Estimating the carbon dynamics of South Korean forests from 1954 to 2012

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Abstract

Forests play an important role in the global carbon (C) cycle, and the South Korean forests also contribute to this global C cycle. While the South Korean forest ecosystem was almost completely destroyed by exploitation and the Korean War, it has successfully recovered because of national-scale reforestation programs since 1973. There have been several studies on the estimation of C stocks and balances over the past decades in the South Korean forests. However, a retrospective long-term study including biomass and dead organic matter C and validating dead organic matter C is still lacking. Accordingly, we estimated the C stocks and their changes of both biomass and dead organic matter C during 1954–2012 using a process-based model, the Korean Forest Soil Carbon model, and the 5th South Korean national forest inventory (NFI) report. Validation processes were also conducted based on the 5th NFI and statistical data. Simulation results showed that the biomass C stocks increased from 36.4 to 440.4 Tg C at a rate of 7.0 Tg C yr^{-1} during 1954–2012. The dead organic matter C stocks increased from 386.0 to 463.1 Tg C at a rate of 1.3 Tg C yr^{-1} during the same period. The estimates of biomass and dead organic matter C stocks agreed well with observed C stock data. The annual net biome production (NBP) during 1954–2012 was 141.3 g C m^{-2} yr^{-1}, which increased from -8.8 in 1955 to 436.6 g C m^{-2} yr^{-1} in 2012. Because of the small forested area, the South Korean forests had a comparatively lower contribution to the annual C sequestration by global forests. In contrast, because of the extensive reforestation programs, the NBP of South Korean forests was much higher than those of other countries. Our results could provide the forest C dynamics in South Korean forests before and after the onset of reforestation programs.

1 Introduction

Forests contain much carbon (C) in vegetation and soils, and play an important role in the global C cycle (Dixon et al., 1994; Pan et al., 2011). The Kyoto Protocol encouraged the promotion of sustainable forest management practices and the contribution of forests to global C sequestration has been recognized (IPCC, 2003; UNFCCC, 1997). Consequently, studies on the C budget of forest biomass and dead organic matter have been conducted to understand temporal forest C stocks and balances (Bellassen et al., 2011; Kurz and Apps, 1999; Luyssaert et al., 2010; Pan et al., 2011; Piao et al., 2012; Stinson et al., 2011; Wang et al., 2007). Furthermore, to display the net C changes in forest ecosystems, the net biome production (NBP), defined as net ecosystem production (NEP) minus disturbance loss and leaching, was also estimated (Luyssaert et al., 2010; Stinson et al., 2011).

To estimate the C stock and balance in forests, inventory-based estimation has been generally used because it could estimate C stock and net C balance directly. However, it has some limitations such as: not giving annual C budget, not necessarily taking into account dead organic matter C, and limitation on extrapolation due to high spatial variability (Fang et al., 2014; Piao et al., 2012; Wang et al., 2007). Recently, process-based modeling has been used for long-term simulation to provide the annual C budget of forests and to estimate C budget beyond the investigated area (Bellassen et al., 2011; Stinson et al., 2011; Wang et al., 2007).

The C dynamics of South Korean forests have varied largely. South Korean forests experienced severe deforestation over the 35 years of Japanese colonization (1910–1945) and the subsequent Korean War (1950–1953) (Kang, 1998; Tak and Wood, 2007). Since 1973, following these periods of serious deforestation, the South Korean government implemented national plantation programs for the recovery of forests. After about 30 years of effort, South

Korean forests have successfully recovered and the stocking volume had increased from 8.2 in 1954 to 125.6 m^3 ha^{-1} in 2010 (Korea Forest Service, 2000, 2011).

Studies on the C stocks and balances over the past decades in South Korean forests have been conducted for many years. Based on the national forest inventory (NFI) and statistical data, the biomass C stocks of South Korean forests over the past decades were estimated (Choi and Chang, 2004; Fang et al., 2014; Li et al., 2010). While this approach could determine the net C change in biomass, dead organic matter C stocks were excluded due to the lack of observed dead organic matter C stock data. Using model, the C balances of South Korean forests were estimated (Piao et al., 2012; Yoo et al., 2013). However, there are some limitations such as: (1) relatively short simulation period, not more than two decades, (2) estimating C fluxes, not stocks, and (3) insufficient validation of dead organic matter C.

