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Article

Future Projection of CO₂ Absorption and N₂O Emissions of the South Korean Forests under Climate Change Scenarios: Toward Net-Zero CO₂ Emissions by 2050 and Beyond

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Abstract: Forests mitigate climate change by absorbing CO₂. However, N₂O emissions in forests, which has 298 times larger global warming potential than CO₂, can diminish the climate mitigation role of forests. Thus, it is crucial to project not only CO₂ absorption but also N₂O emissions in forests to provide a scientific basis for the 1.5 °C Paris Agreement goal. This study used a biogeochemical model, called FBD-CAN, to project CO₂ absorption and N₂O emissions of South Korean forests from 2021 to 2080 under three climate scenarios, including the current climate, Representative Concentration Pathway (RCP) 4.5, and RCP 8.5. From 2021 to 2080, CO₂ absorption decreased from 5.0 to 1.4 Mg CO₂ ha⁻¹ year⁻¹ under the current climate with the aging of forests, while N₂O emissions increased from 0.25 to 0.33 Mg CO₂ eq. ha⁻¹ year⁻¹. Climate change accelerated the decreasing trend in CO₂ absorption and the increasing trend in N₂O emissions. The subalpine region had a faster decreasing trend in CO₂ absorption than the central and southern regions due to its older stand age. These findings provide scientific references for future greenhouse gas reduction plans and broaden our knowledge of the impacts of climate change on the climate mitigation role of forests.

Keywords: climate change; modeling; carbon dioxide; nitrous oxide; greenhouse gas; net-zero emissions



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1. Introduction

In the Paris Agreement, the United Nations Framework Convention on Climate Change (UNFCCC) agreed to limit the increase in global air temperature to below 1.5 °C compared to pre-industrial levels [1]. The Intergovernmental Panel on Climate Change (IPCC) stated that to achieve this 1.5 °C goal, global greenhouse gas (GHG) emissions from human activities need to be reduced to zero by 2050 [2]. Accordingly, all countries are required to report future GHG reduction plans as a long-term vision to achieve the net-zero CO₂ emissions goal [1].

Future GHG reduction plans should consider the role of forests in climate change mitigation. Forests exchange CO₂ with the atmosphere through photosynthetic CO₂ uptake and respiratory CO₂ emissions [3]. From 2001 to 2019, the CO₂ absorption by global forests was 15.6 billion Mg CO₂ year⁻¹ [4], which accounts for 43% of the global fossil CO₂ emissions of 36 billion Mg CO₂ year⁻¹ in 2019 [5]. On the other hand, forest soils emit N₂O, which has 298 times larger global warming potential than CO₂ over a 100-year time horizon [6]. Although N₂O emissions in forests are known to be less than 1 kg N ha⁻¹ year⁻¹ (that is, less than 0.5 Mg CO₂ eq. ha⁻¹ year⁻¹) [3,7,8], global forests account for 38% of the total N₂O emissions from the natural ecosystems with estimates of 1.3 Tg N year⁻¹ because of their vast area [9]. Thus, it is crucial to assess not only CO₂ absorption but also N₂O emissions to provide a scientific basis for future GHG reduction plans.

Modeling has been used to assess CO₂ absorption and N₂O emissions in forests because the IPCC encourages modeling when reporting national GHG inventories [3]. Kurz et al. [10] developed and updated a forest carbon model, called the CBM-CFS, to estimate the carbon stocks and stock changes in Canadian forests. In addition, Inatomi et al. [11] developed a terrestrial ecosystem model, called the VISIT, to estimate the GHG budget (i.e., CO₂, CH₄, and N₂O) in a cool-temperate forest in Japan from 1948 to 2008.

Moreover, modeling has been used to assess the impacts of climate change on forests based on the various climate change scenarios, such as the Representative Concentration Pathway (RCP). RCP is the GHG concentration scenario adopted by the IPCC for the fifth Assessment Report [12]. The RCPs (i.e., RCP 2.6, 4.5, 6.0, and 8.5) are named according to the radiative forcing due to anthropogenic GHG emissions in 2100 (2.6, 4.5, 6.0, and 8.5 W m⁻², respectively) [13]. RCP 4.5 is the most probable scenario with intermediate mitigation efforts [2], whereas RCP 8.5 represents a failure to restrain climate change with no mitigation efforts [14]. In the late 21st century, the global CO₂ concentration would increase to 540 and 940 ppm under the RCP 4.5 and 8.5, respectively, and the global air temperature would rise to 2.8 and 4.8 °C compared to pre-industrial levels under the RCP 4.5 and 8.5, respectively [15]. A forest carbon model, called the KFSC, estimated that the CO₂ absorption of South Korean forests would decrease under RCP 8.5 because the increase in air temperature would accelerate the respiratory CO₂ emissions [16]. In addition, a modeling study reported that CO₂ absorption in western Mediterranean forests would decrease with an increase in air temperature if there is no simultaneous increase in CO₂ concentration under RCP 8.5 [17].

South Korea, the ninth-largest CO₂ emissions country in the world [18], is also expecting forests to contribute to the net-zero CO₂ emissions goal [19]. However, CO₂ absorption by South Korean forests kept decreasing from 58.8 million Mg CO₂ year⁻¹ in 2010 to 43.2 million Mg CO₂ year⁻¹ in 2019 [18]. Moreover, modeling by the National Institute of Forest Science (NIFoS) anticipated that it would further decrease to 14 million Mg CO₂ year⁻¹ by 2050 because of forest aging. This is because the older forests may lose their CO₂ absorption capacity owing to an increase in respiratory CO₂ emissions [20,21]. Additionally, the NIFoS suggested sustainable forest management (e.g., thinning, harvesting, reforestation, and tending) to limit this decreasing trend [19] because thinning and harvesting can decrease the risk of tree mortality in the long term [22].

