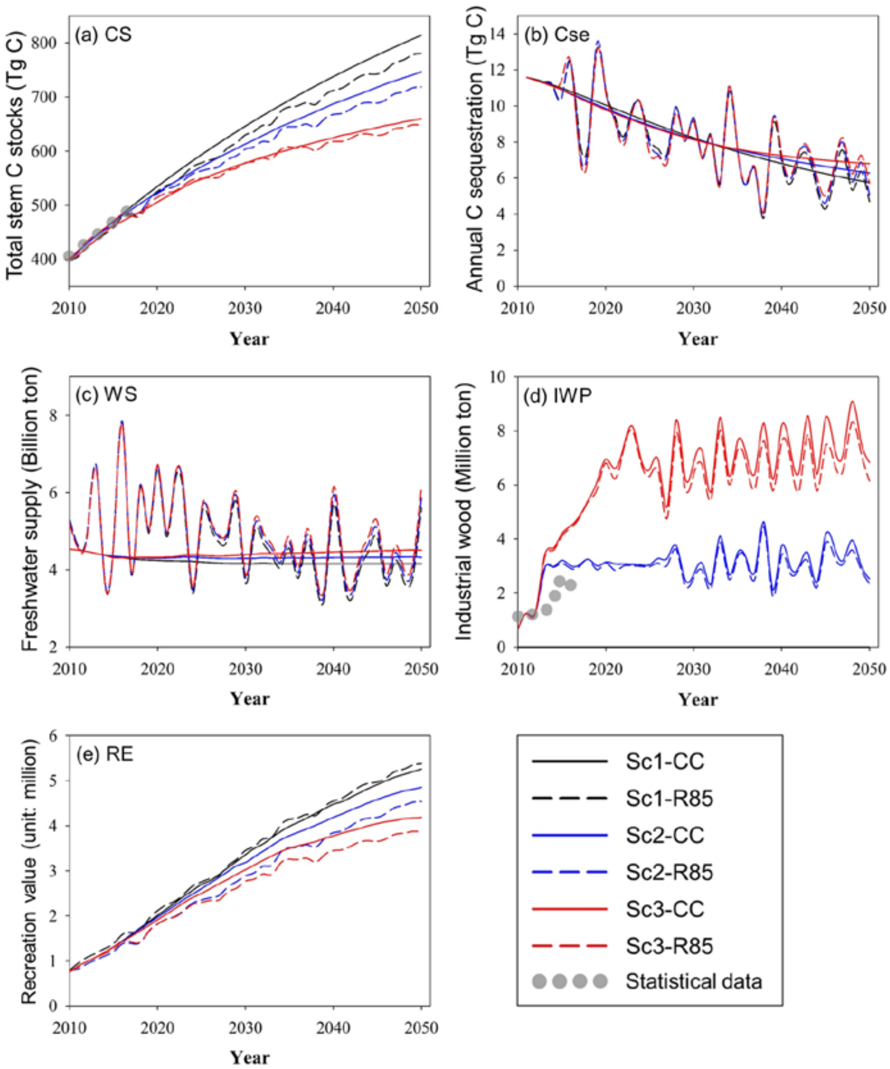

Fig. 1. Supply of ecosystem services such as (a) CS, (b) Cse, (c) WS, (d) IWP, and (e) RE during 2010–2050 in the forest management and climate change scenarios [CS: carbon stock, Cse: annual C sequestration, WS: freshwater supply, IWP: industrial wood production, and RE: potential recreation value].

4. Conclusion

This study projected the changes among ecosystem services with related forest management strategies and climate change using a spatially explicit tool for applying a forest-centered approach. The results showed that different harvest policies and climate change had different effects on potential biomass extraction and other ecosystem services, and these effects changed over time. The forest management scenarios showed trade-offs between RE and CS on one side and between IWP, WS and, to some extent, Cse on the other side. In addition, this study showed that future climate change under RCP8.5 until 2050 in South Korea could have a significant negative influence on forest carbon uptake and storage and could offset the positive effects of harvest activity.

