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Generic Carbon Budget Model for Assessing National Carbon Dynamics toward Carbon Neutrality: A Case Study of Republic of Korea

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Abstract: Forests play a crucial role in South Korea's carbon neutrality goal and require sustainable management strategies to overcome age-class imbalances. The Generic Carbon Budget Model (GCBM) offers a spatially explicit approach to simulate carbon dynamics at a regional scale. In this study, we utilized the GCBM to analyze the carbon budget of forests in South Korea and produce spatiotemporal maps for distribution of the forest biomass. The growth parameters of five representative tree species (*Pinus densiflora* Siebold & Zucc., *Larix kaempferi* Carr., *Pinus koraiensis* Siebold & Zucc., *Quercus mongolica* Fisch. ex Ledeb., *Quercus variabilis* Blume), which are the main species in South Korea, were used to operate the model. In addition, spatial data for harvest and thinning management activities were used to analyze the effects of anthropogenic activities. In 2020, the aboveground and belowground biomass were 112.98 and 22.84 tC ha^{-1}, and the net primary productivity was 8.30 tC ha^{-1} year^{-1}. These results were verified using comparison with statistics, a literature review, and MODIS NPP. In particular, broadleaf is higher than conifer forest in net primary production. The Canadian GCBM with Korean forest inventory data and yield curves successfully estimated the aboveground and belowground biomass of forests in South Korea. Our study demonstrates that these estimates can be mapped in detail, thereby supporting decision-makers and stakeholders in analyzing the carbon budget of the forests in South Korea and developing novel schemes that can serve regional and national aims related to forest management, wood utilization, and ecological preservation. Further studies are needed to improve the initialization of dead organic matter pools, given the large-scale afforestation efforts in recent decades that have established South Korea's forests on predominantly non-forest sites.

Keywords: forest modeling; climate change; forest management; net primary productivity; aboveground biomass; belowground biomass; moderate resolution imaging spectroradiometer; ecological preservation

Citation: Ko, Y.; Song, C.; Fellows, M.; Kim, M.; Hong, M.; Kurz, W.A.; Metsaranta, J.; Son, J.; Lee, W.-K. Generic Carbon Budget Model for Assessing National Carbon Dynamics toward Carbon Neutrality: A Case Study of Republic of Korea. *Forests* **2024**, *15*, 877. https://doi.org/10.3390/f15050877

Academic Editor: Baozhang Chen

Received: 8 April 2024
Revised: 9 May 2024
Accepted: 13 May 2024
Published: 17 May 2024

1. Introduction

The Paris Agreement (PA) provides a framework for all nations to combat climate change, requiring each country to declare its own specific plan for reducing greenhouse gas (GHG) emissions [1]. As of 2023, there are 194 individual nations and the EU that are parties to the PA. South Korea ratified the PA in 2016. The submitted national plans are referred to as nationally determined contributions (NDCs) and encompass several sectors, such as energy, transportation, buildings, and land use. According to the Intergovernmental Panel on Climate Change (IPCC), land—an essential basis for supplying food and water—accounted for 23% (12.0 ± 2.9 Gt CO2 eq yr^{-1}) of the GHGs emitted from anthropogenic activities during 2007–2016. The IPCC developed the Good Practice Guidance for Land Use, Land-Use Change, and Forestry (GPG-LULUCF) for monitoring and reporting forest carbon stocks and their changes. The aim of the GPG-LULUCF is to enhance the existing methodologies, with the main principles being transparency, accuracy, consistency, completeness, and comparability [2]. In the land sector, spatial boundaries can be delineated according to national circumstances, based on the GPG-LULUCF [3,4].

Natural carbon sinks include forests, cropland land, grasslands, wetlands, settlements, and other lands, which are grouped into six LULUCF categories [5,6]. Forests represent a significant portion of natural carbon sinks. Moreover, in 2019, climate crisis response actions were highlighted by the schemes on carbon neutrality developed by the international community, wherein the role of forests was further highlighted. Therefore, forests are important resources for reaching carbon neutrality [7,8]. According to the Global Carbon Project, the CO_2 sink from land use during 2006–2015 was 11.6 Gt CO_2 per year, accounting for approximately 31% of the total annual CO_2 anthropogenic emissions [9].

Carbon neutrality refers to achieving a balance between the amount of carbon dioxide emitted and removed by human activity. Forests play a crucial role in carbon neutrality by acting as carbon sinks, absorbing CO_2 through photosynthesis and storing it in biomass and soil. Their ability to sequester carbon makes forests essential in efforts to mitigate climate change and achieve carbon neutrality. In 2020, South Korea's greenhouse gas emissions (GHG) amounted to 656.22 million tons, with a target set to achieve carbon neutrality by 2050 [10]. This plan contains goals to reduce emission by 40% before 2030 compared to 2018, such as through using carbon sinks to absorb 26.7 million tons CO_2 per year before 2030. Forests account for 63.2% of the land area (100,431 km^2) in South Korea, ranking fourth among the forest-area proportions of the Organization for Economic Cooperation and Development countries [11]. This is the result of the Korean reforestation strategy implemented since the Korean War [12]. However, several challenges arise from the imbalance in age classes stemming from the intensive reforestation strategy. Therefore, understanding the state of forest stands and managing forests through sustainable methods are essential approaches for enhancing their future contributions to carbon sinks.

Climate change affects the growth and productivity of forests by altering the patterns of temperature and precipitation both directly and indirectly [13–16]. These alterations may lead to a decrease in CO_2 absorption resulting from a decrease in tree growth and shifts in the forest distribution and vegetation belts of evergreen coniferous forests [17–19]. This indicates that forest growth patterns are threatened by climate change and directly tied to carbon stocks. This can create challenges in achieving climate action goals. Consequently, additional efforts are required to monitor and mitigate impacts on forests resulting from climate changes [20,21].

Generally, stakeholders are interested in quantifying past and future carbon stocks in forests to make informed decisions related to land-use policies, because international agreements require countries to monitor and report forest carbon dynamics regularly [3]. As explained by the United States Environmental Protection Agency (USEPA), the storage of carbon in forest biological materials (aboveground and belowground biomass, deadwood organic matter, litter, and soil carbon) is crucial for maintaining the stability of forest ecosystems and the global carbon cycle [22]. Notably, a change in carbon storage can occur due to natural and anthropogenic factors such as wildfires, insect infestation, natural reforestation, and harvesting. The biomass of a tree can be calculated from its stem volume [23]. Several coefficients are used for converting stem volume to biomass and carbon, including the basic wood density, biomass expansion factors, and root shoot ratios, which can be based on the IPCC standards. In addition, the biomass production in a forest ecosystem or the creation of new organic matter is essential for understanding the carbon flux of the forest. Net primary production (NPP) and net ecosystem production (NEP) quantify the ability of an ecosystem to capture and store carbon, which is critical for mitigating climate change [24]. By understanding these processes, humanity can manage and protect the environment and assess the overall health of a forest. Furthermore, monitoring the NPP and NEP of a forest can support policymakers in taking informed decisions regarding land use, forest management, conservation, and sustainability.

Forest growth models are powerful tools for understanding and estimating forest ecosystem dynamics [3,5,16]. These models can be used for various applications, such as sustainable forest management and climate change mitigation. However, there are several limitations in using a forest growth model that cannot reflect the complexity of influencing factors such as forest characteristics, environment, or uncertainty regarding land use and natural disasters. In addition, ecological interactions and regional differences should be considered. The Carbon Budget Model of the Canadian Forest Sector (CBM–CFS3) is a representative forest growth model to understand the forest and global carbon cycle, that is consistent with the IPCC guidelines for predicting the emission and removal of GHG emissions from LULUCF [3]. Notably, it is an empirical model used to estimate forest growth and the yields of stands using field data, including the tree diameter, height, age, and on-site conditions. Furthermore, CBM-CFS3 is a time-step-based carbon model that operates at the stand level and utilizes commonly available forest inventory and merchantable yield data from the forest sector to simulate carbon dynamics [15,25].