However, future estimates of NIFoS have several limitations. First, the impacts of climate change especially increase in CO₂ concentration and air temperature, on forests were not considered. When the CO₂ concentration increases, CO₂ absorption also increases because of increased photosynthesis, an effect known as CO₂ fertilization [21,23,24]. Meanwhile, the rise in air temperature increases respiratory CO₂ and N₂O emissions [25]. Accordingly, recent studies have focused on whether the photosynthetic benefit from CO₂ fertilization can compensate for increased respiratory CO₂ and N₂O emissions with climate change [26–28], as this determines the reliability of the estimation [29,30]. Second, although the IPCC considers litter, dead wood, and mineral soil as major carbon pools [3], only estimates of tree biomass were considered in the NIFoS estimation. Indeed, the total carbon stock of litter, dead wood, and mineral soil is approximately 350 million Mg C, which was approximately 70% of the carbon stock of tree biomass in South Korean forests [31]. Third, the spatial variances in the CO₂ absorption of forests were not considered [32,33]. Because CO₂ absorption depends on spatially varying factors, including forest type, stand age, precipitation, and air temperature, neglecting these factors will cause large uncertainty in the estimates [33,34]. In addition, to propose locations where forest management is required, it is necessary to spatially identify where CO₂ absorption is low. Finally, N₂O emissions from South Korean forests have not been quantified.

This study aims to project CO₂ absorption and N₂O emissions of South Korean forests from 2021 to 2080 to provide scientific evidence for future GHG reduction plans. A biogeochemical model simulating carbon and nitrogen dynamics in forests called the Forest Biomass and Dead organic matter Carbon and Nitrogen (FBD-CAN), was used for future

projections. To consider the impacts of increased CO₂ concentration and air temperature on forests, we conducted three independent projections under three climate change scenarios: the current climate, RCP 4.5, and RCP 8.5 [13]. The current climate assumed no further changes in CO₂ concentration and air temperature, whereas RCP 4.5 and RCP 8.5 used increasing CO₂ concentration and air temperature values from the Climate Change Forecast Report by the Korea Meteorological Administration (KMA) [15]. Although CH₄ is a major GHG, the present study excludes it. This is because CH₄ emissions are usually negligible, and it has been reported that CH₄ is absorbed rather than emitted in temperate forests, including South Korean forests [35–39]. Similarly, although the change in precipitation can affect CO₂ absorption and N₂O emissions, this study did not consider it. This is because the difference in changes over time in precipitation between the three climate change scenarios was marginal according to the climate change Forecast Report by the KMA (Figure A1) [15] and the estimates of the multiple-regional climate models [40].

2. Materials and Methods

2.1. Study Forest

The studied forest included the entire South Korean forests of 5,993,900 ha, excluding the bamboo forest, unstocked forest land, and forests of Jeju Island (Figure 1). South Korea is located in Northeast Asia. It has a temperate monsoon climate, with 70% of the annual precipitation falling in the summer (from June to August). The mean annual air temperature and annual precipitation from 1991 to 2020 were 11.9 °C and 1273 mm, respectively [15]. South Korea can be divided into three regions based on elevation and latitudinal ranges: subalpine, central, and southern regions. In this study, the subalpine region was defined as an area with an elevation greater than 1000 m. The central and southern regions were defined as areas where the latitudinal ranges were from 36° N to 39° N and 33° N to 36° N, respectively [41]. The mean elevation of central and southern regions was 365 and 277 m, respectively, and areas with elevations higher than 1000 m were excluded from the central and southern regions.

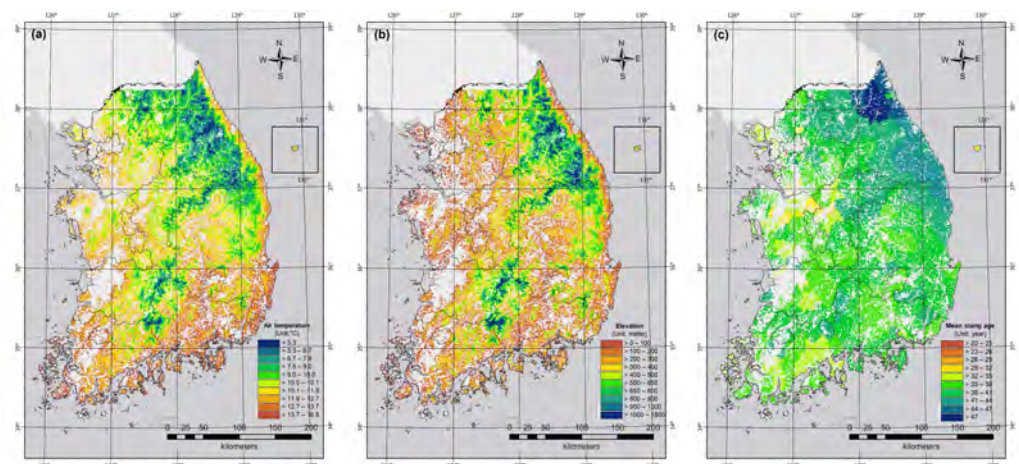


Figure 1. South Korean forest maps of (a) mean annual air temperature during 1991–2020, (b) elevation, and (c) mean stand age during the seventh national forest inventory survey period (2016–2020).

South Korean forests are notable for their young stand age. Although some forests in Kangwon and Kyungbuk province are over 100 years old, the mean stand age in 2020 ranged from 30 to 40 years (Figure 1c) [42]. This is because most South Korean forests were simultaneously rehabilitated under the national rehabilitation plan in the mid-1970s after extensive deforestation owing to the Japanese occupation of Korea and the Korean War [43]. However, the subalpine region has a higher stand age than the central and southern regions [43]. This is because the subalpine region has experienced lower pressure from deforestation due to its high elevation (Figure 1c)[44]. Moreover, the National Forest

Inventory of South Korea reported that the subalpine region has larger carbon stocks in tree biomass, litter, dead wood, and mineral soil than the central and southern regions [45,46]. In addition, the subalpine region had a lower air temperature than the central and southern regions (Figure 1a).

