Can a national afforestation plan achieve simultaneous goals of biodiversity and carbon enhancement? Exploring optimal decision making using multi-spatial modeling

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Abstract

There is a growing awareness of the need to integrate climate and biodiversity policies. As forests play an important role in mitigating biodiversity loss and climate change, numerous countries have established goals and are managing their forests to achieve them. However, forest management measures and land prioritization may differ depending on the target chosen, leading to conflicts. This research aims to seek optimized national afforestation plans in the Republic of Korea by assessing trade-offs between plant biodiversity persistence and carbon stocks. To this end, afforestation scenarios were spatially established based on the national forest management plans, with a target of 5,800 ha expansion by 2022. Generalized Dissimilarity Modelling (GDM) and Global Forest Model (G4M) were applied to the selected afforestable regions to obtain scenarios that maximize biodiversity and carbon, respectively. Furthermore, another afforestation scenario that considers both objectives equally, was proposed using spatial simulated annealing (SSA) optimization algorithm to mitigate trade-offs. The constructed scenarios were compared, both spatially and quantitatively. As a result, the maximization scenarios were found to have few overlapping areas, with both scenarios resulting in ~50% trade-offs. These findings reveal that there is no universal solution and different management strategies are needed to enhance biodiversity persistence and carbon stocks. Thus, to strike a balance among the various goals, forest management requires a compromise solution to minimize trade-offs. Our national-scale assessment can help to guide future planning of national forest management with the consideration of the joint goals of biodiversity and carbon enhancement.

Keywords: plant biodiversity persistence; carbon stocks; optimization; trade-offs; afforestation; national forest management plan

1. Introduction

Biodiversity loss and climate change are the most intractable threats to humans (Folke et al., 2004; Thompson et al., 2009; IPCC, 2014; Oliver et al., 2015; Lecina-Diaz et al., 2018; McVittie and Faccioli, 2020). Climate change is a major driver of biodiversity loss; conversely, biodiversity is the most important basis of ecosystem services, and is an important contributor to climate change adaptation and mitigation (Munang et al., 2013; Pereira et al., 2013; Choi et al., 2019). Accordingly, international organizations, such as the Intergovernmental Panel on Climate Change (IPCC) and the

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) are engaged in increasing awareness of the need to integrate climate and biodiversity policy (Ferreira et al., 2018; Biodiversity and Climate Change Working Group II, 2018; Soto-Navarro et al., 2020). They encourage parties to incorporate climate change issues and related national goals into national biodiversity strategies and action plans; conversely, they want nations to incorporate biodiversity and ecosystem agendas into national policies, strategies, and plans for climate change (Biodiversity and Climate Change Working Group II, 2018).

Forests, accounting for one-third of the Earth's land surface, provide a wide range of ecosystem services (FAO, 2020; Lee et al., 2020), and in particular, play a major role in the global carbon cycle (Sedjo, 1993; Schimel, 1995; Keith et al., 2019). In addition, as they provide important habitats for terrestrial biodiversity (Thompson et al., 2012), forest management remains one of the most effective strategies for enhancing ecosystem services. Accordingly, many countries have established ambitious targets to promote forest conservation, afforestation, and restoration at the national level (Thompson et al., 2009; Shepherd et al., 2016; Bastin et al., 2019). However, these targets differ in their emphasis on increasing carbon stocks or enhancing biodiversity, and may be constrained by limited resources and available land (Lecina-Diaz et al., 2018; Obersteiner et al., 2018; Arneth et al., 2019). Furthermore, it remains unclear whether these goals can be achieved simultaneously. If forests with high carbon stocks do not spatially coincide with biodiversity priorities, this can cause a conflict between which goal is achieved (Reside et al., 2017).

Although a number of studies have been conducted to identify the relationship between biodiversity and carbon stocks, their correlation remains controversial (Evans et al., 2015; Murray et al., 2015; Reside et al., 2017; Ferreira et al., 2018; Girardello et al., 2019; Grass et al., 2020; Blattert et al., 2020). In addition, previous research has focused on existing forests to identify and compare regions with high biodiversity or carbon stocks (Murray et al., 2015; Reside et al., 2017; Lecina-Diaz et al., 2018; Soto-Navarro et al., 2020). However, as afforestation or restoration of degraded forests has been recommended as an efficient strategy to increase carbon stocks or biodiversity, it is necessary to investigate the most suitable areas for its implementation and evaluate its effectiveness. Even though the potential benefits of forest restoration and afforestation on carbon sequestration have been highlighted (Potapove et al., 2011; Erb et al., 2018; Bastin et al., 2019), their implications on biodiversity have not been sufficiently studied; instead, most research has concentrated on biodiversity loss due to degradation of forests or climate change (WWF, 2008; Araújo et al., 2011; Thompson et al., 2012; Newbold et al., 2016; Drielsma et al., 2017; Chaudhary and Mooers, 2018; Choi et al., 2019; Lim et al., 2019a; Di Marco et al., 2019a).

Afforestation and forest restoration are opportunities for both conservation organizations (NGOs), corporations, government, and other stakeholders to conserve species and increase carbon stocks. Conservation organizations need to identify the locations of areas that should not be damaged or that need to be restored to promote species conservation. On the other hand, individual forest owners, local governments, national forest managers, and corporate forestland owners, who wish to obtain certification of carbon absorption through forest management activities, need information on the location and species of trees to plant that can maximize carbon storage (Shin and Yeo-Chang, 2019). For governments that need to simultaneously promote the achievement of biodiversity conservation targets (e.g., Aichi targets) and ‘Net Zero’ emissions, a balanced environmental plan should be established with spatially explicit guidelines for afforestation or restoration. Therefore, in order to establish an effective environmental plan, research should focus on whether forest management can both maximize carbon stocks and ensure biodiversity conservation, simultaneously, or whether biodiversity requires a separate planning approach different from forest management plans that focus on carbon stocks.

This study aims to seek ways to optimize the national afforestation plans of the Republic of Korea (ROK) in consideration of the balance between these competing objectives. The Korean government has devised various forest management plans based on predictions of future environmental changes. For example, due to a decline in human population, development is set to decline, leading to a reduction in forest degradation, and the increase in abandoned lands in rural areas is expected to be converted into forests (Korea Forest Service, 2018). Furthermore, the President of South Korea has declared that the ROK will commit to achieving carbon neutrality (Net Zero) by 2050 during the national assembly on October 27, 2020 ("Statement attributable," 2020). The Government of South Korea announced the '2050 carbon neutral strategy' to achieve this goal, including innovative forest management strategies to secure carbon sinks (The Government of the Republic of Korea, 2020). The majority of forests in Korea are over 40 years old, and at these ages, they tend to have lower carbon dioxide uptake (Li et al., 2011; An et al., 2019). Recognizing this, the Korea Forest Service plans to increase carbon absorption sources by building urban green spaces, restoring degraded lands and planting trees in underutilized lands, and establishing a management system for the newly forested areas (Korea Forest Service, 2018; The Government of the Republic of Korea, 2020). Moreover, as biodiversity decline is predicted due to multiple drivers, including climate change, habitat destruction, and degradation (Choi et al., 2017; Choi et al., 2021), the Government has established various biodiversity conservation strategies under the goal of equitable sharing of natural resources for all citizens through biodiversity conservation and enhancement, and risk management, such as: habitat loss reduction, pressure reduction on vulnerable ecosystems, prevention and control of invasive species, and protection of biodiversity through the expansion of protected areas and restoration of ecosystems (The Government of the Republic of Korea, 2014).

We put the forest management goals and plans currently being pursed in a geographic context to identify strategies to maximize both biodiversity and carbon storage. In particular, we focus on enhancing plant biodiversity and carbon stocks secured through afforestation. Multiple spatial afforestation scenarios using detailed national environmental datasets, global spatial modeling, and optimization algorithms are constructed to maximize biodiversity and carbon storage respectively, and simultaneously consider both objectives. Through a comparative analysis of biodiversity and carbon stock gains for each scenario, the effectiveness of afforestation according to location is quantitatively evaluated, and compromise solutions are examined to minimize the trade-off between the two objectives.

2. Materials and Methods

2.1 Study area

The study area of this study is the whole of the ROK (Figure 1). The ROK is an interesting study area for assessing the effect of forest management, as it has had a successful reforestation history (Bae et al., 2014; Kim et al., 2017; Lee et al., 2018; Kim et al., 2019). During the Korean War (1950–1953), almost half of the forest land was destroyed, and the average volume of the growing stock dropped approximately 36%–40% of the pre-war estimate (Korea Forest Research Institute, 2014), and only 35% of the national land area was forest cover, excluding non-stocked forestland (Bae et al., 2012). However, since the national reforestation programme in the 1970s, 63% of the country area is currently covered by forests, and the government has been carrying out continuous forest management including afforestation (Korea Forest Research Institute, 2014). The eastern region of Korea is extensively mountainous, including the Taebaek Mountain range, which is the main ridge of the Korean Peninsula (Lim et al., 2019b). The Sobaek Mountain Range, which extends from the Taebaek Mountain Range, cut across the center of Korea. The southern tip of Korea is made up of Jeju Island, which has a distinct climate and unique geographical features. Figure 1 demonstrates the topographical characteristics of the study area (left), and land cover with the classification units used for biodiversity modeling (right).