The scenarios could be adjusted and re-run to find more sustainable solutions such as forest management strategies for the spatial distribution of management activities for the equilibrium of demand and supply in ecosystem services. Our findings and tools could be helpful that the synergies and trade-offs between forest ecosystem services can be localized, quantified, and assessed for different land use-related policies and plans, thus providing decision support for sustainable forest management.

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Supplement materials

Table S1. Description of the main models for integrated analysis in this study

Model	Description	Reference
Dynamic growth model	• Contribution: Application to predict forest carbon stock and sequestration under management and climate change scenarios • Input: Environmental factors (Stand age, Site index, Tree species), Climatic factors (Temperature, precipitation), Management factors (Clear cut) • Output: CS, Cse, IWP	Kim et al. 2019; Kim et al. 2017; Piao et al. 2019; NIFoS 2014
Water yield model	• Contribution: Application and spatial expansion, form plot- to national-level, of developed model using spatial analysis and dynamic growth model • Input: Stand age, Tree species, Slope, Precipitation • Output: WS	Tian et al. 2008; Kim 2018
Forest recreation index model	• Contribution: Development of spatial assessment model for forest recreation index using ArcGIS • Input: Stand age, CS, Tree species, Site suitability, Tree species composition • Output: Recreation index	Nielsen et al. 2007 Pang et al. 2017

Table S2. Parameters for stand volume and carbon storage (NIFoS, 2014)

Tree species	Coefficients			[a]BWD	[b]BEF	[c]R-S
	a	b	c			
Red pine	0.034	1.734	1.025	0.472	1.413	0.254
Japanese larch	0.005	2.458	0.904	0.453	1.335	0.291
Korean pine	0.046	1.732	0.896	0.408	1.812	0.283
Cork oak	0.053	1.810	0.881	0.721	1.338	0.324
Mongolian oak	0.098	1.406	1.135	0.663	1.603	0.388

[a]BWD: Basic wood density, [b]BEF: Biomass expansion factor, [c]R-S: Root-shoot ratio

Table S3. The final cutting age of major Korean tree species (KFS, 2015)

Tree species	Final age
Red pine	60
Korean pine	60
Japanese larch	50
Cork oak	60
Mongolian oak	60
Mixed-A	60
Mixed-B	60

Table S4. Data and parameters for assessment of recreational value in forests

Factors		Measurement	Reference
Geographic factors	Accessibility to the forest	The forests within a 2 km radius of housing areas or within 300 m along each side of a road network	Hörnsten and Fredman (2000)
Environmental factors	Maturity	Stand age for coniferous, broad-leaved, and mixed forest is older than 70 years old or stand volume is higher than specific value for each forest type	Pang et al. (2007)
	Species	The coniferous, broad-leaved, and mixed forest was evaluated that its potential RS was multiplied by 0.75, 1.0, and 1.25, respectively	Nielsen et al. (2007)
	Composition with the neighboring areas	The visual and structural diversity is evaluated based on a variety of forest types in the neighborhood area.	Nielsen et al. (2007), Zandersen and Tol (2009)

Table S5. The reference stand volume of forest types for assessment of recreation service in South Korean forests (KFS, 2015)

Forest type	Reference stand volume (m^3 ha^{-1})	Mean volume (m^3 ha^{-1}) (std. dev.)
Coniferous forests	141.87	234.25 (92.38)
Broad-leaved forests	133.53	201.29 (67.76)
Mixed forests	145.38	214.87 (69.49)

Table S6. Comparison of water yield from South Korean forests with that of previous studies

Year or period	Model	Estimate WY (yr^{-1})	Reference
2000s	InVEST	22,210 million m^3	Kim et al. 2017
2011	Statistical model	19,060 million m^3	Kim et al. 2010
2009	Statistical model	18,000 million m^3	Jung et al. 2009
2011	This study	18,562 million m^3	This study
2010s		20,562 million m^3	