2.2. Model Description

The FBD-CAN estimates carbon and nitrogen balances of tree biomass, litter, dead wood, and mineral soil pools in forests by simulating fluxes of carbon and nitrogen: (a) entering the forest through photosynthetic CO₂ uptake, nitrogen deposition, and biological nitrogen fixation; (b) circulating within the forest, such as litterfall, nitrogen mineralization, and nitrogen retranslocation; and (c) exiting the forest through respiratory CO₂ emissions (i.e., both autotrophic and heterotrophic respiration), nitrogen leaching, and denitrification (i.e., N₂O emissions) [47–49].

In FBD-CAN, the photosynthetic CO₂ uptake increases with an increase in the CO₂ concentration and the carbon stock of foliage. Respiratory CO₂ emissions increase with an increase in air temperature, and autotrophic respiration also increases with the carbon stock of tree biomass, including foliage, wood, and fine roots. N₂O emissions increase with an increase in the inorganic nitrogen stock of mineral soil and water availability; the latter was calculated as the difference between precipitation and potential evapotranspiration. Although air temperature affects photosynthetic CO₂ uptake [50], the photosynthetic CO₂ uptake does not change with the changes in air temperature in the FBD-CAN. This is because the impact of air temperature on photosynthesis was incorporated into the impact of air temperature on foliage respiration in autotrophic respiration to simplify non-linear responses of net photosynthesis to air temperature in the FBD-CAN [49].

The FBD-CAN requires (a) climate data, such as air temperature, precipitation, CO₂ concentration, nitrogen deposition, and solar radiation, (b) soil data, such as soil depth and initial carbon and nitrogen stocks of litter and mineral soil, and (c) vegetation data, such as forest type, initial stand age, and initial carbon and nitrogen stocks of dead wood and tree biomass. The FBD-CAN requires neither soil temperature as input data nor a soil energy budget model, which calculates soil temperature from air temperature to calculate heterotrophic respiration from litter, dead wood, and mineral soil pools. This is because the parameters for the heterotrophic respiration function in the FBD-CAN were estimated from air temperature directly rather than from the recalculated soil temperature; in other words, the heterotrophic respiration function is adjusted to be used with air temperature [49].

The reliability and applicability of FBD-CAN to South Korean forests were validated by a pilot study in a *Pinus densiflora* Siebold & Zucc. forest in central Korea [47], a data-model fusion study estimating the carbon and nitrogen turnover times in South Korean forests [49], and a study that quantified the impacts of human activities on the carbon and nitrogen dynamics of South Korean forests from 1973 to 2020 [48].

2.3. Input Data

Forest type and soil depth were extracted from the Forest Type Map provided by the Korea Forest Service [51,52]. Since forest type and soil depth were provided as polygon features, they were converted into raster with a resolution of 100 ha. The initial stand age and carbon and nitrogen stocks were obtained from the modeling results for 2020 by the FBD-CAN [48]. This previous study simulated the carbon and nitrogen stocks from 1973 to 2020 at a resolution of 100 ha by retrieving the stand age of the Forest Type Map provided by the Korea Forest Service [51,52]. Annual precipitation was downloaded from the KMA as raster whose resolution is 100 ha [15]. Annual nitrogen deposition was extracted from the database for the Coupled Model Intercomparison Project Phase 6 with a resolution of 0.1° × 0.1°, and it was resampled to have a resolution of 100 ha [53,54]. Solar radiation was generated as raster with a resolution of 100 ha by the area solar radiation tool in ArcGIS Pro 2.6 using the latitude and digital elevation map [55].

Three climate change scenarios, including the current climate, RCP 4.5, and RCP 8.5, were used to assess the impacts of climate change on CO₂ absorption and N₂O emissions. The current climate used the mean annual values of the CO₂ concentration and air temperature during 1991–2020, which were downloaded from the KMA (Figure A2) [15]. The RCP 4.5 and RCP 8.5 used the mean annual values of CO₂ concentration and air temperature from the Climate Change Forecast Report provided by the KMA. Compared to the current climate, the increase in CO₂ concentration during 2021–2080 was 120 and 520 ppm for the RCP 4.5 and RCP 8.5, respectively, and the increase in air temperature during 2021–2080 was 2 and 4 °C for the RCP 4.5 and RCP 8.5, respectively (Figure A2). The spatial difference in air temperature with elevation and latitude was considered with a resolution of 100 ha, while the spatial difference in CO₂ concentration was not taken into account due to limited data availability.

2.4. Model Simulation and Statistical Analysis

The spatial simulation scale covered South Korean forests of 5,993,900 ha subdivided into 59,939 spatial units of 100 ha each. The temporal simulation scale spanned from 2021 to 2080 with 60 temporal units of one year each. Input data, except for air temperature and CO₂ concentration, was identically allocated to three sets of 59,939 × 60 spatiotemporal units, where each set represented the current climate, RCP 4.5, and RCP 8.5, respectively. With these spatiotemporal units, FBD-CAN simulated photosynthetic CO₂ uptake, respiratory CO₂ emissions (i.e., both autotrophic and heterotrophic respiration), CO₂ absorption (i.e., the difference between photosynthetic CO₂ uptake and respiratory CO₂ emissions), N₂O emissions, and the GHG budget (in this study, the term denotes the sum of CO₂ absorption and N₂O emissions) from 2021 to 2080 [56]. We projected the spatial patterns of the GHG budget across South Korean forests for 2021, 2050, and 2080 using the mapping tool in ArcGIS Pro 2.6 [55]. In addition, the relationships of the GHG budget with stand age and mean annual air temperature were analyzed using linear regression.

3. Results

3.1. Temporal Patterns of Greenhouse Gas Budget

From 2021 to 2080, the RCP 8.5 had a larger photosynthetic CO₂ uptake, respiratory CO₂ emissions, and N₂O emissions than RCP 4.5 and current climate (Figure 2a,b,d). However, CO₂ absorption and the GHG budget were larger in the current climate than the RCP 4.5 and 8.5 (Figure 2c,e). The first year when the GHG budget fell below zero was in 2049 under the RCP 8.5 and in 2053 under RCP 4.5, but the GHG budget did not fall below zero under the current climate from 2021 to 2080 (Figure 2e).