The generic carbon budget model (GCBM) is a spatially explicit model that can simulate the carbon dynamics of a region in a grid-based format and at a user-determined scale [25–27]. The model can be applied to various aspects of forest management, e.g., climate change mitigation, conservation, the distribution and management of mosses and peatlands, and fire severity; the model can be applied to support forest management efforts in various countries [28–31].

Here, we employ the GCBM to develop spatially explicit future forest carbon budgets for South Korea's forest. We introduce climate sensitive growth curves with regional and species-specific parameters to represent the dynamics of relevant Korean tree species under the impacts of climate change.

2. Materials and Methods

2.1. Study Area

This study focuses on South Korea (latitude: 33°09′–38°45′ N, longitude: 124°54′–131°06′ E), which is located in East Asia. South Korea has a temperate climate with four distinct seasons and receives a substantial amount of rainfall, particularly during the summer. The forests in South Korea cover an area of 6,348,834 ha, encompassing mountains and uplands with a complex terrain and consisting of evergreen coniferous (approximately 36.9%), deciduous broad-leaved (approximately 31.8%), and mixed (approximately 26.5%) forests [11]. Five percent of the total forest area is comprised of unstocked forest land and bamboo, both of which have been excluded from this study. In this study, major tree species, namely Red pine (*Pinus densiflora*), Japanese larch (*Larix kaempferi*), Korean pine (*Pinus koraiensis*), Mongolian oak (*Quercus mongolica*), and Cork oak (*Quercus variabilis*), are hereinafter referred to as *P. densiflora*, *L. kaempferi*, *P. koraiensis*, *Q. mongolica*, and *Q. variabilis*, respectively. These species were analyzed to determine the forest carbon dynamics in South Korea (Figure 1).

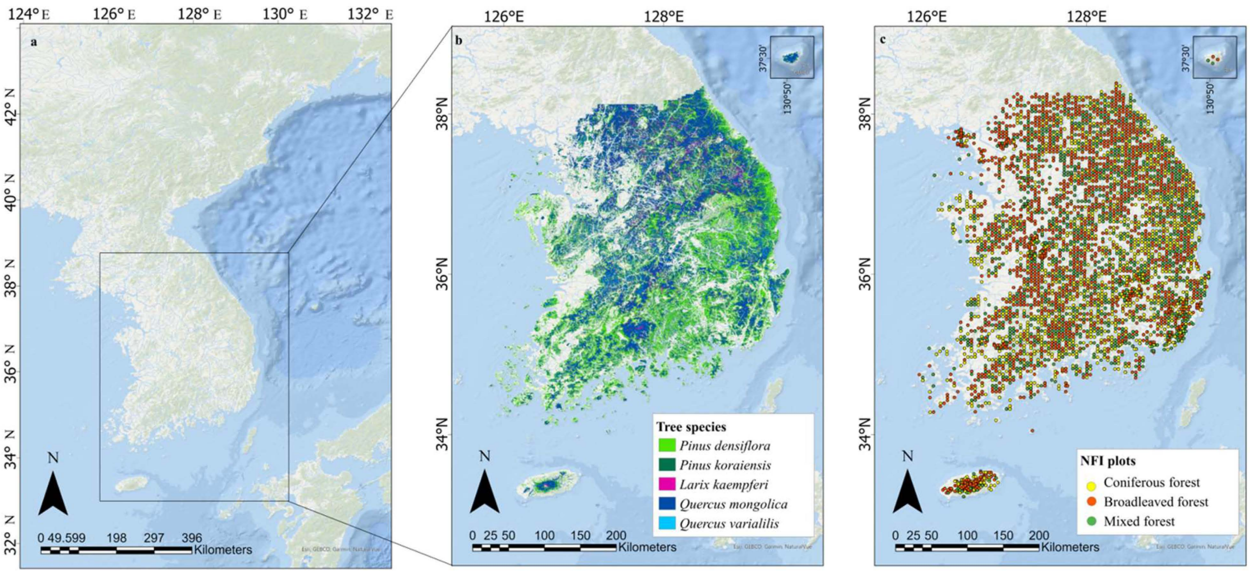

Figure 1. (**a**) Study area; (**b**) forest cover map for South Korea; and (**c**) locations of the National Forest Inventory (NFI) plots used in this study.

2.2. Selection of Key Indicators of Carbon Dynamics for South Korean Forests

In the GCBM, NPP is calculated as the sum of net biomass increment plus litterfall [3]. NEP (NEP = NPP–Rh) is the change in carbon stocks before disturbances and is calculated as the difference between the NPP and the carbon loss from heterotrophic respiration (Rh) [24]. Both NPP and NEP are calculated for each grid cell across the entire study area, based on the boundaries specified by the user [32].

We estimated the amounts of the aboveground and belowground biomass, dead organic matter, NPP, NEP, NBP, and Rh using the GCBM approach, and simulated the future changes in carbon flux in the forests of South Korea for the RCP 8.5 scenario. Our analysis included an analysis of the carbon dynamics of dead organic matter in deadwood, litter, and soil organic matter (pool as defined by IPCC and in [3]). Dead organic matter pools were initialized following the default procedures of the GCBM (and CBM-CFS3) model [3], assuming that the last stand initiating disturbance was wildfire. This may result in the overestimation of deadwood pools, in situations where the last stand replacing disturbance was clear-cut harvest of where stands originate on previously non-forested lands.

2.3. Generic Carbon Budget Model

The GCBM was built on the open source platform of the spatially explicit Full Lands Integration Tool (FLINT) developed by Moja Global [25]. The GCBM uses the scientific algorithms of the CBM-CFS3 in a spatially explicit modeling environment [3,29,32]. The CBM-CFS3 model uses stand growth and yield curves, tree species, age class, disturbance events, and climate conditions to quantify the effects of past and future land use and land-use changes on forest carbon dynamics and to simulate the carbon stock changes in the aboveground and belowground biomass, dead organic matter (DOM), and soil carbon content at the stand and landscape levels [3,15,27]. The carbon stocks of forests include five tree biomass components, specifically merchantable parts, other wood, foliage, coarse roots, and fine roots, within the softwood (coniferous) and hardwood (broadleaf) species group [3]. The spatially explicit GCBM uses parallel processing to simulate each pixel across a timeseries before proceeding to the next pixel, thus enabling the application of the model to large landscapes. However, the model requires spatially explicit disturbance information, including forest management data related to forest thinning and harvesting. These data are input as spatial layers that specify the year and type of disturbance [25]. Thus, we used the data for forest harvesting and thinning and evaluated the forest stand age and volume to specify the anthropogenic activities in the forest lands [5] (Figure 2). In the present study, the spatial data for the GCBM were stored in a format using the EPSG 4326 projection, and the simulation was conducted at the resolution of 0.001° (approximately 100 m in resolution); the climate data were processed at a spatial resolution of 0.01° (approximately 1 km in resolution).

2.4. Data

2.4.1. Forest Cover Map (FCM)

The FCM was used as a representative map of the forest cover in South Korea. The map (1:5000; produced from the NFI data, aerial photographs, and the data of the delineated tree species), which includes DBH class, age, and density (to consider the forest status, species, and age class), was used as the input data (in the form of raster files) (Figure 1). The FCM provides forest status in South Korea. Utilizing this dataset, this study categorized forests into five major tree species for analysis. Additionally, the FCM was utilized to ascertain site index and forest age in 2020. Therefore, this study operated the model under the assumption of no change in forest area.