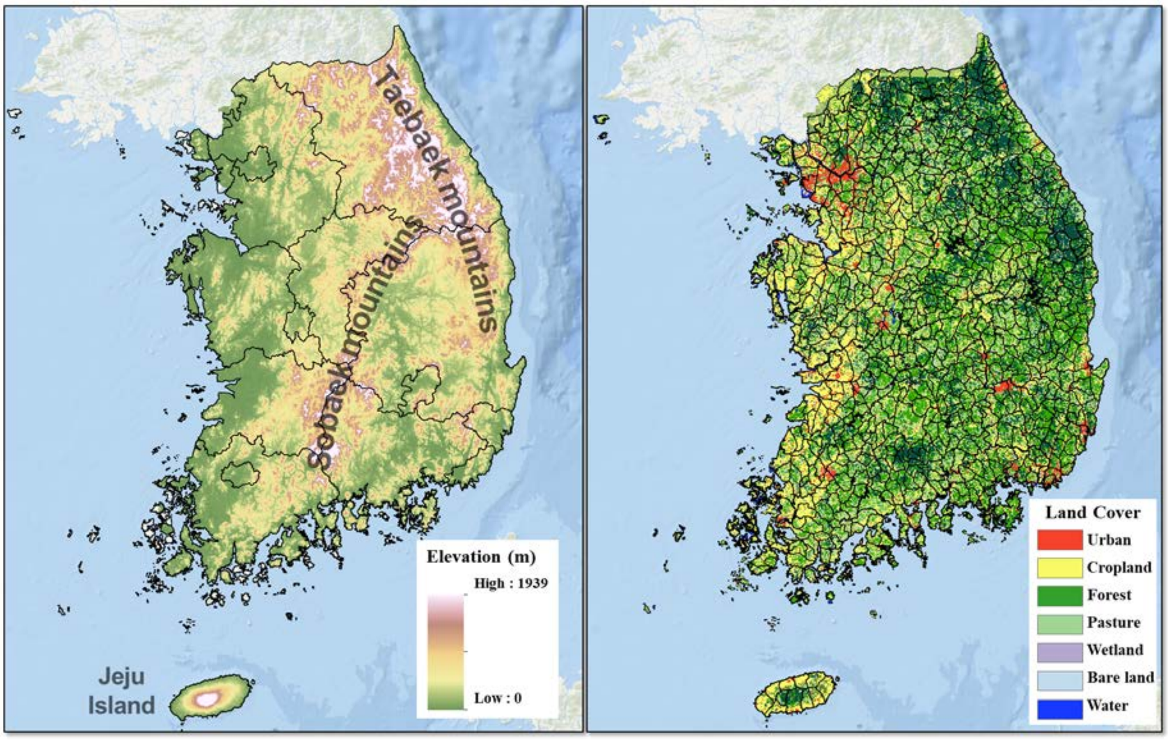

Figure 1. Administrative boundary with elevation information (left) and land cover map with classification units (right) under the World Geodetic System (WGS84) obtained from National Geographic Information Institute in Korea and Ministry of Environment, respectively.

2.2 Review of national plans and method to select afforestable area

In this study, we reviewed two key national plans of the Korean government related to forest management for climate change mitigation, and biodiversity conservation, referring to "Comprehensive plans for improvement of carbon sinks (2018–2022)", "and "The 3rd forest biodiversity master plan (2018–2022)".

The "Comprehensive plans for improvement of carbon sinks (2018–2022)" enacted under the "Act on the Management and Improvement of Carbon Sink" aims to reduce greenhouse gas emissions by 10% of reduction targets through forest management by 2030. Seven % of greenhouse gases are expected to be absorbed through domestic forest management and 3% through overseas REDD+ and forest restoration projects. Domestic forest management includes reduction plans of 20 million tons of greenhouse gas by reinforcing the carbon cycle, for example, promoting tree species renewal. Using domestic timber and expanding new carbon sinks are expected to reduce greenhouse gas emissions by 2.4 million tons and 77,000 tons respectively. The expansion of new carbon sinks, a focus area of this study, is expected to contribute towards 3,000 ha of forests within cities by 2022. It also includes plans to secure 300 ha per year from 2015 to 2020, and 500 ha per year during 2021−2022 through afforestation and restoration of idle land, coastal forests, and damaged areas. Taken together, it can be confirmed that the government plans to afforest a total of 5,800 ha (3,000 + 300 × 6 + 500 × 2) by 2022.

"The 3rd forest biodiversity master plan (2018–2022)" also sets various implementation goals such as the expansion of forest protection areas, conservation of forest species, and restoration of damaged areas. Afforestation includes a plan to restore forests about 96 ha of major mountain range and the Demilitarized Zone (DMZ) area, and 219 ha of other regions, including cities. Although the two plans set their respective targets, both plans have the same goal of restoration or afforestation. They are therefore likely to be applied to overlapping sites during implementation because of the limited land area available Hence, we chose to analyze the impact of achieving the larger 5,800 ha afforestation target from the carbon sinks enhancement plan

Potential afforestation sites were selected by converting a national land cover map (1/25,000) produced by the Ministry of Environment (MoE) in 2007 to a 100-m resolution. We excluded urbanized areas, agricultural areas, forests, wetlands, and water bodies among the 22 land cover classes, as they were unsuitable for afforestation. We further excluded artificial lands, including golf courses, playgrounds, pastures for livestock production, and farms, as implementing public-led afforestation in these areas is difficult because they are private properties. Moreover, afforestation is not feasible in bare land as it includes rocky areas and sandy beaches that hinder vegetation growth. Hence, we only considered natural pastures as afforestable in this study. In Korea, natural pasture is mainly considered as an intermediate transitional stage to forests (Yun and Chang, 1969; Lee, 1992), as Korea's high annual precipitation and average temperature means that natural grasslands cannot achieve climatic climax. In addition, natural pastures include areas of low current carbon and biodiversity value; for instance, small-scale herbaceous plant communities occupying neglected cultivated lands or places with high human interference around cultivated lands or forests destroyed by fires or logging (Lee, 1992), making them particularly suitable for afforestation. Accordingly, of the 53,298 ha of natural pasture in Korea, 5,800 ha were explored to maximize biodiversity and carbon storage.

Figure 2 shows the overall flow of the study. An optimal area was sought to maximize biodiversity and carbon storage by applying generalized dissimilarity modelling (GDM) and the global forest model (G4M), which were used to simulate changes in biodiversity persistence and carbon stock, respectively. Using these, three different scenarios, viz. biodiversity-focused afforestation scenario (BfA), carbon-focused afforestation scenario (CfA), and simultaneously focusing on biodiversity and carbon afforestation scenario (BCA) were derived, and the effectiveness of each scenario was quantitatively evaluated.

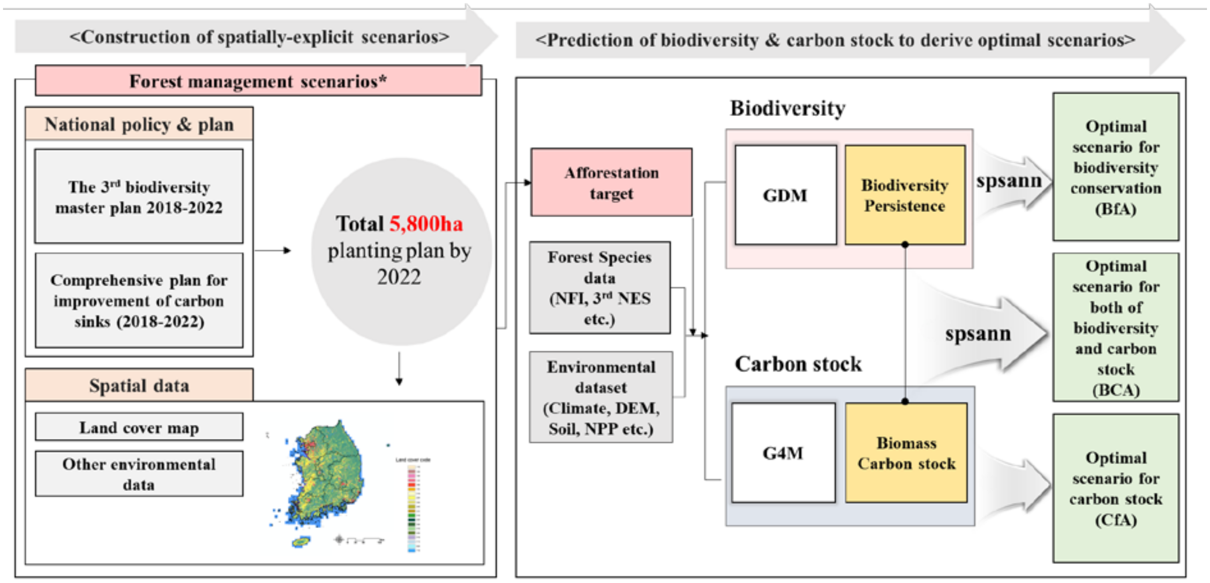

Figure 2. Research flow

2.3 Biodiversity persistence modeling for Biodiversity-focused Afforestation scenario (BfA)

This study adopted the Allnutt et al. (2008) approach to project biodiversity persistence (BP) which has been underpinned by several global studies (Hoskins et al., 2020; Di Marco et al., 2019a). This approach utilized GDM with estimates of habitat conditions for simulating BP (Hoskins et al., 2020; Di Marco et al., 2019a; Di Marco et al., 2019b; Choi et al., 2021). Under the assumption that species composition changes as environmental differences increase along with spatial distance, GDM analyzes the dissimilarity between pairs of sites and projects spatial pattern of species composition (β-diversity) across large regions (Ferrier et al., 2007; Fitzpatrick et al., 2011; Laidlaw et al., 2016; Drielsma et al., 2017; Ware et al., 2018). The BP was calculated using equation (1), as described in detail by Allnutt et al. (2008) and Di Marco et al. (2019a, 2019b).