Both the photosynthetic CO₂ uptake and respiratory CO₂ emissions increased over time (Figure 2a,b). From 2021 to 2050, the annual increments of photosynthetic CO₂ uptake were 0.58, 0.69, and 0.89 Mg CO₂ ha⁻¹ year⁻¹ under the current climate, RCP 4.5, and RCP 8.5, respectively, but these decreased to 0.15, 0.20, and 0.29 Mg CO₂ ha⁻¹ year⁻¹ from 2050 to 2080 (Figure 2a). Similarly, respiratory CO₂ emissions increased at annual rates of 0.65, 0.77, and 1.01 Mg CO₂ ha⁻¹ year⁻¹ from 2021 to 2050 under the current climate, RCP 4.5, and RCP 8.5, respectively, but these rates were decelerated to 0.20, 0.35, and 0.38 Mg CO₂ ha⁻¹ year⁻¹ from 2050 to 2080 (Figure 2b).

Because the increasing trends of respiratory CO₂ emissions were larger than those of photosynthetic CO₂ uptake, CO₂ absorption decreased at the rates of −0.06, −0.10, and −0.11 Mg CO₂ ha⁻¹ year⁻¹ from 2021 to 2080 under the current climate, RCP 4.5, and RCP 8.5, respectively (Figure 2c). Meanwhile, N₂O emissions increased at rates of 2.0, 2.7, and 4.2 kg CO₂ eq. ha⁻¹ year⁻¹ from 2021 to 2080 under the current climate, RCP 4.5, and RCP 8.5, respectively (Figure 2d). The GHG budget decreased at rates of −0.06, −0.10, and −0.11 Mg CO₂ eq. ha⁻¹ year⁻¹ from 2021 to 2080 under the current climate, RCP 4.5, and RCP 8.5, respectively (Figure 2e). Overall, the total amounts of the GHG budget in South Korean forests of 5,993,900 ha in 2021, 2050, and 2080 were 28.6, 17.0, and 6.2 million Mg CO₂ year⁻¹ under the current climate, 28.2, 11.6, and −3.9 million Mg

$\text{CO}_2 \text{ year}^{-1}$ under RCP 4.5, and 28.0, 5.2, and $-11.4 \text{ million Mg CO}_2 \text{ year}^{-1}$ under RCP 8.5, respectively.

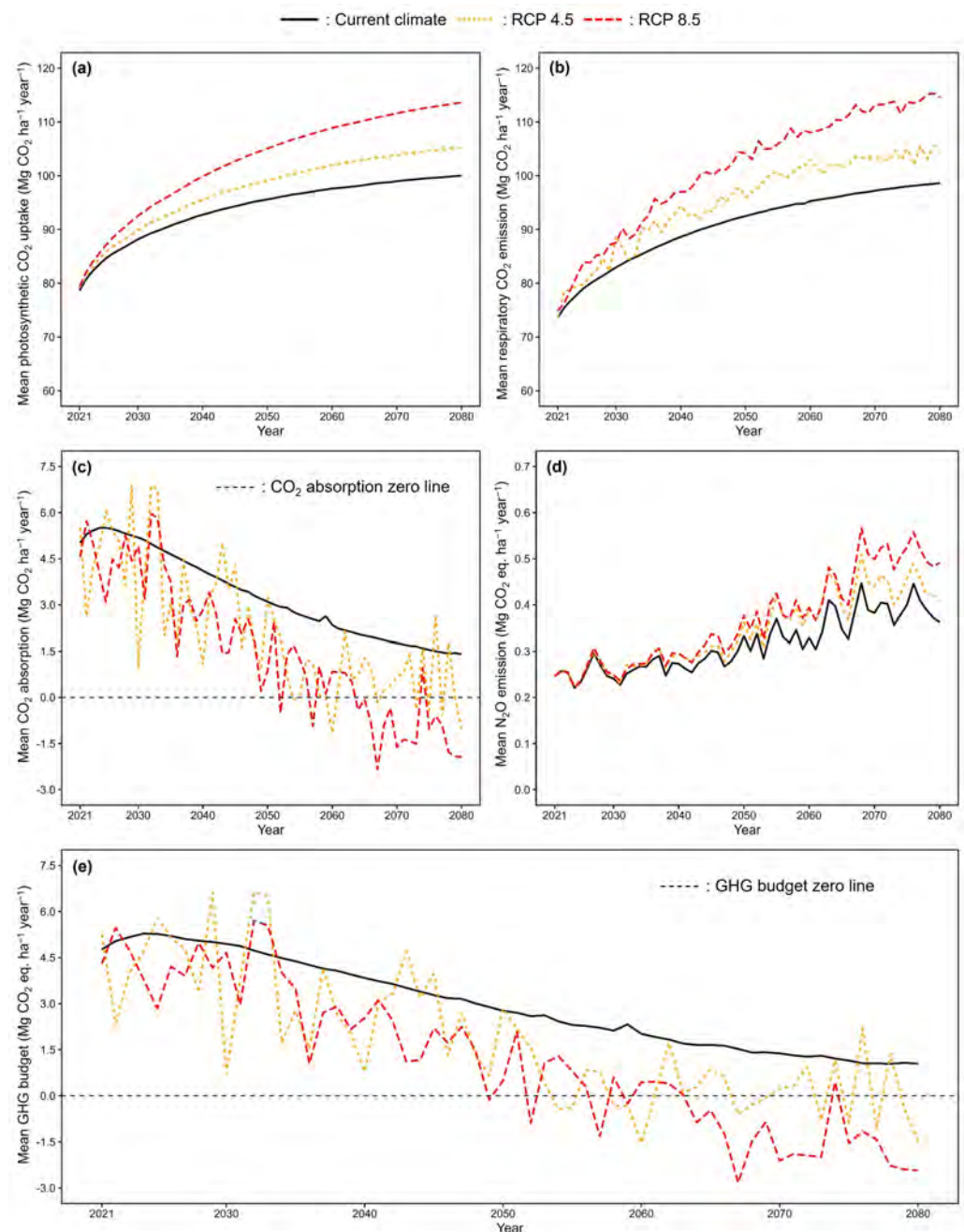


Figure 2. The mean (a) photosynthetic CO_2 uptake, (b) respiratory CO_2 emissions including both autotrophic and heterotrophic respiration, (c) CO_2 absorption, (d) N_2O emissions, and (e) greenhouse gas (GHG) budget (the sum of CO_2 absorption and N_2O emissions) from 2021 to 2080 under the current climate (black solid lines), RCP 4.5 (orange dotted lines), and RCP 8.5 (red dashed lines).