2.4.2. National Forest Inventory (NFI) and Yield Tables

The Korea Forest Service (KFS) released the 5th and 6th National Forest Inventory (NFI) data, collected from 2006 to 2015; these data were previously collected for analyses of forest health, with repeated assessments of tree biomass [33]. The inventory data were collected for approximately 4100 permanent sampling plots on a 4 × 4 km grid (Figure 1). Through a field survey, several forest characteristics, including forest type, tree species, age, diameter at breast height (DBH), height (h), and number of trees (Nha) were recorded alongside the topographical factors such as elevation, slope, aspects, and coordinates of sampling plots. The coefficients required for the GCBM were calculated based on the NFI dataset. In this study, the mean DBH growth was estimated with radial growth considering the climatic conditions and topography (Equation (1)). Height was determined using the site index and the stand's age, which was derived from the age classification provided by the forest cover map (FCM). The FCM categorized forest age into intervals of 10 years, allowing for comparison with age data obtained from the NFI.

$$SG_{ij} = f(WI,\ PEI,\ TWI), \tag{1}$$

Nha reflected the changes in the stand density for each tree species (*P. densiflora*, *L. kaempferi*, *P. koraiensis*, *Q. mongolica*, and *Q. variabilis*) [14,34]. Stands' mortality rates are determined by the relative density index, derived from Sterba's maximum stem number calculation [35]. An equation for estimating maximum stand density is derived using the DBH development formula, based on mean dominant tree height and mean DBH. Kim et al. (2017) not only established the relationship between estimated maximum and actual stand density ratios, but also analyzed the mathematical correlation between maximum stand density reduction and actual mortality [14].

$$\left(\frac{Mortility}{N_{max_i} - N_{max_{i+1}}}\right) = a \cdot e^{b \cdot \frac{Nha_i}{Nmax_i}} Mortality_i = a \cdot e^{b\left(\frac{Nha_i}{Nmax_i}\right)} \cdot (Nmax_i - Nmax_{i+1}) \tag{2}$$

$Mortality_i$ represents the real mortality rate at the stand age i; Nha_i indicates the stand density at the stand age i; and $Nmax_i$ is the maximum stand density at the stand age i (Equation (2)). Additionally, residual and seasonal temperature components of the mortality model for each tree species were analyzed to better understand mortality patterns influenced by climate.

The biomass allometric equations portrayed a significant relationship between the growth rate of stems and other biomass components [23]. The equations for each part (stems, branches, foliage, and roots) were used for the forest biomass estimations (Equation (1)) [23]. Additionally, the yield tables established by the KFS were used to estimate the growth (height) of all the tree stands; this table included the mean and dominant trees, based on the site index and age of each stand, as documented by the National Institute of Forest Science [16,36]. Therefore, the abovementioned coefficients and a raster file for the site index were used as input data to estimate the forest carbon dynamics in the GCBM module.

$$\text{Biomass}_{ij} = a_{ij} \times DBH^{b_{ij}} \times h^{c_{ij}} \tag{3}$$

where i denotes the five major species used in this study, whereas j denotes an individual tree component including the stem, branch, foliage, and root; a, b, and c are the coefficients of the biomass allometric equations (Equation (3); Table 1). The carbon conversion factor (CF), with a default value of 0.5 (from the IPCC), was used for the conversion of biomass to carbon.

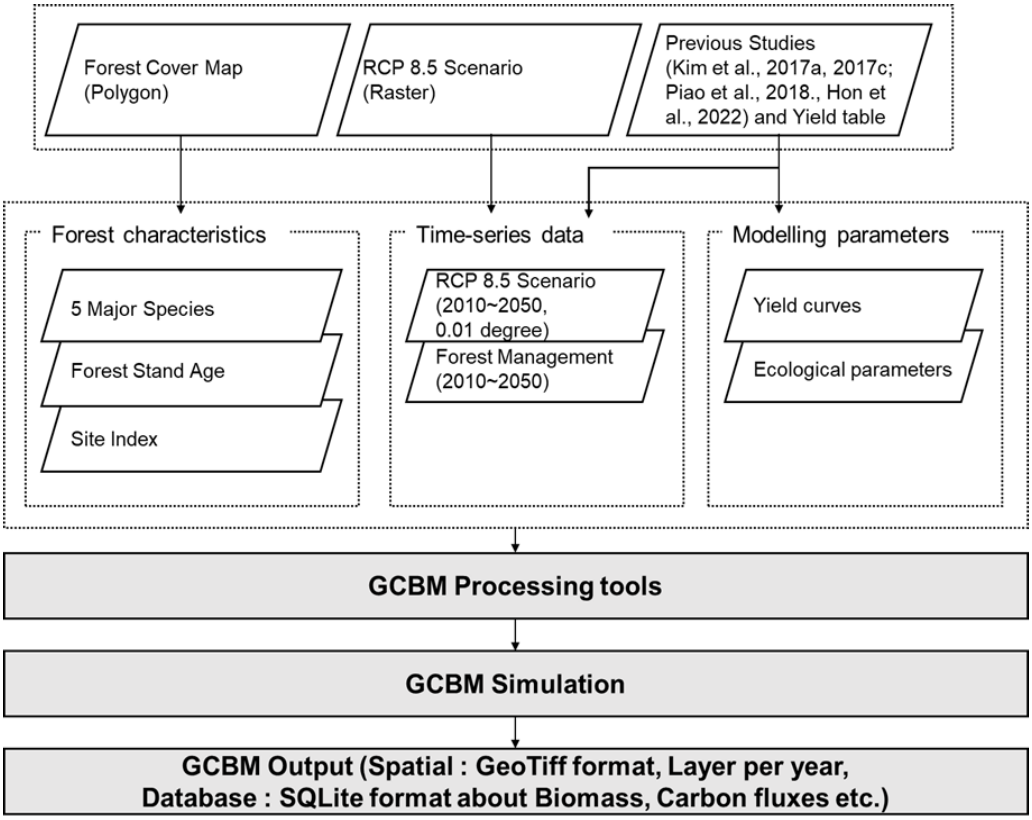

Figure 2. Flowchart portraying the methods used for the generic carbon budget model (GCBM), with climate change projections from the representative concentration pathway (RCP 8.5) [5,14,34,36].

Table 1. Coefficients for biomass allometric equations used in this study [23].

Coefficients		Species				
		P. densiflora	*L. kaempferi*	*P. koraiensis*	*Q. mongolica*	*Q. variabilis*
Stems	*a*	0.034	0.005	0.046	0.098	0.053
	b	1.734	2.458	1.732	1.406	1.81
	c	1.025	0.904	0.896	1.135	0.881
Branches	*a*	0.008	0.143	0.454	0.018	0.082
	b	3.586	4.482	3.574	3.083	2.553
	c	−1.158	−2.90	−2.530	−0.493	−0.608

Table 1. *Cont.*

Coefficients		Species				
		P. densiflora	*L. kaempferi*	*P. koraiensis*	*Q. mongolica*	*Q. variabilis*
Foliage	*a*	0.077	0.022	0.026	0.023	0.108
	b	1.931	1.877	2.471	2.609	1.63
	c	−0.566	−0.023	−2.091	−0.833	−0.406
Roots	*a*	0.034	0.004	0.060	0.312	0.09
	b	2.394	2.588	2.440	1.336	2.217
	c	−0.16	0.541	−0.336	0.551	−0.072

2.4.3. Climate and Topological Data

Representative concentration pathway (RCP) scenarios were used to predict future climatic conditions; this approach is used in various fields of study [37]. In this study, we used the RCP 8.5 scenario, wherein there is no reduction in the GHG emissions (business as usual).

The Korea Meteorological Administration (KMA) provided the data for the RCP 8.5 scenario, which included the timeseries data of the emissions, concentrations of GHGs, aerosols, chemical gases, and land use and land cover of the region [38]. In this study, we used the annual and monthly temperature and precipitation data in the scenario, RCP 8.5, to consider the effects of forest growth and mortality on the forest cover in South Korea from 2010 to 2050. To estimate the tree diameter growth, the warmth index (WI) and precipitation effectiveness index (PEI) were calculated using the monthly temperature and precipitation data [34]. In addition, the data for annual temperatures were used to estimate the tree mortality in each stand through evaluating the changes in the stand density resulting from climate change.