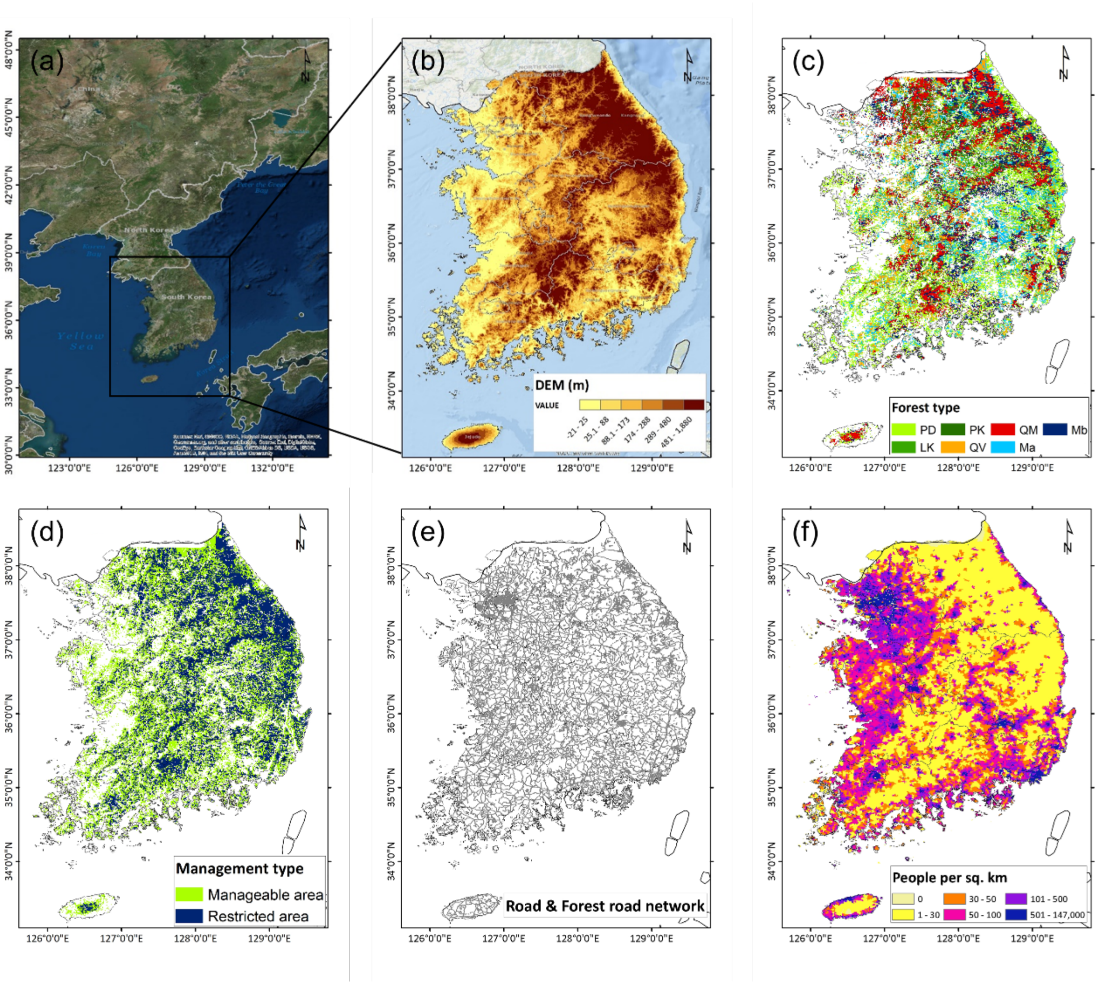

Fig. S1. (a) Geographic location, (b) digital elevation model (DEM), (c) forest type distribution [(PD): *Pinus densiflora*; (PK): *Pinus koraiensis*; (LK): *Larix kaempferi*; (QM): *Quercus mongolica*; (QV): *Quercus variabilis*); (Ma): Mixed forest (PD and QV); (Mb): Mixed forest (PD and QM)], and (d) management type distribution in South Korea. Map of (e) road and forest road system, and (f) population density.