3.2. Spatial Patterns of Greenhouse Gas Budget

The spatial patterns of the GHG budget matched the patterns of air temperature, showing a higher GHG budget in the subalpine region with lower air temperature (Figures 1a, 3a and 4b; Table 1). The subalpine region had a larger GHG budget than the central and southern regions in 2021, 2050, and 2080 under the current climate (Figure 3a,d,g; Table 1). Moreover, the subalpine region had a smaller annual decrease in the GHG budget ($-0.05 \text{ Mg CO}_2 \text{ eq. ha}^{-1} \text{ year}^{-1}$) than in the central region ($-0.10 \text{ Mg CO}_2 \text{ eq. ha}^{-1} \text{ year}^{-1}$)

and southern region ($-0.06 \text{ Mg CO}_2 \text{ eq. ha}^{-1} \text{ year}^{-1}$) from 2021 to 2050 under the current climate. However, this trend changed under the climate change scenarios. The annual decreases in the GHG budget of the subalpine region from 2021 to 2050 under RCP 4.5 and RCP 8.5 were -0.22 and $-0.27 \text{ Mg CO}_2 \text{ eq. ha}^{-1} \text{ year}^{-1}$, respectively, which were larger decreases than those of the central region (-0.19 and -0.21 , respectively) and southern region (-0.11 and -0.14 , respectively). Moreover, the subalpine region had the smallest GHG budget in 2080 under the RCP 4.5 and RCP 8.5 (-0.09 and $-4.2 \text{ Mg CO}_2 \text{ eq. ha}^{-1} \text{ year}^{-1}$, respectively).

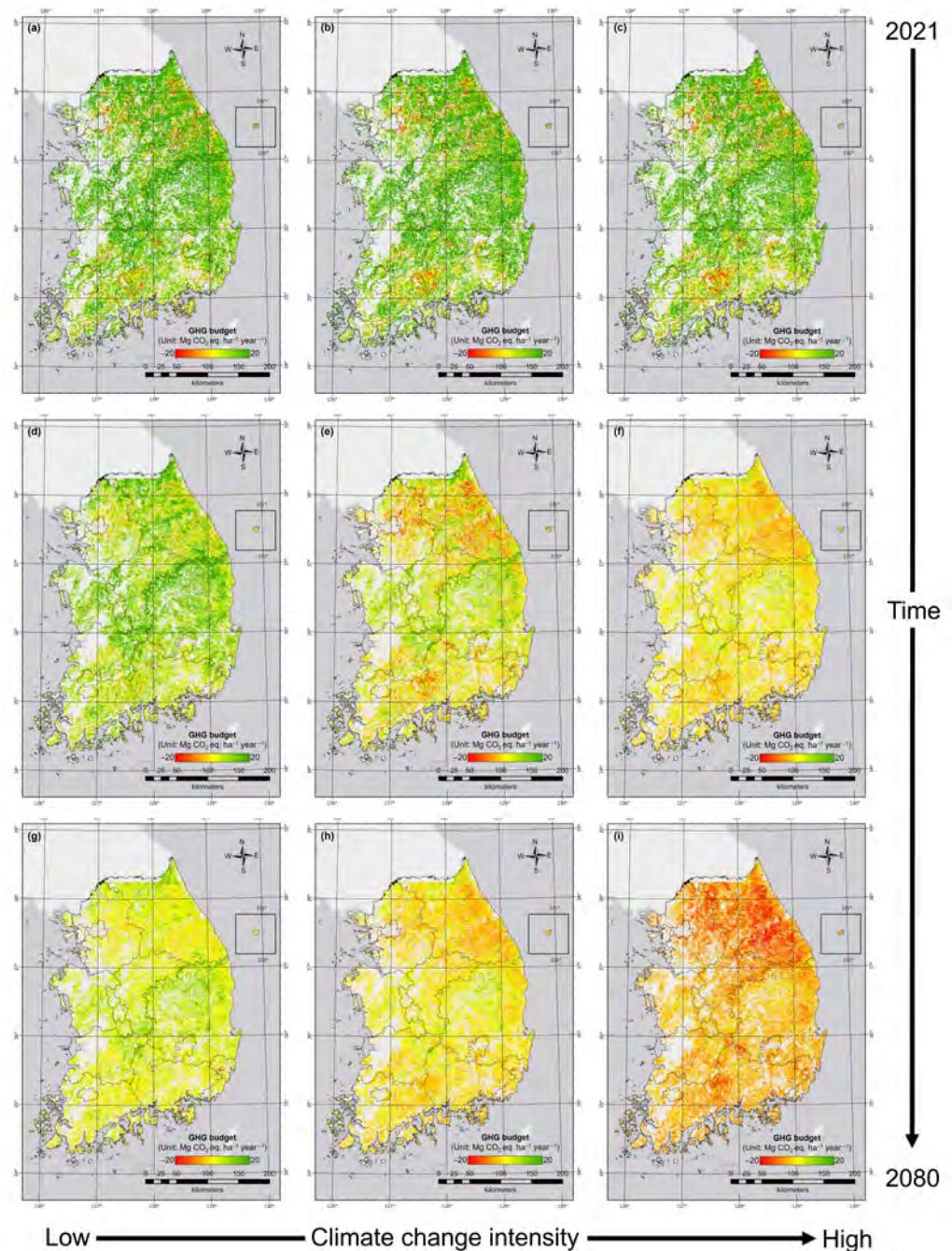


Figure 3. South Korean forest maps of GHG budget (a,b,c) in 2021, (d,e,f) in 2050, and (g,h,i) in 2080 under the current climate (left column), RCP 4.5 (center column), and RCP 8.5 (right column).