$$\mathrm{p}_i = \left[\frac{\sum_{j=1}^{j=n} s_{ij} h_j}{\sum_{j=1}^{j=n} s_{ij}}\right]^{0.25} \quad (1)$$

Here, p_i is the BP for each cell, which indicates the proportion at which the current species composition within cell i will be maintained for a long time. p_i consists of s_{ij} and h_j, which refer to the predicted similarity between cell i and all other cells j; and the habitat condition of cell j, respectively.

To apply the aforementioned methodology, a GDM model-based similarity (s_{ij}) and habitat condition map for h_j were constructed using the national dataset of the ROK. A total of 204,218 records of 2,940 plant species were obtained from the 3rd National Ecosystem Survey (2006–2010) for the application of GDM. We processed these data following Choi et al. (2021) to produce a similarity (s_{ij}) in species composition between pairs of sites using a function of environmental differences (Ferrier et al., 2007; Di Marco et al., 2019a), although we found that the model was more accurate when excluding altitude, land cover, and soil depth; accordingly, only 23 bioclimatic variables derived from CHELSA (Climatologies at high resolution for the earth’s land surface areas) climate dataset (Karger et al., 2017) were utilized. We used the monthly climate average of 2004‒2013 at a 1-km^2 resolution, considering the period of the species survey. Supplementary Table 1 presents the details of predictor variables.

The habitat condition index (HCI) developed by Choi et al. (2021) was also adopted. HCI is an index that evaluates habitat conditions based on the current distribution of species with a massive amount of survey data. Since the relationship between richness or abundance and ecosystem function as habitat is unclear, an equation of HCI weighted the species and abundance equally (see Choi et al., 2021 for further details). Therefore, it reflects the total number of organisms that an ecosystem can support. Accordingly, the BP derived in this study could be regarded as the proportion of the total population expected to persist over a long time under the current environment, rather than the proportion of species as was the case in the study of Di Marco et al. (2019a).

To create a BfA scenario that maximizes BP, the current spatial patterns in BP were simulated, and the points that produced the greatest improvement in BP by afforestation were selected. The calculated BP is non-linear because it depends on the similarity and habitat conditions of all other cells. This implies that it is difficult to obtain an analytical solution to determine the best afforestation area (Aerts and Heuvelink, 2002). Thus, we used a spatial simulated annealing (SSA) optimization algorithm to construct optimal afforestation scenarios. The SSA optimization algorithm is an iterative, combinational, model-based sampling optimization that yields the best quality alternative (in this case, the maximization of biodiversity persistence) by slightly and randomly changing the combination (van Groenigen and Stein, 1998; Brus and Heuvelink, 2007; Szatmári et al., 2015). By applying this optimization technique, we explored areas that can maximize their biodiversity persistence by replacing natural pastures with forests. However, a change in the habitat condition of one cell can affect the persistence of all other cells, leading to a computational challenge in cell-based optimization.

Thus, we used classification units to represent a certain spatial range with similar environmental characteristics (Figure 1). In order to systematically survey and manage the natural environment in Korea, the Ministry of Environment has divided the nation into 794 small regions with respect to natural ecological characteristics, administrative district boundaries, and areas of each zone. In addition, each region is subdivided into three classes: natural, semi-natural, and artificial. This division is based on biological habitats to ensure the homogeneity of each zone (Choi et al., 2017). A total of 2,349 zones were used to perform optimization, where persistence was repeatedly calculated using the similarities between zones with the average habitat conditions of each zone. Optimization was carried out by setting the objective function to select zones that maximized the overall average of biodiversity persistence across the country, when the zonal habitat condition score increased. We conducted SSA optimization using the spsann package of R Statistical Environment version 3.6.1. with an acceptance probability of 0.95, a decreasing factor of 0.95, and 300 iterations.

Selecting the optimal zones for biodiversity persistence selected more than the 5,800-ha target of natural pasture, so we subset this to the target amount using several additional criteria. Natural pastures belonging to legally protected areas were excluded, and areas with a deep effective soil depth, at which plants can spread their roots to breathe and absorb nutrients. In addition, low- altitude areas were chosen preferentially in consideration of the ease of afforestation and management. The increase in BP due to afforestation was derived by converting the habitat condition of the selected 5,800 ha natural pastures to that of forests. The natural pasture was selected on a land cover map with 100-m resolution, but BP simulation through GDM was performed at 1 km resolution. Accordingly, the habitat condition map integrating afforestation was resampled at a resolution of 1 km, using the bilinear resampling technique in ArcGIS 10.3.

2.4 Carbon stock modeling for Carbon-focused Afforestation scenario (CfA)

Carbon stocks were simulated using the species in their potential optimal habitats. The seven major tree species in Korea include *Pinus densiflora*, *Pinus rigida* , *Pinus koraiensis*, *Quercus acutissima*, *Quercus variabilis*, *Quercus mongolica*, and *Larix kaempferi*. Potential habitats were pre-selected using the optimal habitat range of bioclimatic indices assuming that maximum carbon stocks can be obtained in suitable habitats and that 35-year-old forests with the largest mean annual increment (MAI) are planted. Choi et al. (2011) presented the optimal range of warmth index (WI), minimum temperature of the coldest month index (MTCI) and precipitation effectiveness index (PEI) for Korean major tree species by comparing with the actual habitat boundaries of each tree species (Lim et al., 2018). In this study, we extracted regions that met the optimal range of these three indices under the current climatic conditions (Table 1). To determine the optimal and non-optimal regions as conservatively as possible, regions within each optimal range of WI, MTCI, and PEI were detected for each tree species. Regions satisfying all three index conditions were then classified as optimal regions by overlapping them, and the remaining regions were classified as non-optimal. The maximum carbon stocks were simulated only for the selected optimal area. For the remaining regions, except for urban and aquatic regions that could not be reforested, a minimum value of carbon stock was assigned.

Table 1. Major tree species with optimal range of Warmth Index (WI), Minimum Temperature of the Coldest Month Index (MTCI), and Precipitation Effectiveness Index (PEI)

Species Code	Scientific name	English name	Warmth Index (WI)		Minimum Temperature of the Coldest Month Index (MTCI)		Precipitation Effectiveness Index (PEI)	
			Min	Max	Min	Max	Min	Max
PD	*Pinus densiflora*	Red pine	71.9	105.2	−82.7	−37.5	77.8	112.6
PR	*Pinus rigida*	Pitch Pine	87.5	105.4	−68.2	−35	85.6	102.7
PK	*Pinus koraiensis*	Korean pine	46.5	87.1	−102.2	−62.3	88	144.6
LK	*Larix kaempferi*	Japanese larch	69	95.4	−85.8	−55.1	79.7	113.8
QA	*Quercus acutissima*	Sawtooth oak	87.2	106.5	−68.8	−35.4	82.1	100.9
QV	*Quercus variabilis*	Cork oak	74.9	101.6	−80.8	−41.7	80.3	108.5
QM	*Quercus mongolica*	Mongolian Oak	61.9	94.6	−94.6	−54.5	79.5	122.3

The International Institute for Applied Systems Analysis (IIASA)’s Global Forest Model (G4M) was used to predict carbon stocks and derive a scenario that maximized carbon storage, which was observed to be CfA. G4M estimates the impact of climate, soil properties, landscape and management activities on biomass, stem volume, and carbon stocks (Kindermann et al., 2008). As input parameters, it uses the growth curve for each species as well as the site index (SI) presenting the production capacity of the land, which is derived from the net primary productivity (NPP) for a specific region (Kraxner et al., 2014; Kim et al., 2018). The model is spatially explicit and was applied to a grid with regular pixels of approximately 1 square km in this study.