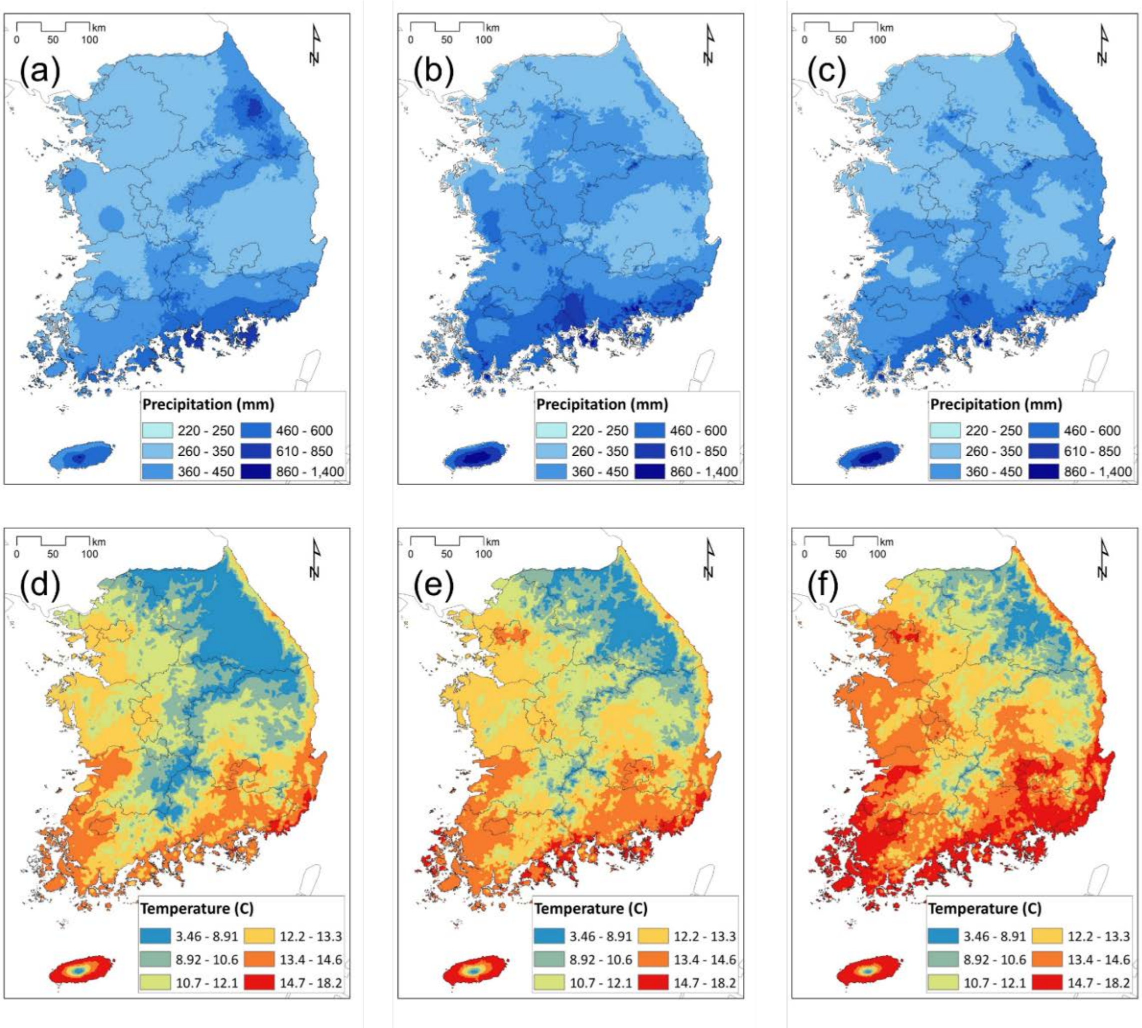

Fig. S2. The projection of mean spring (March-May) precipitation and temperature over South Korea in the 2000s (a,d), 2020s (b,e), and 2040s (c,f) under Representative Concentration Pathway 8.5 (RCP8.5)