Furthermore, we used the topological data of the region and a digital elevation model (DEM) to calculate the topographic wetness index (TWI), which is a measure of the biological processes of the forest stand, including the forest site quality, vegetation patterns, and annual NPP. The TWI was calculated based on the slope and the flow direction and accumulation using the DEM; the data were input in the model in the form of a raster file [39–41]. The index was used for estimating the tree diameter growth in each forest stand.

Therefore, the calculated climate and topological data, including the WI, PEI, annual temperature, and TWI, were used as the input data for the spatial layer of the GCBM module. These parameters modified annual growth rates. WI, PEI, and annual temperature were factors affecting forest growth. WI, calculated based on annual temperature, influences radial growth. Specifically, while the radial growth of coniferous trees in South Korea decreases, that of oak forests tends to increase with WI [13,34]. It means that increasing temperature will change the pattern of forest growth, distribution, and mortality of South Korea's forest [13,18,34]. Meanwhile, TWI exhibits a positive correlation with radial growth, suggesting greater water availability, especially in flat areas where TWI tends to be higher compared to steep terrain.

2.4.4. Forest Management Scenario Data

Carbon from the atmosphere can be stored in forests, and ecosystem services can be enhanced through sustainable forest management [30,41,42]. Enhancing carbon storage through forest management can contribute to the long-term accumulation of forest carbon stocks [43,44]. The GCBM requires spatial data to identify the spatial locations and year of anthropogenic activities, including those related to forest management; specifically, harvesting and thinning. In the present study, the data were input to simulate future forest conditions, with a focus on the effects of thinning and harvesting. The spatial data about forest management from a previous study were used as the input data for 2011–2050 [5]. South Korea is experiencing an imbalance in its forest age structure, resulting in a higher incidence of early-stage forest management, such as intensive thinning in the initial phases of model operation. From 2023 to 2033, there appears to be a relatively lower level of forest management activity. The amount of overall forest practices is considered the target of the forest management policy in the 6th Basic Forest Plan of South Korea. The previous study conducted research on forests in South Korea, dividing them into managed forests and protected forests. The forest management area pertains to managed forests, while it was assumed that protected forests undergo no harvesting and thinning (Figure 3). To achieve the target of the plan, the data related relating to forest thinning were considered for calculating the stand volume, and the harvesting data were considered based on the rotation age of each species. The harvesting data were implemented using the clear-cut harvesting with salvage disturbance type in the GCBM framework [32]. The thinning data, based on the spatial location of the forest management area, were utilized to apply commercial thinning to 25% of the designated area within the GCBM.

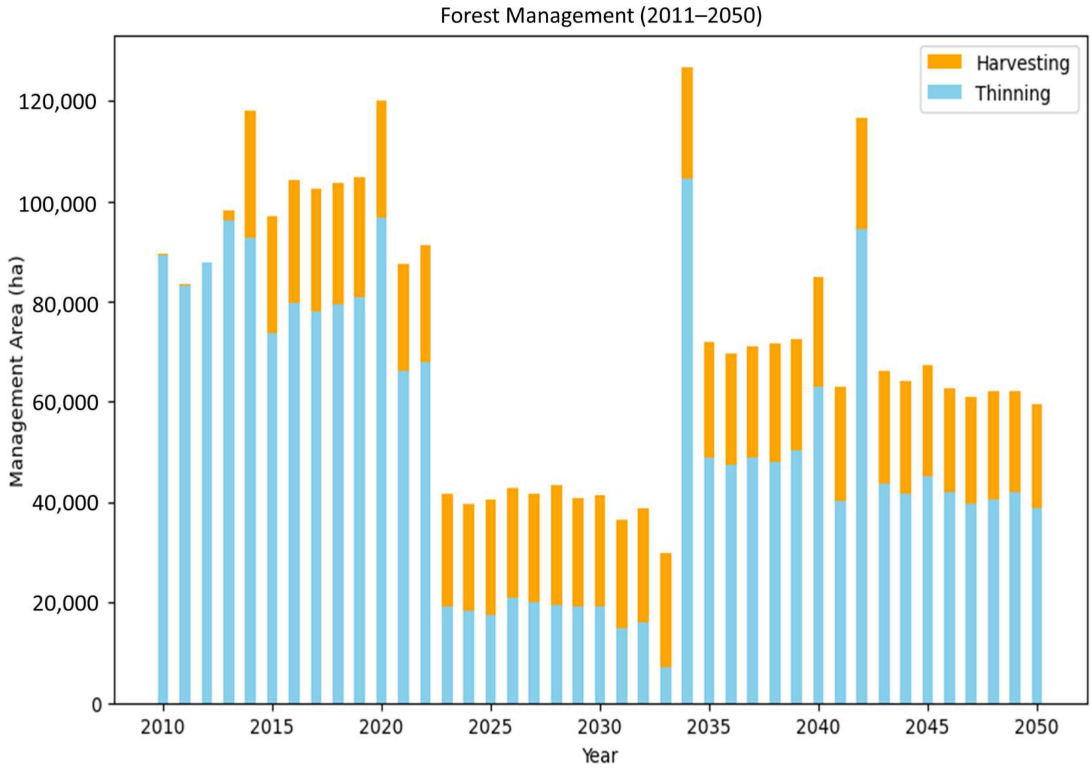

Figure 3. Results for the forest management (harvesting and thinning) scenario for the study area, based on the 6th Basic Forest Plan (2011–2050).

2.4.5. Moderate Resolution Imaging Spectroradiometer (MODIS) 17A3H

The MODIS 17A3H dataset, derived from the MODIS sensor, provides terrain metrics such as elevation and slope. This dataset is valuable for terrain analysis and environmental modeling. In our study, we compared the GCBM results, specifically net primary productivity (NPP), with MODIS-derived NPP values from 2020. A random sampling approach was utilized, dispersing 1000 points across the study area. At each point, net primary productivity (NPP) values were extracted from both the GCBM and MODIS 17A3H datasets. Subsequently, scatterplots were generated to compare these NPP values with those from 2020. Additionally, the slope, intercept, correlation, *p*-value, and standard error were determined to further analyze the relationship between the two datasets.

3. Results

The GCBM simulation covered an area of approximately 6.3 million ha, which is the total forest land area of South Korea. We used anthropogenic disturbance data to determine the forest growth and mortality resulting from the impacts of climate change for the entire simulation period. Using the model, we developed spatially explicit annual maps of the forests in South Korea at a resolution of 1 hectare. The maps portray the spatiotemporal distribution of the total biomass across the forests within the country in raster form; the data depicted include the aboveground and belowground biomass, along with the carbon fluxes in South Korea. These data were summarized to portray the annual time-series of forest carbon fluxes. The data for carbon fluxes from 2011 to 2050 were estimated to analyze how carbon fluxes represent forest growth and mortality changes and how they are, in turn, influenced by climate change (RCP 8.5). This study evaluated the generalizability of the model by applying a Canadian-developed model, GCBM, to Korea. This approach underscores the ability of our developed model to be applied across broader contexts, rather than being limited to specific regions or time frames. By applying the Canadian model to Korea, we demonstrated the applicability and effectiveness of the model across diverse environments, thus providing valuable insights to support decision-making in forest and carbon management.

3.1. Comparison of Biomass and Carbon Flux Estimates

3.1.1. Estimation of Aboveground, Belowground Biomass and Dead Organic Matter

The total biomass increased during the simulation period (2011–2050) (Figure 4). Biomass decreased every ten years, followed by an increase in 2018, 2028, 2030, and 2048, which could be attributed to the effects of forest management activities on the total biomass (Figure 5). The average aboveground biomass amounts were 112.97, 121.63, 129.48, and 136.46 tC ha^{-1} for 2020, 2030, 2040, and 2050, respectively, within the RCP 8.5 scenario (Table 2). The average belowground biomass amounts are increasing to 22.84, 24.05, 25.19, and 26.24 tC ha^{-1} for 2020, 2030, 2040, and 2050, respectively, for the RCP 8.5 scenario.