We performed parameterization of growth curves for each species based on empirical forest yield tables. This illustrated the expected volume of wood according to characteristics, such as age and SI (Palahí et al., 2003). We used Chapman-Richards growth functions (Pieneaar and Turnbull. 1973) to estimate the growing stock volume with respect to age and site index:

$$f(Age, SI) = p_0(SI) \cdot (1 - \exp(-p_1(SI) \cdot Age))^{p_2(SI)} \quad (2)$$

where f is the growing stock volume, SI is the site index, and p_0, p_1, p_2 are coefficients calibrated for each tree species. We applied G4M to estimate the potential forest NPP in the afforestable areas. The NPP block was calibrated based on the annual. MODIS NPP maps over 2006-2015 for forest areas in South Korea. A calibrated G4M model could predict the NPP values for non-forest areas based on bioclimatic variables, soil, and landscape information. In this study, the NPP model was based on random forest regression which is part of the machine learning toolbox “sci-learn” in Python (Pedregosa et al., 2011). Input variables included the four bioclimatic variables (WI, MTCI, PEI, and GDD), altitude, and effective soil depth. Afterwards the estimated NPP values were scaled to SI for each species based on their yield tables and calibrated growth curves (Equation 2). We used the mean absolute percentage error (MAPE) as a loss function in the machine learning procedure. MAPE was calculated using the following formula:

$$MAPE = \frac{1}{n} \cdot \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A_t} \right|$$

where A_t is the actual value, F_t is the predicted value, n is the dataset size. Therefore, the accuracy of the predicted NPP was assessed using the following formula:

$$Accuracy = 100\% \ \ (1 - MAPE)$$

The maximum stem volume (m3/ha) was estimated for the pre-selected habitats and converted to carbon storage (tC) by applying basic wood density, biomass expansion factor, and root-shoot ratio, which was proposed by the National Institute of Forest Science (Jung et al., 2014). Furthermore, the results were converted to annual CO2 absorption (tCO2/ha/yr). Additionally, we overlapped the results for all species and extracted the maximum carbon storage. Then, 5,800 ha of natural pastures that could achieve maximum carbon storage were selected as the afforestation area for the CfA scenario.

The uncertainty analysis included uncertainty propagation from site index assessment to computation of carbon stocks per tree species within the G4M model, that is, spatially explicit confidence intervals were constructed for each species, which were aggregated to total carbon and associated uncertainty intervals.

2.5 Simultaneously focusing on Biodiversity and Carbon Afforestation scenario (BCA) and assessing trade-offs

The SSA optimization algorithm was used to generate an integrated scenario to consider both objectives with equal weighting; this scenario was BCA. To this end, we defined the objective function as:

$$\text{Objective} = \text{Minimize}\left[\left(\frac{Best_{carbon} - Performance_{i,carbon}}{Best_{carbon} - Worst_{carbon}}\right) + \left(\frac{Best_{biodiversity} - Performance_{i,biodiversity}}{Best_{biodiversity} - Worst_{biodiversity}}\right)\right]$$

where, $Best_{carbon}$ is the maximum carbon stocks and $Worst_{carbon}$is the minimum carbon stocks that can be obtained by planting in 5,800 ha of land. The same is applicable to biodiversity; $Best_{biodiversity}$ is the maximum of the biodiversity persistence and $Worst_{biodiversity}$ is the minimum of the biodiversity persistence that can be obtained from planting in 5,800 ha of land. $Performance_i$ is the gains in carbon stocks and biodiversity persistence secured according to the 5,800 ha of afforestation scenarios. This objective function indicates the rank of each scenario (alternatives of 5,800 ha selections) relative to the maximization scenario, that is, BfA and CfA. To derive the BCA, zones that were applied to the BfA were used. Moreover, zones that maximized the sum of the performance of the two objectives were selected. Thus, 5,800 ha of natural pastures were extracted in the selected zones.

Finally, spatial locations that were derived from each afforestation scenario, that is, BfA, CfA, and BCA were compared, and changes in biodiversity persistence and carbon stock were quantitatively evaluated for each scenario. To evaluate these scenarios, we normalized and summed the performance of these scenarios.

3. Results

3.1 Biodiversity focused Afforestation scenario

The results of BP and afforestation areas (BfA) with maximum biodiversity potential, derived through the SSA optimization algorithm, are shown in Figure 3. The BP was found to be an average of 90.6884% (between 89% and 92%) with spatial distribution, which reflects the characteristics of Korea's environment (Choi et al., 2020). This indicates that under the current environment, 10% of the plant population on average are at risk of loss in the long term. From the perspective of spatial distribution, plant communities that are more likely to be vulnerable in terms of persistence are located on the southwest coast of Korea and Jeju Island. The reason behind the low BP found in the two regions was that the southwest coast region mainly consists of cities and croplands with a low habitat condition score, while Jeju Island has the lowest similarity owing to its unique geographical and climatic characteristics. On the other hand, as it is assumed that the climatic and land cover conditions will remain the same, the plant communities present in major mountain ranges nearby Taebaek and Sobaek were expected to be more stable.

Afforestation areas (BfA) with maximum biodiversity potential, derived through the SSA optimization algorithm, are shown in Figure 3 and are marked as red triangles. When these areas are afforested, habitat conditions are improved, and these points show the greatest increase in overall persistence. These points are located mainly in low-altitude regions adjacent to cities or croplands. This indicates that to enhance biodiversity persistence across the country, afforestation or restoration should be in areas with low habitat condition scores.

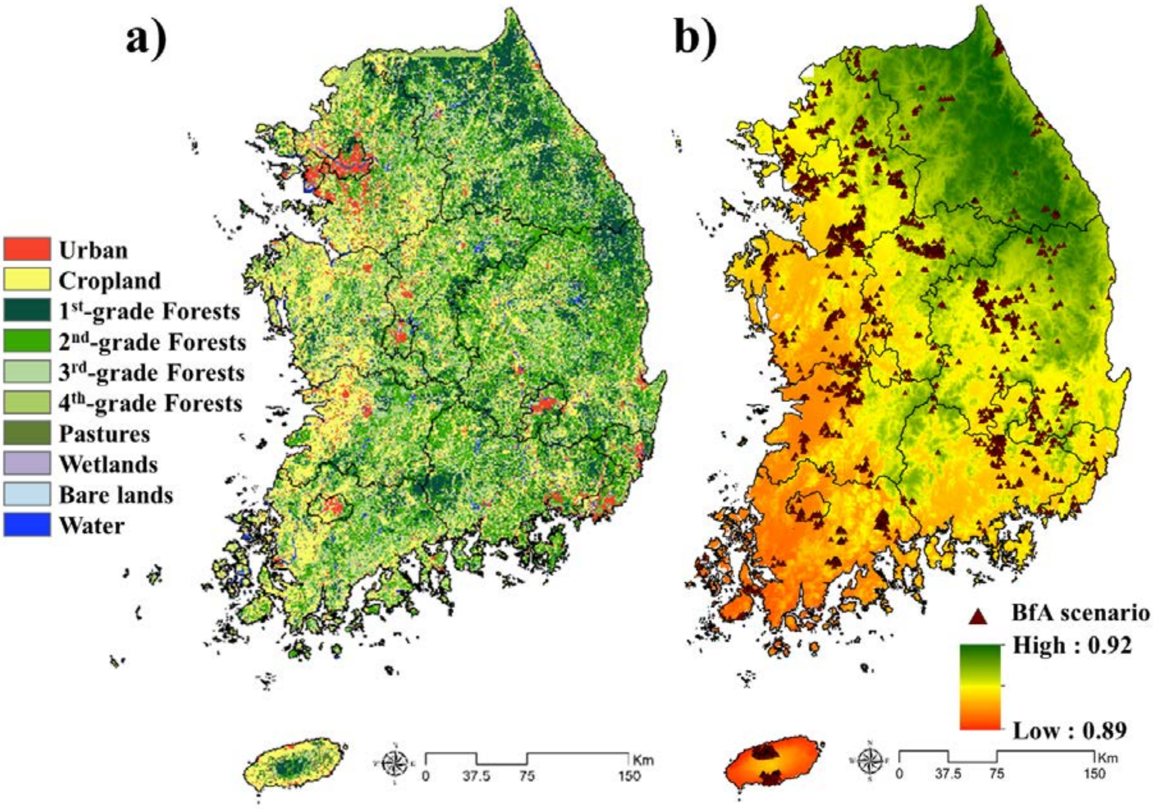

Figure 3. a) Land cover map with forest naturalness grade, which is the basis of habitat condition map b) Biodiversity persistence map with BfA scenario. Values indicate the proportion of species expected to persist over the long term and BfA scenario (red triangles) represents the location that can maximize overall BP by afforestation.

3.2 Carbon stock focused Afforestation scenario

NPP (SI) can be predicted using random forest regression estimation with an accuracy of 93.72% (Figure 4). MTCI was observed to be the most influential predictor, followed by altitude, PEI, GDD, WI, and effective soil depth. The mean absolute error was estimated at 54.95 gC/m2/yr. Using the predicted SI with high accuracy, the maximum carbon stocks were simulated for each species.