The primary objective of this study was to estimate the C stocks and their changes in South Korean forests, including biomass and dead organic matter during the post-war period (1954–2012), using the Korean Forest Soil Carbon model (KFSC; Yi et al., 2013) and the 5th South Korean NFI as input data. To estimate the effect of reforestation programs, we provided the annual C balance and NBP of South Korean forests before and after the onset of those programs. The estimated biomass and dead organic matter C stocks were validated by comparing with the observed data in 5th NFI and statistical data. Furthermore, we compared the annual C balance and NBP of South Korean forests with those of major countries and global forests.

2 Materials and methods

2.1 The 5th South Korean NFI data

We used the 5th South Korean NFI data to prepare input data for the KFSC model and to validate the estimated dead organic matter C stocks. The latest 5th NFI applied systematic cluster sampling for surveys at intervals of 4 km along the longitude and latitude (1 or 2 km for small forested areas), and obtained data from approximately 4000 plots during 2006–2010 (Korea Forest Research Institute, 2011). It provides information about forest type, species composition, diameter at breast height (DBH), age-class, stand density, topographical factors, observed C stocks of pools, and other data of each sampling plot. Each simulation unit represents a forest grid cell of 1 km × 1 km (43 cells), 2 km × 2 km (241 cells), or 4 km × 4 km (3606 cells). To upscale the plot-level data to the forest grid cells, the plot-level data were extrapolated and averaged to each forest grid cell. As denuded and bamboo forests were excluded in the simulation, 3890 cells (5870300 ha) were selected from the entire South Korean forests.

2.2 The KFSC model

2.2.1 Model description

The KFSC model is an empirical and dynamic soil C model that consists of the five biomass compartments (stem, branch, foliage, coarse root, and fine root), five primary dead organic matter compartments (aboveground woody debris from stem, aboveground woody debris from branch , aboveground litter, belowground woody debris, and belowground litter), and three secondary dead organic matter compartments (aboveground humus, belowground humus, and soil organic C) classified according to the degree of decomposition and kinetics (Fig. 1). This model simulates forest C processes as follows: atmospheric C is converted to biomass, biomass becomes input to primary dead organic matter pools as litter and woody debris, litter and woody debris are decayed to humus (aboveground and belowground humus), humus is decayed to soil organic C, and soil organic C is decayed to atmospheric C (Yi et al., 2013). Harvest is considered to be the only disturbance in the model. The performances of the KFSC model are described and validated in Park et al. (2013) and Yi et al. (2013). We parameterized the model for three needleleaf species (*Pinus densiflora*, *P. rigida*, and *Larix kaempferi*) and three broadleaf species (*Quercus variabilis*, *Q. mongolica*, and *Q. accutissima*).

To simulate the biomass C stocks, we followed the processes as follows: estimation of the growth of stemwood volume, conversion of stemwood volume to C stocks, and estimation of C stocks of other biomass compartments (branch, foliage, coarse root, and fine root). First, based on a yield table (Korea Forest Service, 2009), the growth functions of stemwood volume for each species and site index were parameterized using the Gompertz function (Table A1). An observed stemwood volume was assumed to follow the nearest stemwood growth function and site index. To calibrate the difference between the estimated stemwood volume from a selected growth function and the observed stemwood volume in the 5th NFI data for each stand, we multiplied the growth modifier used in Yi et al. (2013) with a selected growth function. The following equation describes the growth modifier used:

$$Growth\ \ \mathrm{mod}ifier = \frac{Vol_{obs}}{Vol_{est}} \tag{1}$$

where, Vol_{obs} is the observed volume of each stand in the 5th NFI data and Vol_{est} is the estimated volume of each stand from the estimated growth model. Second, by multiplying the estimated volume with wood density (0.474, 0.508, 0.452, 0.720, 0.728, and 0.707 g cm^{-3} for *P. densiflora*, *P. rigida*, *L. kaempferi*, *Q. variabilis*, *Q. mongolica,* and *Q. accutissima,* respectively; Korea Forest Research Institute, 2010) and C concentration (50%), the C stocks of stemwood were estimated. Third, the other compartments of biomass were calculated by multiplying the C stocks of stemwood with biomass conversion factors (BCFs), which describe the ratio of branch, foliage, and coarse root to stemwood and are shown in Table B1. Since the growth of fine root has been poorly studied for these species in Korea, Yi et al. (2013) used the ratio of fine root to foliage described by Vanninen et al. (1996) as shown in Eq. (2):

$$Fine\ \ root / Foliage\ \ ratio = 0.0016 x\, S\tan d\ \ age + 0.1012 \quad (r^2 = 0.67) \tag{2}$$

For the needleleaf species, this ratio was multiplied with the C stocks of the foliage to estimate the C stocks of fine root. Since the growth function of fine root in South Korean forests was unavailable, the static ratio of fine root to coarse root (11:89; Millikin and Bledsoe, 1999) was used to estimate C stocks of fine root for broadleaf species. By multiplying this ratio with the estimated C stocks of the coarse root, we estimated C stocks of the fine root. The dead organic matter C dynamics are the same as described by Yi et al. (2013); the detailed description of the dead organic matter C dynamics in the KFSC model is given in Yi et al. (2013).

2.2.2 Input data and parameters

The required input data consisted of representative species, site index, growth modifier, forest age, and mean air temperature of each grid cell. The representative species was determined as the tree species occupying the largest basal area (m^2) in each sampling plot. We used the forest age of each plot from the 5th NFI tree-ring data. For the plots without tree-ring data, the forest age was assumed to be 5, 15, 25, 35, 45, and 55 for age class I, II, III, IV, V, and VI, respectively, as reported in the 5th NFI data. The mean air temperature of each grid cell was the average of the observed mean annual temperature from 1971 to 2000 from 75 weather stations over South Korea. It was interpolated with a 0.01° (~1 km) grid size by the Kriging method, taking into consideration of the temperature lapse rate by elevation (Choi et al., 2011;

Lee et al., 2007). The turnover rates of biomass C pools and decay rates of dead organic matter C pools were required to simulate forest C processes (Table 1). The decay rate of aboveground litter and turnover rates of branch and foliage were estimated by 2 years of field work data from 54 plots throughout South Korea (Lee et al., unpublished). The others were cited from other studies (Kim, 2002; Kurz et al., 1992; Liski et al., 2005; Noh, 2011; Park et al., 2006; Park et al., 2010; Yoon et al., 2011). A detailed description of the modeling processes is given in Yi et al. (2013).

2.3 Simulation

2.3.1 Model initialization and simulation

The method of reconstructing the forest age distribution is important for accurate simulation (Bellassen et al., 2011; Wang et al., 2007). Due to the lack of age information over the past decades, the forest C dynamics of each grid cell in South Korea during 1954–2012 were simulated by two scenarios, the spin-up scenario and the forest recovery scenario, reconstructing the forest age of each grid cell based on the recent age information in the 5th NFI. The spin-up scenario was applied to some stable stands during the simulation period and the recovery scenario was applied to most stands that experienced severe deforestation due to exploitation and war.