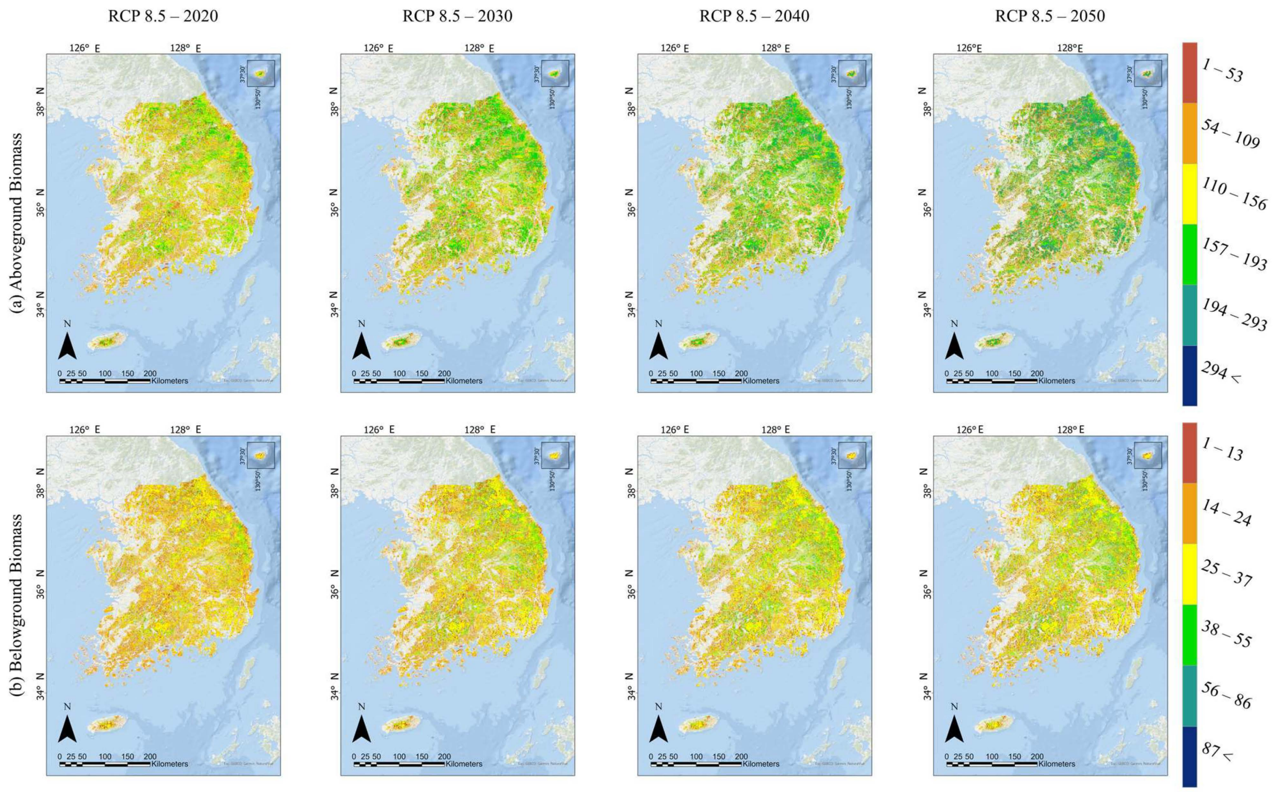

Figure 4. (**a**) Aboveground and (**b**) belowground biomass estimations for 2020, 2030, 2040, and 2050 (from left to right) for the representative concentration pathway (RCP) 8.5.

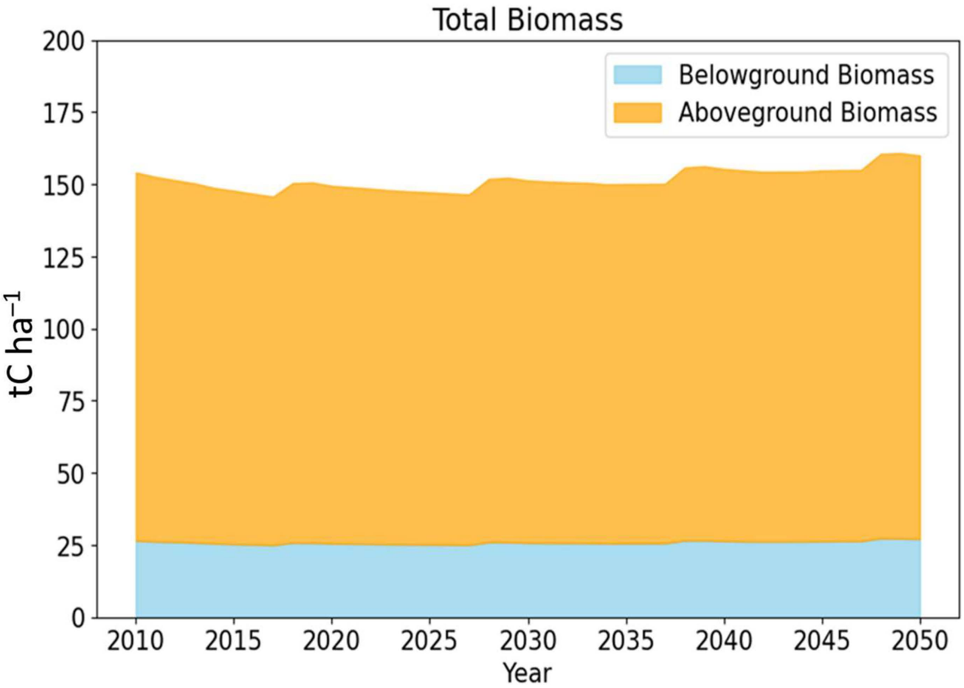

Figure 5. Aboveground and belowground biomass estimations for the forests of South Korea for the representative concentration pathway (RCP) 8.5.

Table 2. Aboveground and belowground biomass in the representative concentration pathway (RCP) 8.5 scenario.

Stock (tC ha^{-1})		**Year**			
		2020	**2030**	**2040**	**2050**
Aboveground biomass	Min	0.00	0.00	0.00	0.00
	Mean	112.97	121.63	129.48	136.46
	Max	279.89	356.86	533.28	713.72
Belowground biomass	Min	0.00	0.00	0.00	0.00
	Mean	22.84	24.05	25.19	26.24
	Max	62.13	79.22	118.38	158.44

Carbon density in the soil and litter carbon pools remained relatively stable. Soil C stocks decreased by 2.39 tC ha^{-1} or 1.4%, while litter C stocks increased by 1.89 tC ha^{-1} or 2.9%. A large reduction in the deadwood carbon pool was estimated by the GCBM. Carbon stocks in the deadwood C pool decreased by 30 tC ha^{-1} or 43.2% from 2010 to 2050 (Figure 6; Table 3).

Table 3. Relative and absolute change in carbon density in deadwood, litter, and soil C pools from 2010 to 2050 in the representative concentration pathway (RCP) 8.5 scenario.