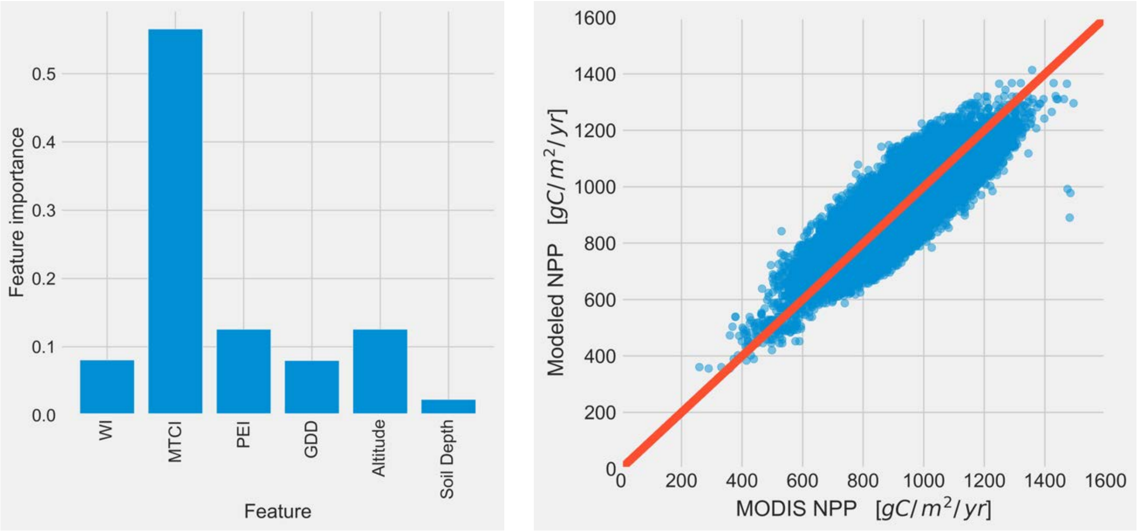

Figure 4. Results of modeling forest NPP using G4M model based on annual MODIS NPP over 2006-2015. Warmth Index (WI), Minimum Temperature of the Coldest Month Index (MTCI), Precipitation Effectiveness Index (PEI), and Growing Degree Days (GDD).

Figure 5 shows the results of extracting optimal habitats for each species according to bioclimatic limiting factors. Optimal habitats listed in descending order were *Pinus densiflora* (PD), *Quercus acutissima* (QA), *Quercus variabilis* (QV), *Pinus rigida* (PR), *Quercus mongolica* (QM), *Larix kaempferi* (LK), and *Pinus koraiensis* (PK). PD, which is found in large parts of Korea, except in the western and southern regions; it is the most widely distributed tree species in the country. Due to its resilience, it is known to grow relatively well even in dry and barren areas. QA and QV are representative oak species in Korea. An ideal habitat for QA is the mid-range mountainous area, that is , having an altitude of less than 800 m. On the other hand, QV can be found at higher altitudes ranging from 50 m to 1800 m. PR has strong drought tolerance. As it grows well in dry and barren mountains, its optimal habitat is observed to be the central region under the current bioclimatic conditions. For QM, LK, and PK, high-altitude mountainous areas were found to be optimal.

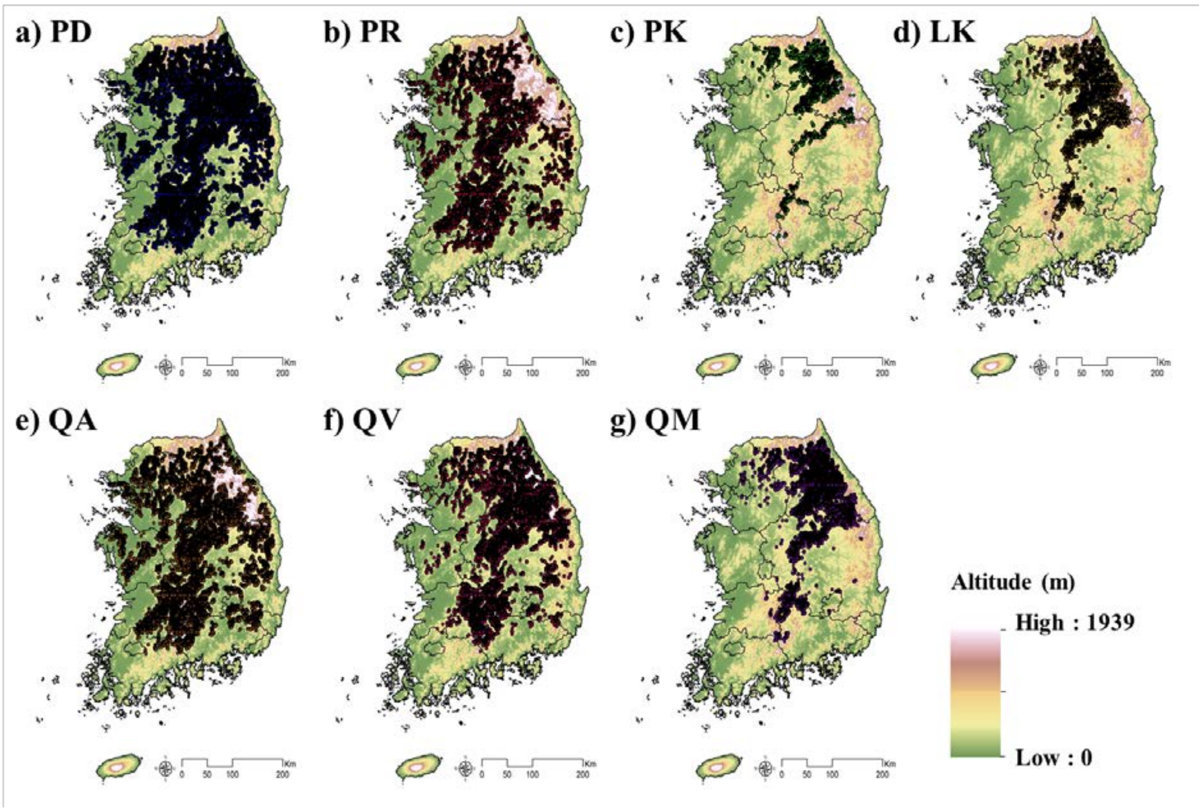

Figure 5 Optimal habitat locations of major tree species. a) *Pinus densiflora*, b) *Pinus rigida* , c) *Pinus koraiensis*, d) *Larix kaempferi*, e) *Quercus acutissima*, f) *Quercus variabilis*, and g) *Quercus mongolica*. Black dots represent locations of optimal habitats of each species on the altitude map.

Estimations and compilation of the maximum carbon storage within the optimum habitat range of each species are shown in Figure 6 and Table 2. Although PD had the largest optimal habitat area, it accounted for only 12% of the maximum carbon stocks. This is because pine trees typically have lower carbon stocks than oak trees. Thus, QV, QA, and QM accounted for 46%, 24%, and 13% of the maximum carbon stock, respectively. The ROK contains a large area of mountainous terrain, resulting in considerable differences in the climate and land cover, depending on the altitude (i.e., the distribution of each tree species is greatly affected by altitude) (Lim et al., 2018), thereby affecting carbon storage. Understanding the distribution of tree species representing the maximum carbon storage with altitude can provide important insights into forest management. According to the distribution of carbon stocks by altitude inferred in this study (Table 2), an altitude between 200 m and 400 m accounted for 28% of the carbon stock, with large amounts of stock in QV and QM, followed by an altitude ranging from 400 m to 600 m with carbon stocks of 27%. Carbon stocks showed a decreasing trend at altitudes above 600 m. In the case of QM, the highest proportion of carbon stock was found at 800–1000 m, whereas the carbon stocks in QA and PD were mostly distributed in the lowlands, that is, below 400 m. Although the total amount of carbon stock in PK was small, more than half of it was distributed at an altitude of 800 m or more. PR and LK were found to have some areas with more carbon stocks than the other species. It was observed that it is difficult to secure carbon stocks in sub-alpine regions above 1200 m.