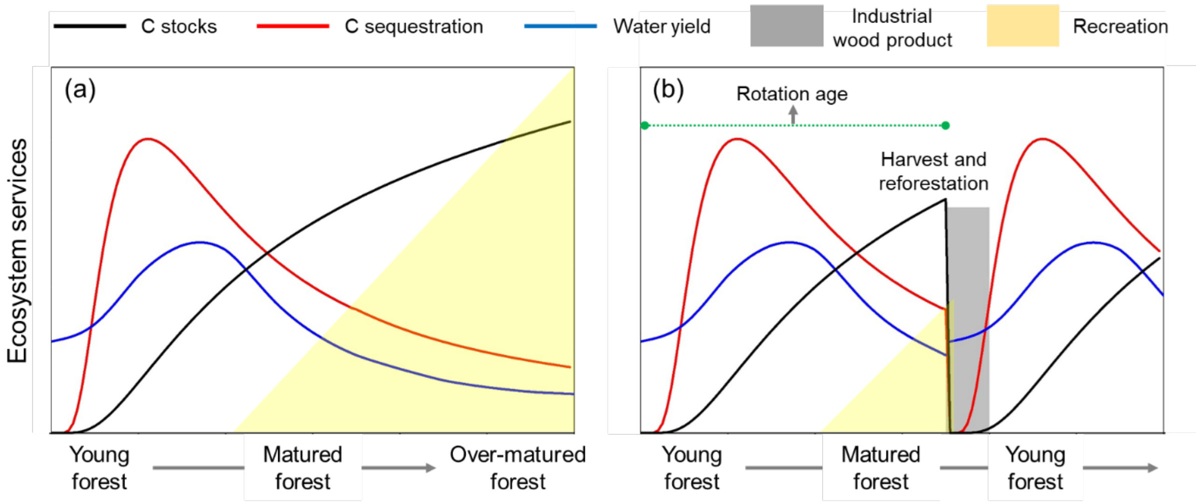

Fig. S3. Forest ecosystem services of (a) a non-harvest forest and (b) a managed forest relative to stand maturity.