Carbon Stock (tC ha^{-1})	**Year**					
	2010	**2020**	**2030**	**2040**	**2050**	**Ratio (Change)**
Dead Organic Matter (DOM)						
Deadwood	69.56	60.89	51.96	45.06	39.54	0.568 (−30.01)
Litter	66.35	69.75	69.54	69.19	68.24	1.029 (1.89)
Soil Carbon	175.07	175.08	174.53	174.04	172.68	0.986 (−2.39)

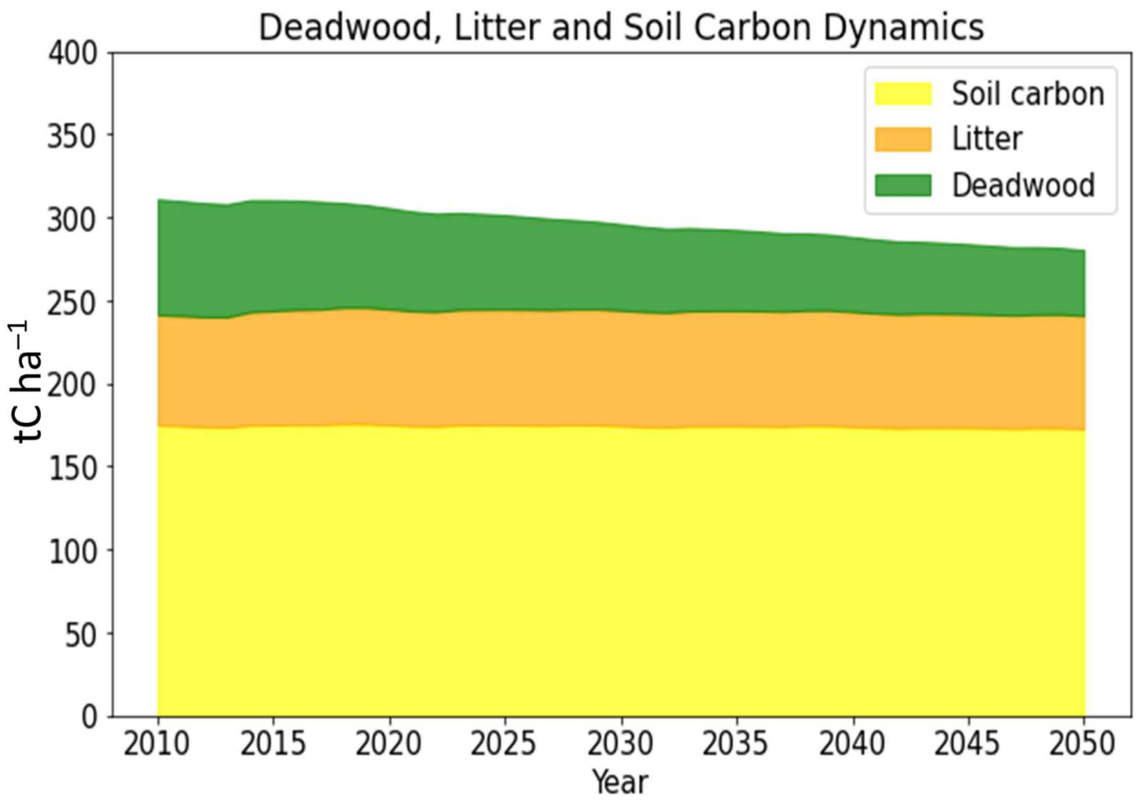

Figure 6. Average carbon density (tC ha^{-1}) in deadwood, litter, and soil carbon pools.

3.1.2. Estimation of Net Carbon Fluxes

From 2010 to 2050, NPP and NEP increased (Figure 7). Heterotrophic respiration (Rh) initially increased to 2017, then decreased, levelling off in the last decade. The NPP values for 2020, 2030, 2040, and 2050 were 8.30, 8.36, 8.51, and 8.70 tC ha^{-1} year^{-1}, respectively, within the RCP 8.5 scenario; for the same years, the NEP values were 0.12, 0.35, 0.57, and 0.75 tC ha^{-1} year^{-1}, respectively, and the Rh values were 8.34, 8.16, 8.09, and 8.11 tC ha^{-1} year^{-1} (Table 4), respectively. These values were significantly influenced by the amount and type of forest management. In the initial period, the net biome production (NBP) was negative, reflecting the high harvest rates in the first years of the simulation.

Table 4. Carbon flux within forests (South Korea) in the representative concentration pathway (RCP) 8.5 scenario.

Carbon Flux (tC ha^{-1} year^{-1})		**Year**			
		2020	**2030**	**2040**	**2050**
Productivity					
Net Primary Production (NPP)	Min	0.06	0.01	0.01	0.01
	Mean	8.30	8.36	8.51	8.70
	Max	24.29	45.58	37.76	43.50
Net Ecosystem Production (NEP)	Min	−21.85	−22.42	−20.34	−26.37
	Mean	0.12	0.35	0.57	0.75
	Max	13.65	−22.42	−20.34	−26.37
Emissions					
Heterotrophic Respiration (Rh)	Min	3.30	2.02	1.59	1.48
	Mean	8.34	8.16	8.09	8.11
	Max	24.24	24.99	23.33	26.46

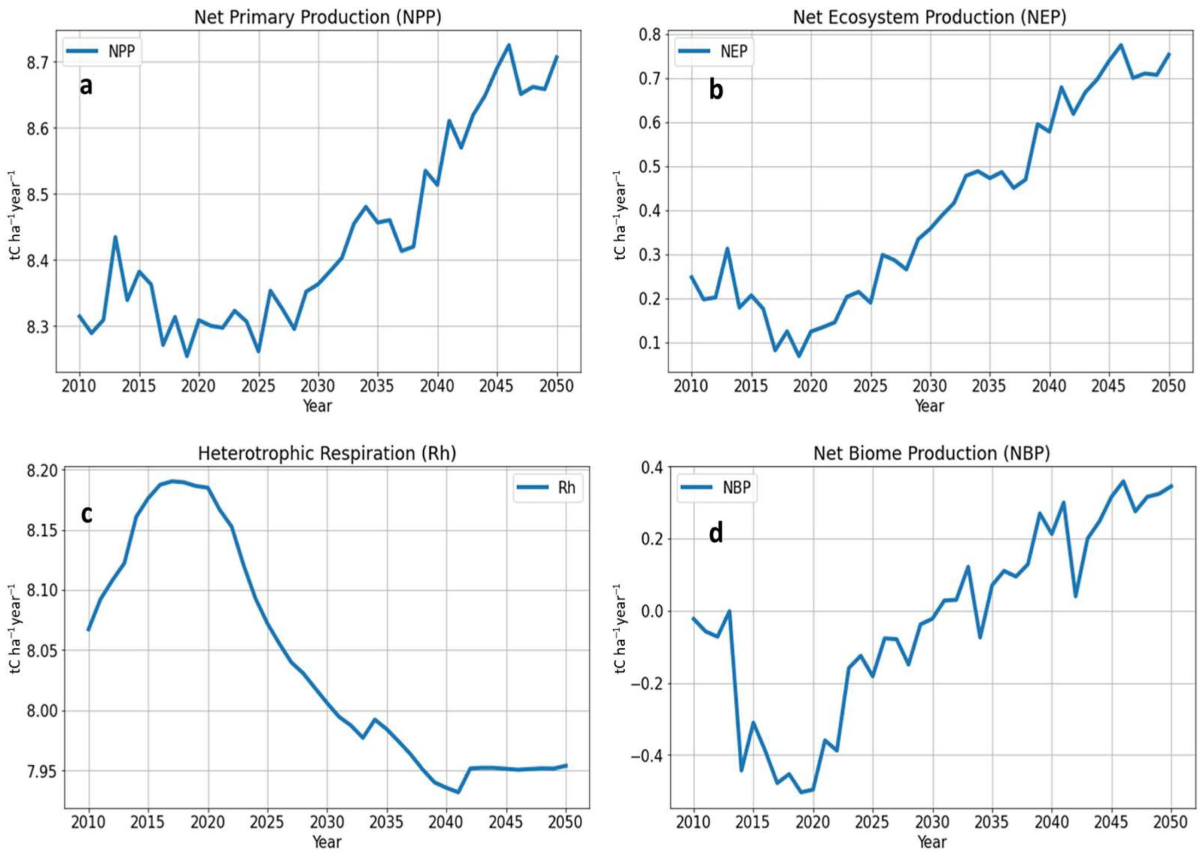

Figure 7. (**a**) Net primary production (NPP); (**b**) net ecosystem production (NEP); (**c**) heterotrophic respiration (Rh); and (**d**) net biome production (NBP) for 2011–2050 for the representative concentration pathway (RCP) 8.5 scenario.