Table 2. Percentage of maximum carbon storage distribution by species and altitude (unit: %)

Altitude (m)	PD	PR	PK	LK	QA	QV	QM	Total
1–200	2	0	0	0	9	2	0	13
201–400	5	0	0	0	10	11	1	28
401–600	3	0	1	0	4	18	2	27
601–800	1	0	1	0	1	12	4	2
801–1000	1	0	1	0	0	2	5	9
1001–1200	0	0	1	0	0	0	1	2
1201–2000	0	0	0	0	0	0	0	0
Total	12	1	4	0	24	46	13	100

Since previous studies have simulated carbon stocks for existing forests, a direct comparison of this value is difficult; however, the spatial distribution was found to be similar (Yu et al., 2013; Kraxner et al., 2014; Kim et al., 2019). The highest carbon stock was found in northeast and central South Korea, near the Taebaek Mountain Range and the Sobaek Mountain Range. The carbon stock value was about twice as high when compared with a previous study, species-wise (Yu et al., 2013). Given that natural pastures (CfA) can secure the highest carbon stock (Figure 6b), ~50% of the natural pastures were selected in the 100–400-m mountain range and 40% were chosen in the middle-mountainous area near the main mountain range of Korea. When planting in 5,800 ha of pastures to secure the maximum carbon stock, QV should be planted in the largest area (44%); however, the largest carbon stock could be obtained in the QA afforested area, which accounted for less than this area (36%). This is because many regions where the carbon stock of QA is higher than the other species are located at altitudes of 100–400 m, where most of the pastures are located. In the case of pastures that are situated above 1000 m, planting PK seems to be suitable for securing carbon stocks.

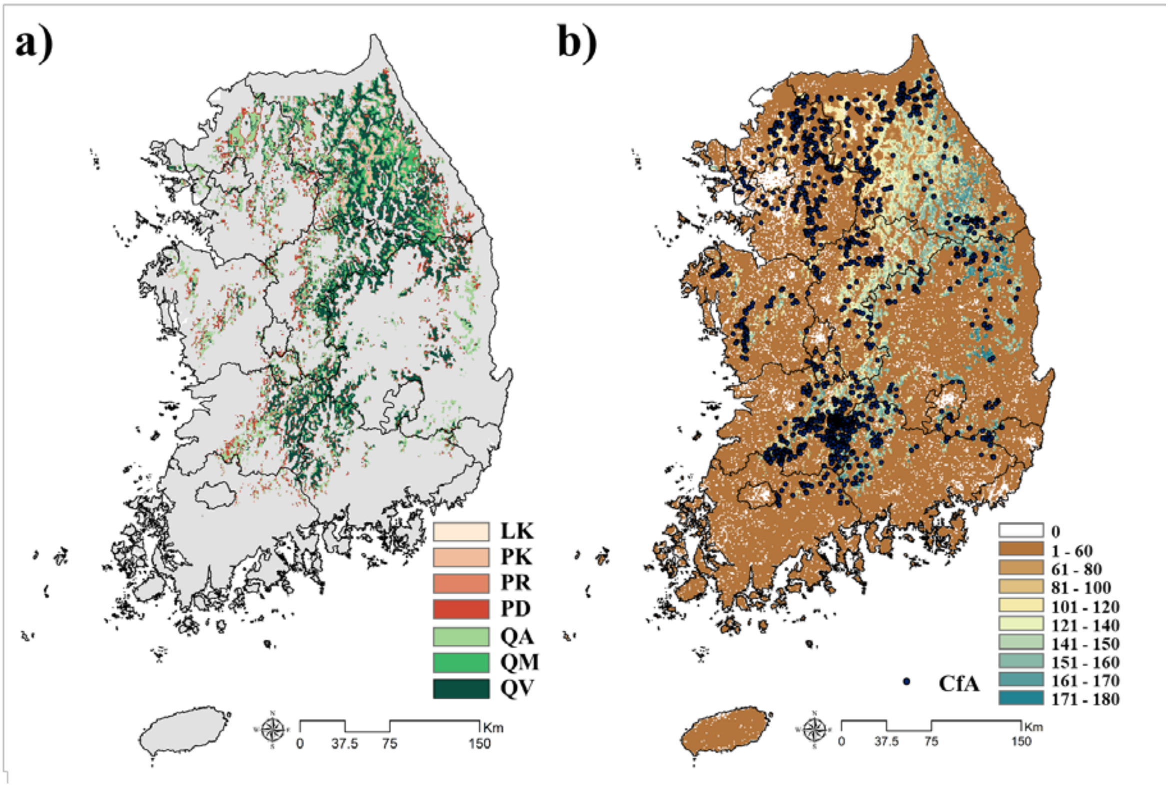

Figure 6. a) Species distribution representing maximum carbon stocks and b) maximum carbon storage (tC) with CfA scenario. CfA scenario (blue dots) represents the location that can maximize overall carbon stocks by afforestation.

3.3 Simultaneously focusing on Biodiversity and Carbon Afforestation scenario (BCA) and assessing trade-offs between biodiversity and carbon

Figure 7 illustrates the overlapping locations of natural pastures derived from each scenario. As mentioned in previous reports, the BfA scenario revealed that pastures were found in regions with a low habitat condition score around the city and cropland, while in the CfA scenario, they were located in regions near the main mountain range with higher altitude and better habitat conditions. In the BCA scenario derived through optimization, the pastures were observed to be distributed between CfA and BfA. This is because it is advantageous to secure carbon stocks as one goes up toward the mountainous area, while it is better to enhance biodiversity in regions with a low habitat condition score at lower altitudes.

Table 3 summarizes the distribution area and ratio for every 100-m altitude for each scenario. In the case of BfA, the average altitude of the afforestation location was 151 m. Approximately 48% of the pastures were located below 100 m. In the case of CfA, about 57% of the pastures were located between 200 m and 500 m, with an average altitude of 397 m. In the BCA scenario, pastures had an average altitude of about 236 m, located between BfA and CfA, of which 72% were distributed below 300 m.

There was only an 8% overlap between the two scenarios (overlapping points of BfA and CfA). These regions should be the highest priority for afforestation. With respect to biodiversity conservation, it is more effective to afforest areas with a low habitat condition score; however, it may be difficult to secure a large amount of carbon storage because the environment is not suitable for certain species to grow. These results suggest that afforestation or restoration priority should be decided based on each individual goal.

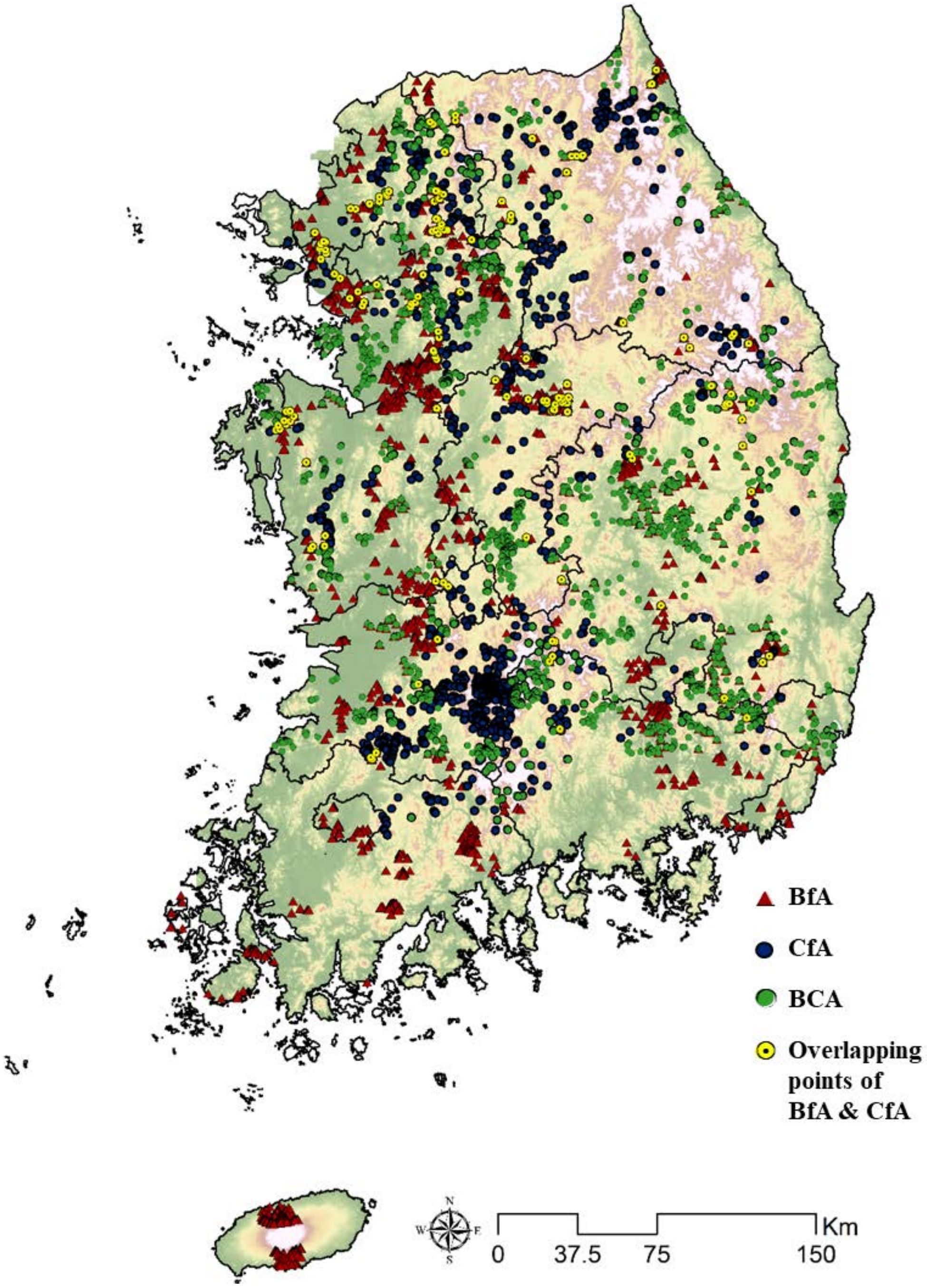

Figure 7. 5,800 ha of afforestation locations by scenarios. Red triangles, blue dots, green dots, and yellow dots indicate scenarios of BfA, CfA, and BCA, and overlapping points of BfA and CfA respectively.