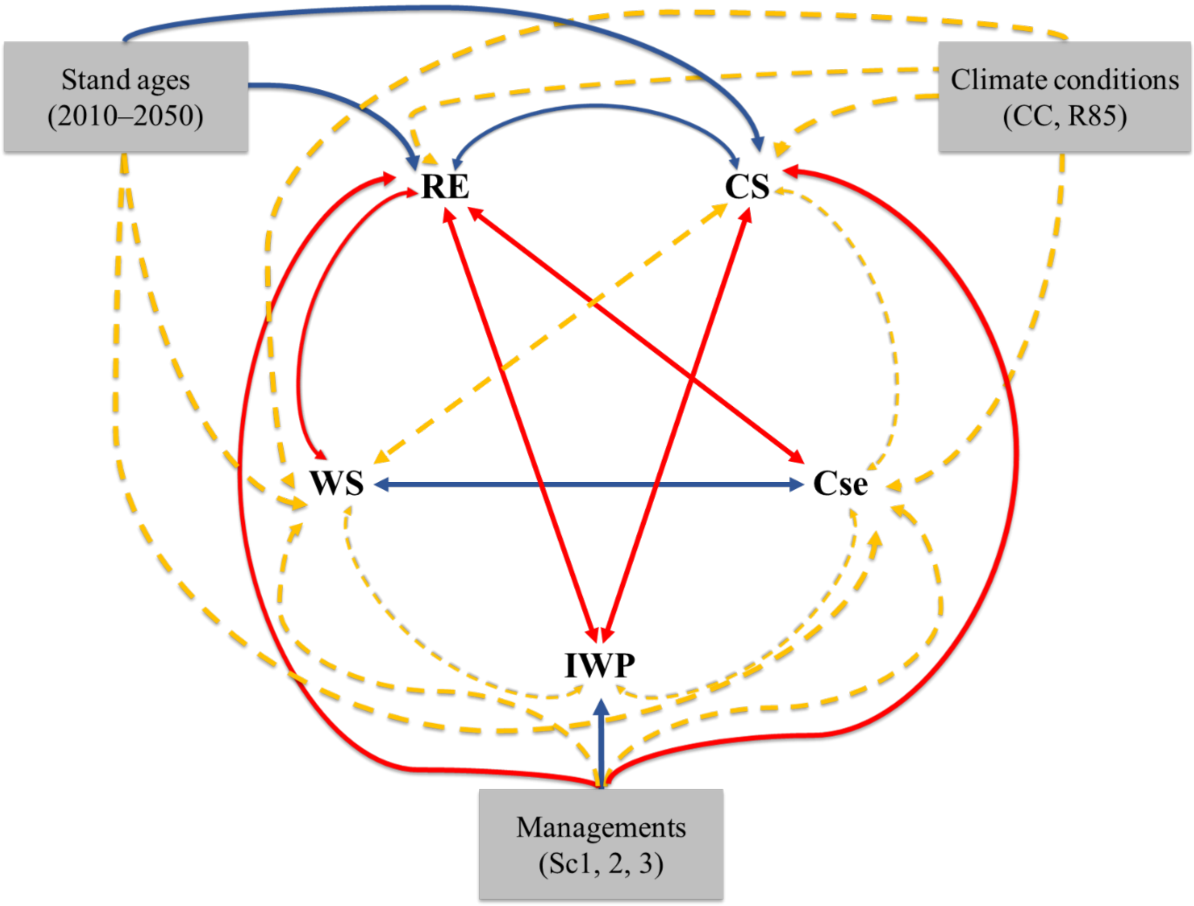

Fig. S4. Flow chart of management, age, and climate change effects on forest ecosystem services. Blue and red solid arrows indicate positive and negative effect. Orange dashed arrow means an intermediate effect. Abbreviations: CS – carbon storage, Cse – carbon sequestration, IWP – industrial wood production, WS – fresh water supply, RE – forest recreation, Sc1-3 – these are management scenarios that the Sc1, Sc2 and Sc3 are defined by the maximum annual harvest area (Sc1: zero, Sc2: 15,000 ha, Sc3: 35,000 ha), CC – climate conditions remained at current levels (2000–2010) until 2050, R85 – the projected climate conditions by Representative Concentration Pathway 8.5