Table 1. GHG budget (mean±standard deviation Mg CO₂ eq. ha⁻¹ year⁻¹) of subalpine, central, and southern regions in 2021, 2050, and 2080 under the current climate, RCP 4.5, and RCP 8.5.

Region	Current Climate			RCP 4.5			RCP 8.5		
	2021	2050	2080	2021	2050	2080	2021	2050	2080
Alp ¹	7.6 ± 4.5	6.1 ± 3.3	2.1 ± 2.0	7.5 ± 4.8	1.1 ± 3.3	-0.9 ± 1.4	7.5 ± 4.7	-0.3 ± 3.6	-4.2 ± 1.8
Cent ²	6.6 ± 5.0	3.6 ± 2.7	1.4 ± 1.7	6.5 ± 5.2	1.0 ± 2.6	-0.2 ± 1.9	6.5 ± 5.1	0.5 ± 2.7	-2.4 ± 2.2
South ³	3.8 ± 4.6	2.3 ± 2.6	0.9 ± 2.0	3.7 ± 4.8	0.4 ± 2.4	-0.5 ± 2.4	3.7 ± 4.8	-0.5 ± 2.3	-2.1 ± 3.1

¹ Subalpine region; ² Central region; ³ Southern region

3.3. Relationships of Greenhouse Gas Budget with Stand Age and Air Temperature

The GHG budget for 2021 decreased with stand age and mean annual air temperature in 2021 (Figure 4). The bivariate distribution between stand age and the GHG budget in the subalpine region was skewed to the right and above the linear regression line (Figure 4a). This indicated that the subalpine regions had older stand age than the central and southern regions and had a relatively higher GHG budget compared to the central and southern regions with the same stand age. Linear regression shows that the GHG budget may fall below zero when the stand age exceeds 60 years. The bivariate distribution between the air temperature and the GHG budget showed that the GHG budget decreased as the air temperature increased in the order of the subalpine, central, and southern regions (Figure 4b). However, only a small part of the full distribution of the GHG budget was explained by the air temperature ($R^2 = 0.07$) compared to the stand age ($R^2 = 0.26$).

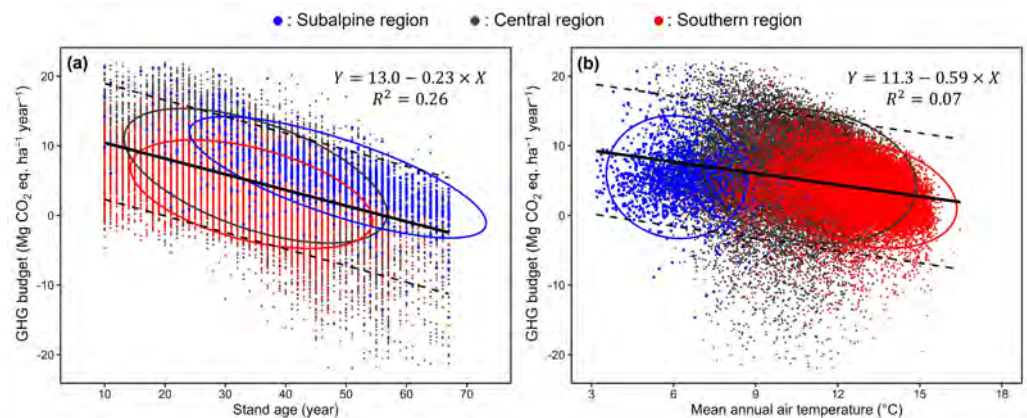


Figure 4. Bivariate relationships between both (a) stand age and (b) mean annual air temperature in 2021 and GHG budget for 2021 under the current climate. A dot indicates each result of the whole simulation unit of 59,939. Black solid lines are linear relationships between two variables for the whole simulation unit ($p < 0.05$). Black dashed lines are 95% prediction intervals. An ellipse indicates a 95% confidence level for each region's bivariate distribution.

4. Discussion

4.1. Changes in Greenhouse Gas Budget over Time under Climate Change

The aging of forests and the subsequent growth of carbon stocks caused a faster increase in the respiratory CO₂ emissions than that in the photosynthetic CO₂ uptake, resulting in a decrease in CO₂ absorption over time (Figure 2c). Indeed, a decrease in CO₂ absorption over time in South Korean forests has been reported in previous studies. Modeling studies on the carbon dynamics of South Korean forests have reported that CO₂ absorption increased after 1973, when the national forest rehabilitation plan was made by the South Korean government [48]. Still, this increasing trend stopped in the 2000s [57] or in the 2010s [48]. In addition, these modeling studies anticipated the gradual decrease in CO₂ absorption after the 2020s with the aging of forests over time, as evidenced in the present study (Figures 2c and 4a).

Moreover, previous studies have shown a decrease in CO₂ absorption with forest aging. A global meta-analysis study reported that CO₂ absorption declined progressively with increasing stand age and suggested that the increase in autotrophic respiration with aging would be the major cause of such a decline [58]. Chronosequence studies have also shown that older forests have lower CO₂ absorption than young forests, mainly due to increased autotrophic respiration with the aging of forests [59,60]. It has also been suggested that increases in live tissues, complex structured tissues, transport cost of carbohydrates through lengthened phloem, and turnover of fine roots with aging are the major causes of the increasing autotrophic respiration with aging [58].