3.2. Comparison of the Results of Previous Studies and Moderate Resolution Imaging Spectroradiometer (MODIS) 17A3H

The aboveground and belowground biomass and carbon fluxes estimated from the GCBM in this study were compared with those estimated in previous studies and the national statistics, and MODIS data. One thousand points across South Korea were randomly distributed, with each point representing one pixel, and the NPP values at those points were extracted for comparison. The results of these studies were used to carry out direct or indirect comparisons.

The estimated NPP was 8.30 tC ha^{-1} in this study. The NPP data were cross-referenced with the MODIS NPP (MOD17A3H) project conducted by the National Aeronautics and Space Administration (NASA). The MODIS NPP dataset spans the period from 2000. The MODIS NPP data from 2020 were compared with the model estimates. Although the NPP data obtained from the GCBM simulation, which accounted for climatic fluctuations, and the MODIS NPP dataset, which was based on distinct spectral reflectance characteristics, exhibited temporal variations, they also demonstrated an overall positive correlation. However, the GCBM results often underestimated the NPP compared to the values derived from the MODIS NPP product (Figure 8).

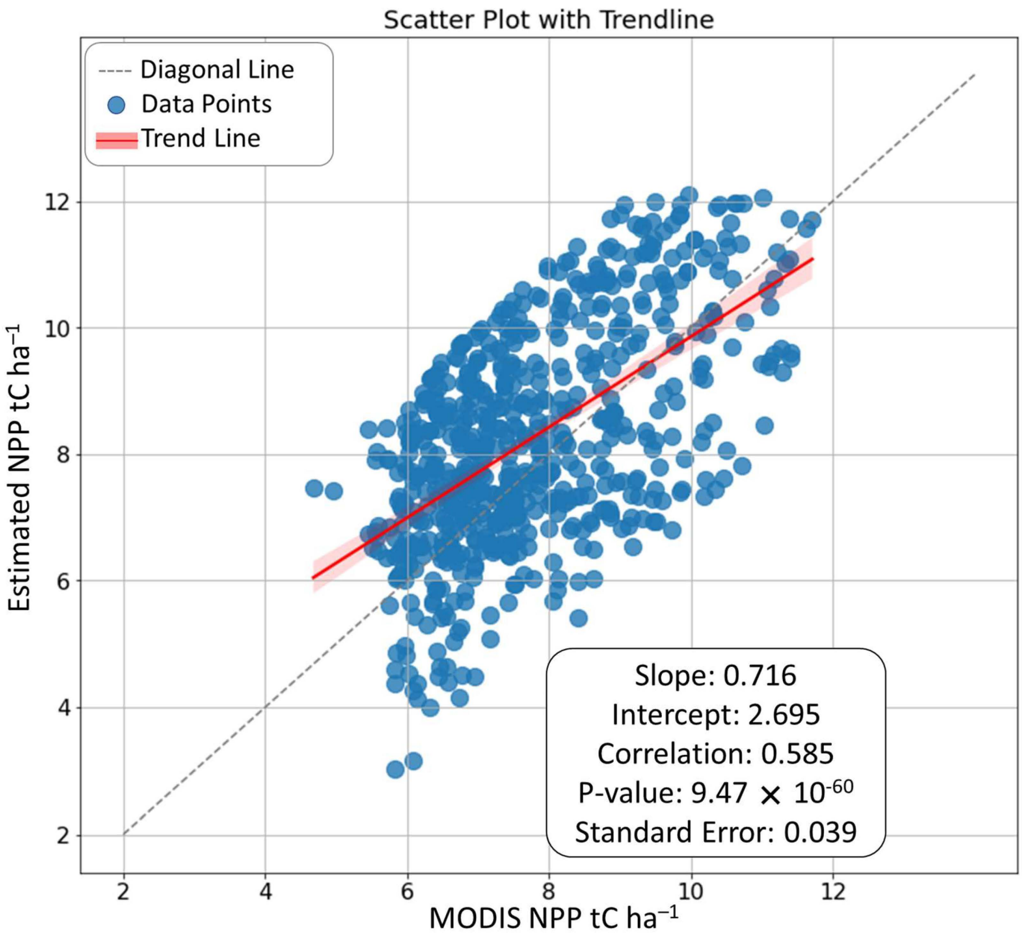

Figure 8. Relationship between net primary production (NPP) from the generic carbon budget model (GCBM) and moderate resolution imaging.

4. Discussion

The results of our study were obtained using a national-scale approach based on the GCBM results of spatially explicit estimates of the carbon dynamics of the forests in South Korea. Some parameters for the major species found in South Korea were used with the GCBM to evaluate the effects of climate variability and the changes in biomass and carbon fluxes. The existing studies that used CBM-CFS3 have not provided accurate maps as output data, which can benefit various stakeholders and support decision-makers through depicting the temporal and spatial patterns in forests. More specifically, these results can be provided as a time series of spatially explicit maps (with a resolution of 100 m) for supporting the decision-making process related to forest management. In addition, through the maps produced by the model, the spatial distributions of aboveground and belowground biomass can be evaluated to facilitate a comparison between the regional and local scales. A resolution of 100 m was used to accurately capture forest characteristics. This resolution reflects the forest distribution characteristics at the region, landscape, and stand levels. The average area of private forests in South Korea is less than 3 ha [45]. Therefore, a resolution of 100 m was useful in studying common forests.

The data used to run the GCBM were based on spatial data (including forest cover maps and climate data). Thus, the results from the GCBM may be different with national statistics based on field surveys. South Korea utilizes forest area data from the Forestry Statistics Yearbook for calculating the greenhouse gas inventory in the forest sector, which diverges from the forest area determined by spatial data. As the results of GCBM were derived from spatial data as the primary dataset, values from GCBM could be different for the national statistics. South Korea is currently exploring diverse approaches to establish a comprehensive land-use matrix. The national statistical data were obtained by identifying the aboveground and belowground biomass of the forests through field surveys and by evaluating the characteristics of each tree species that grow throughout South Korea [33]. In South Korea, several studies estimated the ecosystem carbon and nitrogen storage in various species, including *P. densiflora*, *L. kaempferi*, *P. koraiensis*, *Q. mongolica*, and *Q. variabilis*. Noh et al. (2013) estimated the carbon and nitrogen storages in ecosystems in 2011 by dividing the low and high density stands of *P. densiflora* (low: 95.5 ± 13.6; high: 97.3 ± 10.6) [46]. Lee et al. (2009) estimated the carbon storage of *P. densiflora*, *Quercus spp*., and mixed forests (199.6, 192.5, and 169.1 MgC ha^{-1}, respectively) [47]. Seo et al. (2016) estimated the total carbon stocks of *Pinus rigida* (139.27tC ha^{-1}) [48]. Although it is difficult to compare the exact values estimated in two studies, a comparison is possible by understanding the overall trend. In 2020, the estimated aboveground and belowground biomass were 112.97 and 22.84 tC ha^{-1}, respectively. This can be compared with the South Korea's statistical data, forest resource assessment (FRA), obtained from the Food and Agriculture Organization (FAO). With respect to the aboveground and belowground biomass, the values from the GCBM were 112.97 and 22.84 tC ha^{-1}, which were lower than the statistical data of 131.69 and 41.88 tC ha^{-1}, respectively. We divided the forest in South Korea into managed forest and protected forest. Since GCBM requires spatial data on forest disturbances, we were able to apply forest management only to managed forest and exclude protected forest from harvest. Therefore, the aboveground biomass value is higher in protected than managed forests, because protected forests were not harvested.