Table 3. Distribution area (ha) and ratio (%) of natural pastures derived by altitude and scenarios

Altitude (m)	BfA		CfA		BCA		Overlapping points of BfA and CfA	
	Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
0–100	2781	47.9	297	5.1	1820	31.4	93	21.0
100–200	1344	23.2	729	12.6	1440	24.8	124	28.0
200–300	847	14.6	1118	19.3	929	16.0	93	21.0
300–400	375	6.5	1037	17.9	509	8.8	68	15.3
400–500	257	4.4	1123	19.4	421	7.3	43	9.7
500–600	151	2.6	563	9.7	239	4.1	12	2.7
600–700	23	0.4	373	6.4	152	2.6	3	0.7
700–800	15	0.3	268	4.6	153	2.6	2	0.5
800–900	4	0.1	148	2.6	45	0.8	3	0.7
900–1000	2	0.0	62	1.1	33	0.6	2	0.5
1000–1100	1	0.0	35	0.6	32	0.6	0	0.0
1100–1200	0	0.0	27	0.5	27	0.5	0	0.0
1200–1300	0	0.0	16	0.3	0	0.0	0	0.0
1300–1400	0	0.0	4	0.1	0	0.0	0	0.0
Sum	5800	100.0	5800	100.0	5800	100.0	443	100.0
Average altitude	**157.73**		**396.95**		**236.83**		**232.68**	

The amount of carbon stocks, total annual CO_2 absorption, average biodiversity persistence, and additional persistence compared to current persistence are shown in Table 4. In the CfA scenario, a total of 741,207 (90% confidence interval [CI] ranges from 675,091 to 818,649) tons of carbon can be additionally secured, which equates to 77,650 [70,724 to 85,763] tCO_2/yr of annual carbon dioxide absorption. This amount corresponds to 100.84% of the target value of 77,000 tCO_2/yr, intended to be secured in the form of a new plantation by 2030. On the other hand, in the BfA scenario, only 347,264 [342,645 to 352,502] tons of carbon, which is ~46.9% of CfA (47.25% of the national target), can be stored. In the case of BCA, approximately 417,703 [401,240 to 437,700] tons of carbon can be obtained, which is 56.4% of the CfA (56.8% of the national target) and 9.5% more than the BfA.

In terms of biodiversity persistence, BfA was able to maintain an additional 0.141% of the current average biodiversity persistence of 90.54%. On the other hand, CfA can maintain 0.067% more than the current biodiversity persistence, whereas BCA can maintain 0.128% more.

Table 4. Quantitative comparisons of carbon stocks and biodiversity persistence in different scenarios

		BfA	**CfA**	**BCA**
Carbon	**Max carbon stock (tC)**	347,264 (342,645-352,502)	741,207 (675,091-818,649)	417,703 (401,240-437,700)
	Annual CO_2 absorption (tCO_2/yr)	36,380 (35,896-36,929)	77,650 (70,724-85,763)	43,759 (42,035-45,854)
	% of the national targets	47.25	100.84	56.8
Biodiversity	**Average % of biodiversity persistence**	90.6884 (89.9636-91.3394)	90.615 (89.8668-91.2808)	90.6763 (89.9306-91.3325)
	Average % of additional persistence compared to current persistence	0.141	0.067	0.128

In our trade-offs assessments, it was indicated that achieving individual objectives would inevitably result in trade-offs on other objectives; in terms of carbon stocks, maintenance of high levels of biodiversity persistence (BfA) entails a loss in carbon stock of 393,943 tons compared to the maximum storage capacity (CfA). In contrast, by applying CfA, 0.073% of BP will be lost compared to the maximum BP that can be secured (BfA). In case of BCA, the trade-offs are slightly lower in both aspects, that is, losses of 323,504 tons of carbon stocks and 0.012% of BP.

This inevitable trade-off implicates the need to choose a suitable scenario. To provide a guide for scenario selection, an evaluation was performed when both aspects were considered simultaneously. To evaluate these scenarios, we normalized and added the performance in terms of biodiversity and carbon (Figure 8). The BCA and CfA scenarios exhibited the same performance at different ratios, followed by BfA. However, this is a simple comparison, given that the values of biodiversity and carbon stocks were considered equally. The scenario evaluation can be modified depending on the weighting of each aspect by the decision makers.

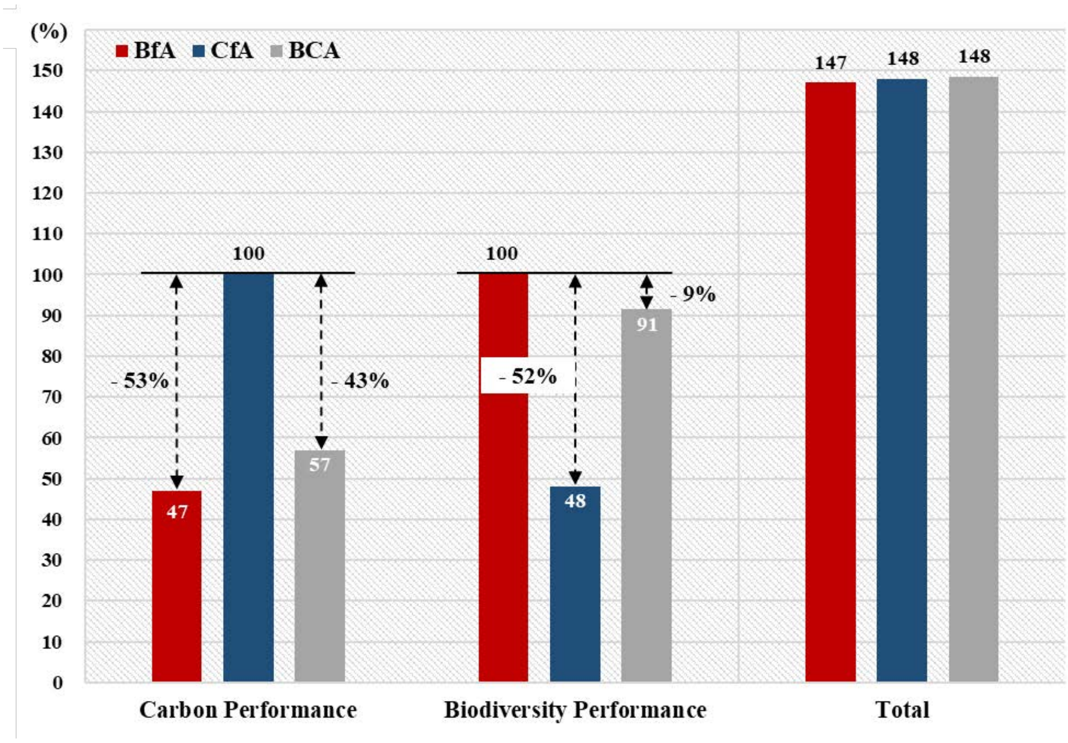

Figure 8. Assessing trade-offs based on performance evaluation. Bar graphs represent the performances of each scenario (red for BfA, blue for CfA, and grey for BCA). Total indicates the sum of carbon and biodiversity performances.

4. Discussions

4.1 Assessments of national plans

Plans for carbon enhancement

The national plans for carbon enhancement aim to absorb 77,000 tons of CO_2 through the expansion of new carbon sinks. The findings of this study conclude that this target can be achieved only in the CfA scenario, in which the carbon target was set as the top priority. The BfA and BCA scenarios were found to be 47% and 57% lower than the target, respectively. This study assumed an ideal situation in the CfA scenario. Tree species that can represent the maximum regional carbon storage in the age of 35 years showing the largest mean annual increment, were planted. The maximum carbon stocks that can be secured through planting are likely to be less than the maximum value, as this assumption is ideal. Accordingly, it is necessary to set an afforestation target for a wider area to achieve the target sufficiently.

In addition, considering that most of the regions with high carbon storage are southern parts of major mountain ranges suitable for oak tree growth, efforts to explore afforestable areas in these regions are necessary to maximize carbon storage. Damaged areas are considered suitable for afforestation within mountainous areas; therefore, efforts to detect damaged areas in advance and present them as potential candidates for afforestation are required nationally. By pre-simulating the amount of carbon storage that can be secured through afforestation in the detected damaged areas, it will be possible to secure more carbon by preferentially inducing restoration where carbon storage can be maximized.