The larger photosynthetic CO₂ uptake and respiratory CO₂ emissions under the RCP 4.5 and RCP 8.5 than under current climate are due to the increase in CO₂ concentration and the increase in air temperature, respectively [21,23–25]. The faster-decreasing trend of CO₂ absorption under the RCP 4.5 and RCP 8.5 compared to current climate shows that the photosynthetic benefit from CO₂ fertilization would not fully compensate for accelerated respiration from increased air temperature under climate change [28,61]. Heimann and Reichstein [26] forecasted that the acceleration of respiratory CO₂ emissions would overwhelm CO₂ fertilization effects on photosynthetic CO₂ uptake in most global terrestrial ecosystems under climate change, and most global terrestrial ecosystems will eventually speed climate change through positive feedback. However, our projections showed that the South Korean forests would continue acting as a CO₂ sink until 2050 under RCP 4.5 and RCP 8.5 (Figure 2c), slowing climate change. This is because most South Korean forests are young forests with a higher sensitivity to CO₂ fertilization effects [21,62,63] and larger growth potential than older forests [31,44,48]. However, as forests age, they are likely to act as a CO₂ source, thereby accelerating climate change, as evidenced by the GHG budget after 2060 under RCP 8.5.

Our estimates for N₂O emissions under the current climate (0.20–0.42 Mg CO₂ eq. ha⁻¹ year⁻¹) were consistent with the previously reported range in East Asia (less than 0.5 Mg CO₂ eq. ha⁻¹ year⁻¹) [3,7,8]. N₂O emissions increased over time because the FBD-CAN increases N₂O emissions with an increase in the nitrogen stock of mineral soil [47,48,64]. Meanwhile, the larger increasing trend in N₂O emissions under the RCP 4.5 and RCP 8.5 than under current climate is because the increase in air temperature accelerated nitrogen mineralization, thereby increasing nitrogen that would be used for denitrification [47,64,65].

The GHG budget decreased over time because the CO₂ absorption decreased, while the N₂O emissions increased over time (Figure 2c,d,e). The decrease in the GHG budget due to N₂O emissions was marginal in 2021 because N₂O emissions were only 0.25 Mg CO₂ eq. ha⁻¹ year⁻¹, while CO₂ absorption was 5.0 Mg CO₂ ha⁻¹ year⁻¹. However, the decreasing effects of N₂O emissions on GHG budget increased over time because CO₂ absorption continued to decrease. Meanwhile, under the RCP 4.5 and RCP 8.5, the decrease in the GHG budget over time was accelerated compared to those under current climate because CO₂ absorption decreased while N₂O emissions increased under climate change.

4.2. Spatial Variation in Greenhouse Gas Budget

The larger loss in the GHG budget in the subalpine region under climate change than in the central and southern regions is due to the larger carbon stocks of litter, dead wood, and mineral soil in the subalpine region [46]. Generally, the respiratory CO₂ emissions from litter, dead wood, and mineral soil increase with the amount of carbon stock when factors that affect decomposition rates, including air temperature, which accelerates decomposition rates, are constant [29]. However, with the increase in air temperature under the RCP 4.5 and RCP 8.5, large amounts of carbon in the litter, dead wood, and mineral soil pools in the subalpine region were emitted through elevated decomposition rates. Indeed, a soil warming study reported that soils from alpine forests emitted more respiratory CO₂ and were more sensitive to warming than soils from forests at lower elevations because of the larger soil carbon stocks in alpine forests [66,67]. Another study across biomes showed that soils from alpine forests have lower decomposition rates because of lower air

temperature in the alpine region, but their decomposition rates showed a higher sensitivity to the increase in air temperature than soils from forests at lower elevations [67]. These findings indicate that the subalpine region is more vulnerable to climate change in terms of its climate mitigation role. Meanwhile, the relatively lower air temperature and the older stand age in the subalpine region are likely underlined to cause a faster decrease in the GHG budget than in the central and southern regions (Figure 4). Therefore, replacing the older forests in the subalpine region with younger forests through regeneration could be an effective strategy to sustain the GHG budget in the future. However, conversion of the older forests to younger forests can decrease the carbon stock of the mineral soil and microbial biomass due to the significant decrease in litter input [68]. Thus, the regeneration should be conducted carefully with consideration of available forest management options. For instance, spreading plant residues after the regeneration can compensate for the loss in litter input [68]. Harvesting the old trees can convert the carbon stock in tree biomass into a more stable CO₂ sink; harvested wood products [69]. Additionally, thinning and tending can increase the life-span of the harvest wood products by increasing the size and quality of merchantable timbers [70].

4.3. Total Amount of Greenhouse Gas Budget

The total amount of the GHG budget of South Korean forests in 2050 under the current climate (17.0 million Mg CO₂ eq. year⁻¹) was larger than the previous estimate for CO₂ absorption in 2050 by NIFoS (14 million Mg CO₂ year⁻¹) [19]. This is because our estimate included not only the contribution to the CO₂ absorption of tree biomass but also those in the litter, dead wood, and mineral soil. As expected from previous modeling studies and NIFoS [19,48,57], the GHG budget decreased over time with the aging of forests but more rapidly under RCP 4.5 and RCP 8.5. Since the net-zero CO₂ emission goal tries to limit the increase in global air temperature to below 1.5 °C compared to the pre-industrial level [2], the total amount of the GHG budget under the current climate, which assumes no further increase in air temperature, is likely to be over-estimated. Rather, if the achievement of net-zero CO₂ emissions by 2050 is assumed, the feasible estimate in 2050 might be between the estimate under the RCP 4.5 and the estimate under the current climate (11.6–17.0 million Mg CO₂ eq. year⁻¹).

4.4. Limitations of the Simulations

Our future projections reported that CO₂ absorption will decrease over time with the aging of forests at higher rates under climate change. However, this study has several limitations. The FBD-CAN does not consider the acclimation of forests to increasing air temperature and CO₂ concentration [47], but biogeochemical models that do not consider this acclimation can exaggerate the impacts of the interaction between the forest and atmosphere [71]. The composition of tree species in South Korean forests is also expected to change as a result of climate change [41]. However, our simulation assumed that the forest type in 2021 will not change until 2080. Since the rates of growth and CO₂ absorption differ depending on the tree species [31], this assumption can lead to the over- or under-estimation of CO₂ absorption. Moreover, we did not account for the future change in forest land area that can largely affect the total volume of the GHG budget. Particularly, as the government of South Korea is planning to afforest bamboo forests, unstocked forest land, abandoned land, and other lands at a rate of 25,000 ha year⁻¹ to achieve net-zero CO₂ emissions by 2050 [19], our estimate of the climate mitigation role of South Korean forests might be under-estimated. Lastly, although climate change is likely to increase natural disturbances over time, such as forest fires, insect outbreaks, and droughts, the impacts of natural disturbances on forests were not considered [72]. Thus, the FBD-CAN needs to consider these time-varying processes, such as the acclimation of forests to climate change, changes in species distribution, increase or decrease in forest land area, and natural disturbances, to improve the reliability of the simulations.