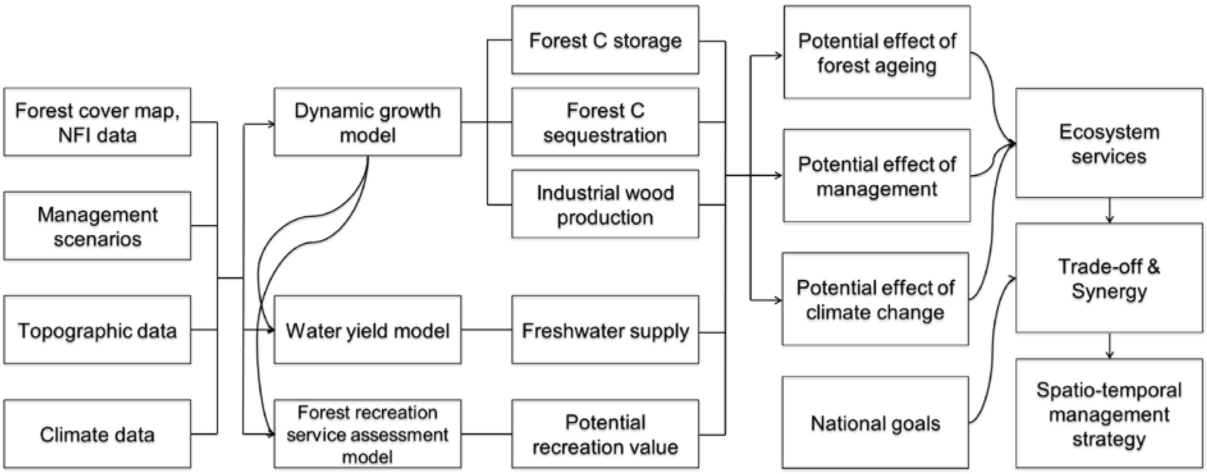

Fig. S5. Framework for assessing the temporal variation and spatial scales of trade-offs and synergies among multiple ecosystem services.