Plans for biodiversity enhancement

Although the ROK’s national plan includes a variety of action indicators (e.g. the expansion area of protected areas), biodiversity state indicators (e.g. the number of species to be maintained) promoted by the implementation of the plan are not presented; therefore, this limits the direct evaluation of the target achievement through afforestation scenarios. However, the finding that only 89% to 92% of plant species are expected to persist means that approximately 10% of species (or populations) are endangered. Enhancing this up to 0.14% through afforestation of 5,800 ha may not be sufficient to preserve the integrity of biodiversity. Therefore, the government should adopt more ambitious goals and make additional investments in effective conservation projects to halt biodiversity loss. In addition, developing quantitative indicators to represent the state of biodiversity and evaluate national biodiversity conservation plans is necessary. Accordingly, a variety of biodiversity indicators measuring state and progress have been developed to evaluate global biodiversity loss; such as the Red List Index (Butchart et al., 2007), Living Planet Index (Collen et al., 2008), and Biodiversity Intactness Index (Newbold et al., 2016). These indicators need to be incorporated into national plans; we can then measure the status of biodiversity with a consistent indicator, evaluate the effectiveness of national plans, and guide management. In addition, the BP presented in this study could be used as an indicator.

In the discussion of integrating climate action and biodiversity conservation policy in South Korea, a specific strategy has not been proposed yet, and each plan established by the government pays little attention to potential impact on the other. If both goals are difficult to achieve, even though afforestation strategies have been established to maximize the performance of each goal, additional strategic measures are required. However, policy documents to date have not mentioned these measures or provided methods to quantitatively evaluate actions taken, including afforestation, and way to consider both targets simultaneously.

A portion of our study area had lands that could be simultaneously managed for both biodiversity and carbon assessment. Results from the comparisons between scenarios, however, suggest that trade-offs are inevitable if the two strategies are implemented separately, and that choices are needed depending on the value pursued by policymakers and planners. Therefore, this study emphasizes that solutions which provide compromises between the two objectives should be explored. Our national-scale assessment can help guide future planning of afforestation by considering the simultaneous goal of maximizing biodiversity and carbon stocks.

4.2 Technical significance and limitations

Even though our analysis is carried out at the broad-scale, if finer-scale specific proposals emerge for tracking the change of biodiversity and carbon stock according to the forest management, then future studies can employ the methodology demonstrated in this study. For further extension of our study, the technical significance and limitations of each step are presented, as follows:

Constructing afforestation scenarios

This study presented the potential trade-offs between plant biodiversity persistence and carbon stocks secured through afforestation and derived a scenario to mitigate trade-offs using multi-spatial modeling. To the best of our knowledge, this was the first attempt at applying multi-spatial modeling including GDM, G4M, and SSA optimization algorithm to identify optimal afforestation areas.

However, this study considered only natural pastures as afforestable areas, even though the plan included plantations in abandoned lands, urban forests, and damaged area as these areas were difficult to detect spatially. The actual afforestable area must be preferentially detected before applying the methodology to produce more realistic results. If spatial data for these areas are constructed, the same method can be applied to select the optimal afforestation location within them. In addition, this study spatially constructed only forest area expansion as a scenario. Thus, further studies are needed to evaluate the effects of diverse forest management scenarios, such as an expansion of conservation areas, forest thinning, or tree species selection that could cause qualitative changes in forests.

Biodiversity persistence modeling

To cope with biodiversity loss, the most common approach to predicting consequences has been to simulate expected changes in individual species (Guisan and Thuiller, 2005; Elith and Leathwick, 2009; Guisan et al. 2017). These predictions can be useful to make a plan for conserving specific species of interest but they are less relevant to establish conservation strategies for biodiversity as a whole (Mokany and Ferrier, 2011). As an alternative strategy to individual species modeling, the focus is shifting to community-level modelling of the attributes of biodiversity (Ferrier and Guisan, 2006; Mokany and Ferrier, 2011). Accordingly, this study employed BP, which is simulated based on composition turnover modeling with detailed national survey datasets of the ROK. As a result, we explored areas where plant communities suffer from the highest decline in persistence, based on similarities in bioclimatic conditions between sites and current land cover. We also presented a methodology for exploring optimal afforestation areas to maximize biodiversity persistence by applying optimization algorithms.

However, given that plants are fundamental components of most ecosystems (Giam et al., 2010), and with consideration of their relationship with carbon stocks, our estimates considered only plant species. Therefore, future research that considers biodiversity as a whole is needed by adopting other taxa to explore the most efficient conservation and restoration areas. In addition, the application of HCI in this study to other regions requires thorough examination, because the HCI has only been shown to be suitable for the ROK thus far (Choi et al., 2021).

Moreover, these estimates rely heavily on model-based predictions and inferences (Ferrier et al., 2007; Hoskins et al., 2020; Di Marco et al., 2019a), which have inherent uncertainties. Using the classification units to simulate optimization with the average value of habitat conditions was one of the factors that can cause uncertainty. We considered that this strategy is valid in GDM, which simulates the distribution of species composition. Since the modeling considers the species distributed within a certain area as a community, clustering areas with similar environmental conditions and using the average habitat conditions in those areas were reasonable. In addition, using regional blocks has the advantage of allowing the selection of natural pastures and other afforestable areas within the selected zone. However, this spatial aggregation is likely to cause uncertainties; the result obtained using fine-resolution habitat conditions may differ from those obtained using an aggregate or summary of the fine-resolution data. Despite this limitation, the strategy discussed above was applied because this study focused on the comparison of BP predicted under different afforestation scenarios, rather than the absolute valuation of individual scenarios. The degree of uncertainty is likely to operate equally across all scenarios because our methodology was applied consistently. This facilitated a direct comparison of estimates obtained under different scenarios.

Carbon stocks modeling

In order to simulate the maximum carbon stocks that can be secured by newly planted species, the optimal habitat for each species was extracted and the maximum carbon stocks were predicted, regardless of the current forest distribution. To this end, the random forest regression was applied based on national environmental datasets, including climate, altitude, and soil depth to estimate forest NPP across the country including non-forest areas. Coupled with the growth curves calibration in the framework of the G4M model this method allowed us to assess spatially explicit SI per species in afforestable areas. Application of machine learning technique is a new development of the G4M model that allows for more flexibility in terms of input parameters, which may vary in different regions of the world. In this study, the method was successfully applied to bioclimatic variables calculated for ROK, as well as national soil and landscape information.

However, accuracy may be reduced due to the spatial resolution (1-km^2) compared to the amount of afforested target. Simulating at a higher resolution than 1 km^2 on a national scale is very difficult by considering the available climate and environmental data. Basically, since climate data has a resolution lower than 1 km^2, other studies also were performed at 1-km^2 (Sung et al., 2016) or lower resolution at 0.25 degree (Kraxner et al., 2014) to estimate NPP or biomass with this model. Despite this limitation, we tried to analyze the trade-offs by evaluating the effects of afforestation between scenarios since this study aimed at relative comparisons among scenarios rather than precise estimates of carbon storage. In addition, it was simulated for all the optimal regions, assuming 35-year-old forests consisting of species with the largest mean annual increment (MAI). Therefore, this scenario can be considered optimistic. Moreover, a minimum value is assigned to the remaining regions where the tree species that are selected in this study cannot survive. To derive more realistic results, detailed studies would apply particular species and the forest age for actual afforestation to afforestable areas.

Optimization and trade-offs assessment

The SSA optimization algorithm was applied to generate an afforestation scenario that reduces trade-offs between the two objectives. The optimization results yielded a good scenario, i.e., BCA, for mitigating trade-offs between the two scenarios. However, a realistic plan requires more detailed modeling. Although, only two goals were considered in this study, the optimal afforestation location can be explored by including more goals, such as minimizing costs and maximizing other ecosystem services (i.e., reducing landslides and purifying air quality). The weights can also be adjusted, depending on the decision maker’s opinion. This study assigned equal weighting to both objectives. Thus, the derived scenarios may be evaluated differently depending on the value assigned to each purpose.

5. Conclusions

This study offers several insights into forest management and provides useful information for policy support and design. Herein we investigated the potential trade-offs between plant biodiversity persistence and carbon stocks secured through afforestation, which is one of the important strategies for biodiversity conservation and climate change mitigation. This study constructed optimal afforestation scenarios (i.e., BfA and CfA) in order to maximize each objective and quantitatively compare them. These two scenarios were found to have few overlapping areas; furthermore, both scenarios resulted in approximately 50% trade-off at the other objective. These findings reveal that there is no one-size-fits-all solution and different management strategies may be needed to enhance carbon stocks and biodiversity persistence. Moreover, herein we proposed another afforestation scenario, i.e. BCA, that can mitigate trade-offs to a certain extent. Thus, in order to strike a balance among the separate goals, a compromised forest management solution should minimize trade-offs. This research can be referred to by policy-makers and planners in establishing the next phase of forest planning, and the approach presented here can also be adapted to any spatial units with consideration of other multi-objectives.

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