Meanwhile, the present study has uncertainties in the simulation that arise from input data, especially from the initial carbon and nitrogen stocks. This is because these data were estimated by the FBD-CAN rather than directly measured. Although the reliability of the FBD-CAN was validated by using the National Forest Inventory data in 2018, the remaining uncertainties in the previous estimation by the FBD-CAN could be inherited as input data in the simulation of the present study [48]. For example, young forests with large carbon and nitrogen stocks in mineral soil were another source of the negative GHG budget, although their stand age was less than 60 years old. This was because of higher respiratory CO₂ emission and N₂O emission from the large carbon and nitrogen stocks in mineral soil compared to relatively low photosynthetic CO₂ uptake (Figure 4a). However, young forests with large carbon and nitrogen stocks in mineral soil are unlikely and scarcely reported in South Korean forests [73], indicating potential uncertainties in the initial condition of the simulation of the present study.

5. Conclusions

This study used FBD-CAN to project the future contribution of South Korean forests to GHG reduction. We showed that the GHG budget of South Korean forests will decrease over time, and this decreasing trend will be faster under climate change. Specifically, CO₂ fertilization with the increase in CO₂ concentration would not fully compensate for the increase in respiratory CO₂ emissions due to the increase in air temperature. The negative contribution of N₂O emissions to the GHG budget became more significant over time and as climate change intensifies. The decrease in CO₂ absorption over time was mainly due to the aging of forests. The decreasing trend in the GHG budget was faster in the subalpine region than in the central and southern regions due to the lower air temperature and the older stand age in the subalpine region. Replacing older forests in the subalpine region with younger forests through regeneration could be a feasible option to minimize the future decrease in CO₂ absorption. However, regeneration can cause soil disturbance. Thus it should be conducted carefully with consideration of available forest management options, including harvesting, thinning, and tending. Our study provides a scientific basis for guiding governmental decisions on climate mitigation strategies to achieve net-zero CO₂ emissions by 2050 and beyond. Moreover, our findings will also improve our understanding of the impacts of future increases in CO₂ concentration and air temperature on the GHG budget of forests.

Author Contributions: H.-S.K., F.N., N.J.N. and Y.S. conceptualized the main idea; H.-S.K. conceived and designed the methodology; H.-S.K. wrote and prepared the original draft; H.-S.K., F.N., N.J.N. and Y.S. reviewed and edited the manuscript; H.-S.K. visualized the research findings; Y.-W.S. acquired funding and supervised this study as a project administrator. All authors have read and agreed to the published version of the manuscript.

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Appendix A

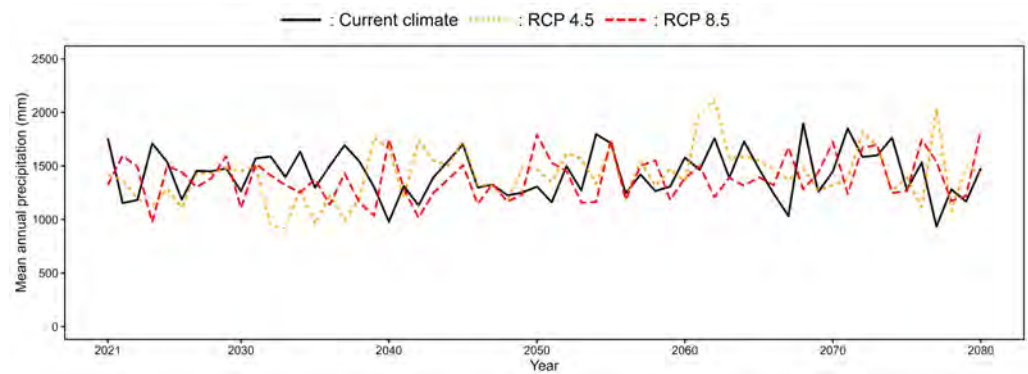


Figure A1. Mean annual precipitation from 2021 to 2080 under current climate (black solid line), RCP 4.5 (orange dotted line), and RCP 8.5 (red dashed line) scenarios.

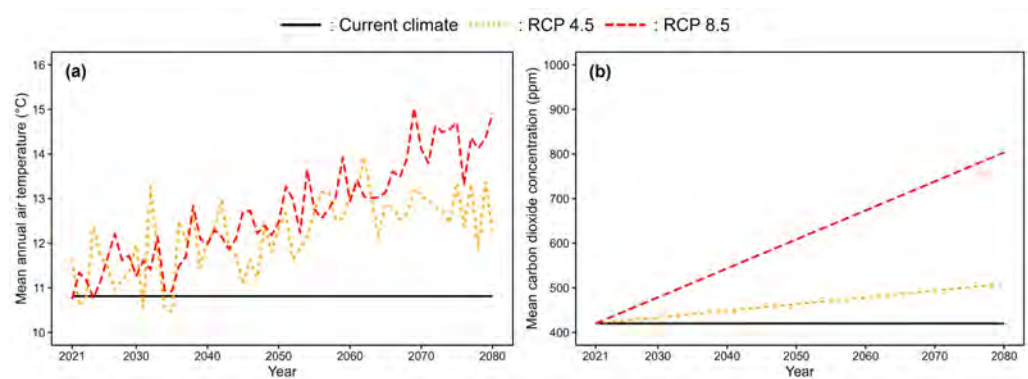


Figure A2. Mean (a) annual air temperature and (b) CO₂ concentration from 2021 to 2080 under current climate (black solid lines), RCP 4.5 (orange dotted lines), and RCP 8.5 (red dashed lines) scenarios.

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