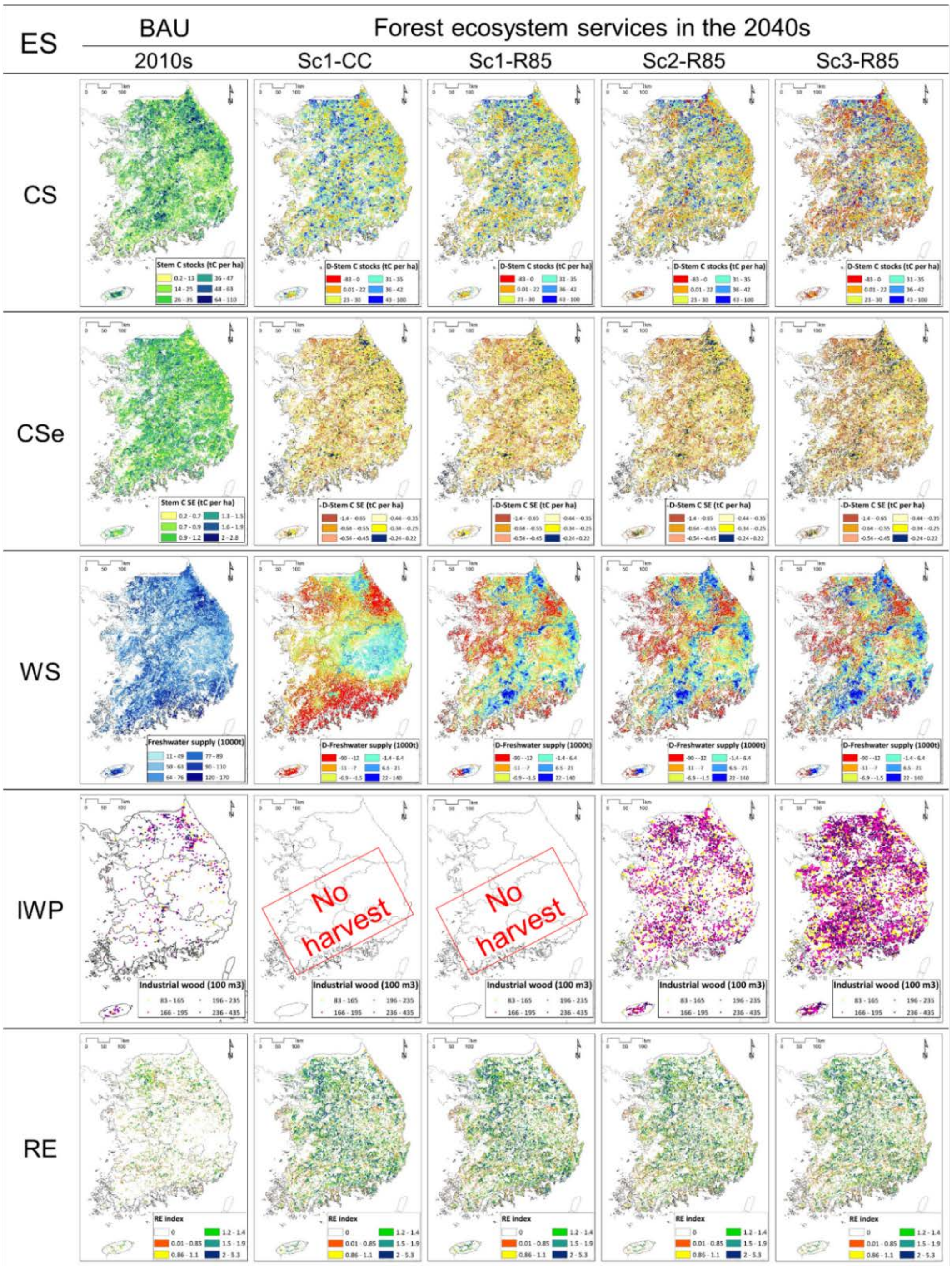

Fig. S6. The difference in forest ecosystem services (CS, Cse, and WS) between each scenario in the 2040s and in the 2010s. Time and space distribution of IWP and RE in the forest areas of South Korea from the 2010s to the 2040s (CS: forest carbon storage, Cse: annual C sequestration, WS: fresh water supply, IWP: industrial wood production, RE: recreation service).

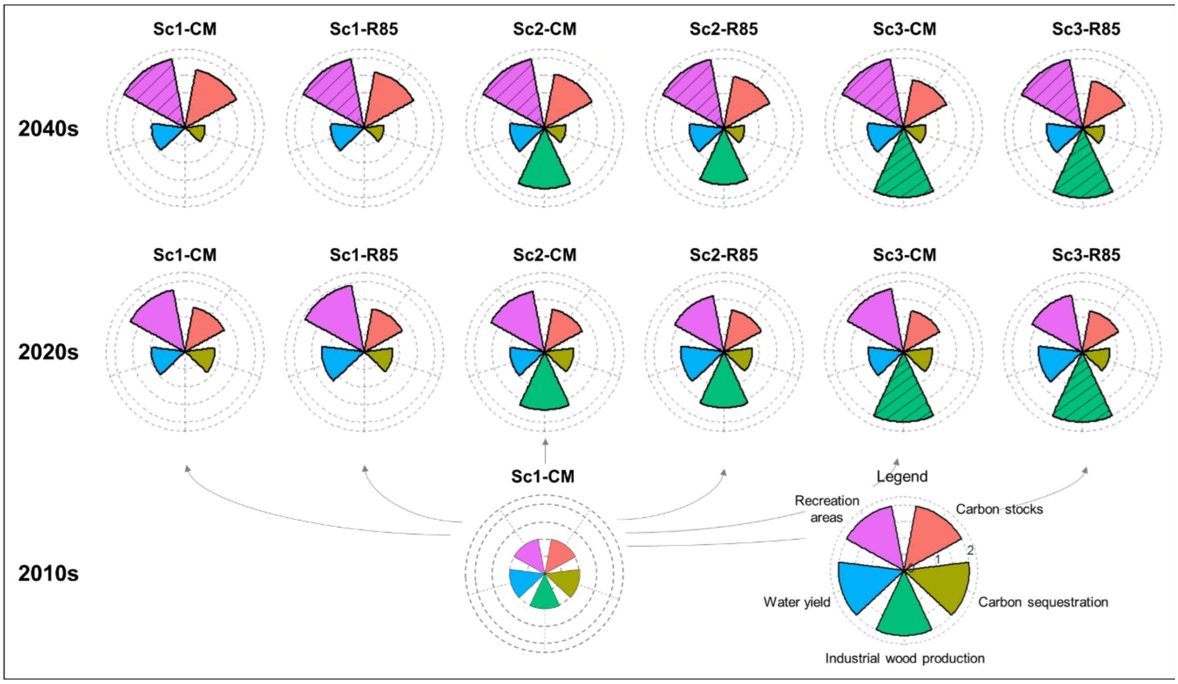

Fig. S7. Flower diagrams. Estimated changes among forest ecosystem services by each scenario in the 2020s and 2040s from the services in the 2010s (as % of 2010s values). Values with slashes exceed 200%. Diagrams reveal the percentages for each forest ecosystem service through petal length, with each flower representing one scenario in a certain decade.