In terms of dead organic matter dynamics, changes in soil C and litter C stocks are well within the measurement uncertainty of soil and litter carbon pools in forest ecosystems. On the other hand, a large reduction in deadwood carbon pools may be the consequence of the initialization of deadwood pools in the model run. Future research should focus on alternative assumptions about the initialization of deadwood pools, specifically the amount of deadwood and litter carbon present at the time when the large-scale afforestation program in South Korea was initiated. Moreover, in the early decades after afforestation, residential firewood collection in many forests was an ongoing process that would have reduced deadwood pools. Firewood collection is currently not represented during model initialization. In recent years, firewood collection was greatly reduced and eliminated, allowing for increases in deadwood pools. Uncertainty in the initial values and subsequent dynamics of the deadwood carbon pools also affects the overall conclusions of this study. Total ecosystem C stocks in aboveground and belowground biomass and all dead organic matter pools decreases by 5.3% from 2010 to 2050. Excluding the deadwood carbon pool estimates, remaining ecosystem C stocks increase by 1.4% from 2010 to 2050.

In none of these analyses have we included carbon stored in harvested wood products derived from timber harvesting or the climate mitigation benefits of the use of such wood for products or energy. In the context of land-based climate mitigation strategies, sustainable forest management plays an important role by continuously removing carbon dioxide from the atmosphere, storing some of it in forest ecosystems, and some in harvested wood products, with other biomass carbon contributing to the reduction in emissions associated with the substitution of emission-intensive materials (e.g., steel and concrete) and fossil fuels [30,49,50]. Through the large-scale afforestation efforts of South Korea over the past decades, the forest area has been greatly increased putting into place sustainably managed forests that over the period 2010 to 2050 contributed to the forest products' sector 204.9 Mt C of which 141.0 Mt were obtained through clear-cut harvest and 63.9 Mt C were obtained through thinning. Future research should quantify the long-term C storage in harvested wood products derived from wood harvested in South Korea and the emission reduction benefits from the use of wood products to substitute other emission-intensive materials and fossil fuels.

In this study, the results indicated a decrease in the rate of growth of both the aboveground and belowground biomass; this finding could be linked to a decrease in the forest sequestration capacity from forest age as well as the changes in growth rates due to the climate responses [51,52]. In addition, the activity of microorganisms in the soil may be attributed to the climate-related changes in the regional precipitation and humidity [53,54]. However, in terms of the NPP, the difference in the value may be large depending on the climate change and environmental factors that influence the climate sensitive growth curves that we have implemented [37]. The NPP calculated in this study was higher than that reported in previous studies (4.30–6.70 tC ha^{-1} [55,56], and 7.99 $\pm$ 0.62 tC ha^{-1} in 2000s [57]); the values of NPP differed depending on whether the tree was a conifer or broadleaf. In this study, broadleaf forests exhibit a higher mean NPP than conifer forests, which is similar to the results of other studies [58,59]. Additionally, the differences in the NPP were observed among several species; e.g., pine and larch [59,60]. For each species, we noted the differences in the physiological characteristics and environmental conditions, such as photosynthetic characteristics and the growth rate, that affect the NPP [61]. In addition, previous studies used different models such as the VISIT (a process-based terrestrial ecosystem model) and the BioGeoChemistry Management Model (BGC-MAN), which are generally used to estimate carbon fluxes in the atmosphere [57,59,60]. The model results portrayed that the value of NPP from previous studies using VISIT and BGC-MAN was slightly smaller than the value of NPP from the GCBM. This is because VISIT and BGC-MAN estimated NPP by considering the forest cover and not the tree species in South Korea; the results were generalized based on point data [57,59,60]. Therefore, a direct comparison of the results was not applicable. The results from this study were also compared with the MODIS NPP from 2020, and a positive relationship between the two was observed. The results were within the range of values representing MODIS NPP, portraying an overall positive correlation. These findings suggest a notable linear correlation between GCBM and MODIS NPP, as indicated by the relatively strong positive correlation coefficient (0.5849). The low p value shows that the observed relationship is unlikely to be due to random chance. Furthermore, slope (0.716) and intercept (2.695) show the direction of this relationship. Lastly, the standard error of the regression coefficient estimates is approximately 0.039. In summary, these results indicate a statistically significant positive linear correlation between GCBM and MODIS NPP.

The NBP portrayed negative values in the early years of model operation, indicating that the forest carbon stocks were reduced, largely as a result of harvest and thinning. Some of this carbon will be stored in harvested wood products, the remainder will have been emitted to the atmosphere. Therefore, sustainable and appropriate forest management is the key to mitigating the reduction in carbon sequestration and positive carbon flux, which is necessary to ultimately combat climate change [62].

The aboveground and belowground biomass and the carbon fluxes of five main tree species in South Korea were identified in the present study. Our findings notably support the model's potential for applications to other regions. In addition, these results detail the nationally determined contributions through forest management.

In this study, we used the RCP 8.5 scenario. In accordance with the 6th IPCC report, the shared socioeconomic pathway (SSP) scenarios consider radiative forcing intensity, along with economic and technology developments, welfare, resources, and ecosystem factors. Identifying changes in forest growth resulting from the implementation of SSP scenarios in the future is necessary. Finally, the model was applied to post-harvest stands assuming the same tree species composition as in the pre-harvest stands; however, this approach does not account for the species used in reforestation as a response to climate change.

Therefore, to develop a model more suitable for South Korea, future studies should evaluate the fine roots, soil, and reforestation characteristics (after harvesting), as well as multiple climate scenarios.

5. Conclusions

In this study, we used the GCBM module to analyze the forests in South Korea; the results were displayed on a spatiotemporal map to portray the forests' distribution, carbon stocks, and stock changes. The Canadian forest model was used successfully to estimate the aboveground and belowground biomass and carbon fluxes in the forests in South Korea. This success corroborates the applicability of GCBM as an operable tool for estimating and identifying forest carbon budgets in other regions. Negative NBP values and a decrease in the rate of increase in the total biomass can be attributed to high harvest rates and the imbalance in the age-class structure. It means that it is crucial to emphasize that forest management should consider the local environment and ecology to avoid excessive intervention. Sustainable forest management is necessary to overcome the current imbalance in the age-class structure following intensive afforestation efforts and to achieve carbon neutrality by reducing carbon emissions and by protecting and maintaining carbon stocks. Although the NPP values appeared to be higher than the estimates obtained in previous studies, they differed depending on the forest type, and the results were verified using the MODIS-derived estimates. In this study, we utilized the GCBM framework to identify the results of the aboveground and belowground biomass and the NPP, NEP, Rh, and NBP values for the forests in South Korea. Our findings can support decision-makers and stakeholders for the planning, development, and implementation of effective forest management strategies. Furthermore, we simulated biomass and the carbon flow according to forest management practices, and our findings can contribute to achieving carbon neutrality in South Korea through enhancing carbon storage and absorption capabilities.

Further studies are needed to improve the initialization of dead organic matter pools, given the large-scale reforestation efforts in recent decades that have established South Korea's forests on predominantly non-forest sites.

Author Contributions: Conceptualization, Y.K., C.S., W.A.K., J.M. and W.-K.L.; data curation, Y.K., M.H., J.S. and J.M.; model runs, Y.K. and M.F.; formal analysis, Y.K.; methodology, Y.K., W.A.K., M.K. and W.-K.L.; supervision, W.-K.L.; validation and visualization, Y.K., M.F. and W.A.K.; writing—original draft, Y.K. and C.S.; writing—review and editing, Y.K. and W.A.K.; project administration, W.-K.L.; funding acquisition, W.-K.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported by the OJEong Resilience Institute (OJERI) at Korea University under the Basic Science Research Program through the National Research Foundation of Korea (NRF) (NRF-2021R1A6A1A10045235), the 'R&D Program for Forest Science Technology (Project No. FTIS2022464A00-2324-0201)' provided by the Korea Forest Service (Korea Forestry Promotion Institute), and Korea Environment Industry & Technology Institute (KEITI) through 'Climate Change R&D Project for New Climate Regime (Project No. RS-2022-KE002294)', funded by the Korea Ministry of Environment (MOE).

Data Availability Statement: The original contributions presented in this study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to thank the collaborative research between Korea university and Canadian Forest Service Carbon Accounting Team.

Conflicts of Interest: The authors declare no conflicts of interest.

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