The 265 forest grid cells simulated by the spin-up scenario were initialized by a spin-up process until the quasi-steady-state, such that the difference in the C stocks of soil organic C between two successive iterations was < 1% (Fig. 2a). After that, the model simulated forest C processes by forest age in 2012. In forest recovery scenario, 3625 grid cells that experienced severe deforestation were also initialized by the spin-up process, while all dead organic matter C pools, except soil organic C, were assumed to be zero in 1954, taking into consideration of land degradation caused by severe deforestation (Fig. 2b). Then, regeneration was assumed to be suppressed until the recent regeneration. Soil organic C continued to decay slowly until the vegetation recovered sufficiently. As the vegetation recovered, biomass and dead organic matter input started increasing. The forest grid cells simulated by the spin-up scenario were determined by the following criteria: (1) the stands regenerated before 1954 (over 60 years old), or (2) a stand located at the highest elevation for each forest age and province (Gangwon, Chungbuk, Chungnam, Chonnam, and Gyungbuk) from which the highest volume was harvested during 1970–2010 (Korea Forest Service, 1974, 1988, 2000, 2005, 2010, 2012). These criteria assumed that stands that were old and located at high altitudes were not disturbed by exploitation and war. The other stands were assumed to had been severely destroyed, and were thus simulated by the forest recovery scenario.

2.3.2 Calculation of forest C stock, annual C balance, and NBP

To calculate the C stocks of the biomass and dead organic matter pools in South Korean forests, we applied Eq. (3):

$$C \quad stock \quad (Mg \quad C) = \sum_{k=1}^{3890} mean \quad C \quad density_k \quad (\quad Mg \quad C \quad ha^{-1}) \quad A_k(ha) \qquad (3)$$

where, k is the identification number of each sampling plot, mean C density is the simulated biomass or dead organic matter C per hectare, and A is the size of the grid cell, including each sampling plot.

The annual C balance and NBP were calculated to estimate the change in C stocks in South Korean forests. The annual C balance (Tg C yr^{-1}) was defined as the annual change in C stocks in the entire South Korean forest ecosystem. In contrast, the NBP (g C m^{-2} yr^{-1}) is generally defined as the net primary production minus the heterotrophic respiration and the disturbances (fire, harvest, pests, land-use change, and other disturbances), and represents an average of the net ecosystem C balance over space and time (Chapin et al., 2006). In South Korea, because of the extensive management of insect populations and negligible damage by forest fire (< 5% of annually harvested stemwood volume), the disturbances such as insects and fires could be ignored (Korea Forest Service, 1985, 1997, 2002, 2012). As 80-year-interval clear-cut was assumed to be the only disturbance and land-use change was not considered in this study, this model could simulate the net change of C stocks in the forest biome. To calculate the NBP of South Korean forests during certain period, the change in C stocks in South Korean forests were divided by the total simulation area (5870300 ha) and the corresponding period (yr).

2.3.3 Model validation

We validated the estimated biomass and dead organic matter C stocks by comparing the estimated values to observed values from the statistical data and the 5th NFI data. For biomass, the estimates of stocking volume on a national scale during 1954–2010 were compared to the Statistical Yearbook of Forestry (Korea Forest Service, 2000, 2011) to indirectly validate the estimated biomass C stocks. Since observed data for dead organic matter C from the past does not exist, the dead organic matter C stocks in the 5th NFI data were used to validate the estimates. The estimates of C stocks in soil layers (belowground humus + soil organic C) were multiplied by 0.6 (Lee et al., 2009) for comparison with the observed data, which was sampled at 0–30 cm depths. The estimates of other dead organic matter values, excluding dead woods (aboveground woody debris from stem, belowground woody debris, and belowground liter; data is unavailable in the 5th NFI), were added to those of soil C for validation. The performance of the model in predicting dead organic matter C stocks was analyzed using the root mean square error (RMSE).

3 Results and discussion

3.1 The C stocks and annual C balances of biomass

An increase in C stock of biomass in South Korean forests was observed with the data increasing from 36.4 Tg C in 1954 to 440.4 Tg C in 2012 (Fig. 3). The annual C balance from biomass was 0.15 Tg C yr^{-1} before the onset of reforestation programs (1954–1973). The annual C balance of biomass was higher at a rate of 10.3 Tg C yr^{-1} after the onset of those programs (1974–2012). Averaged over the entire 1954–2012 period, the annual C balance of biomass was 7.0 Tg C yr^{-1}.

The estimated stocking volumes simulated by the KFSC model were compared with observed stemwood volume data to indirectly validate the estimated biomass C stocks. The time series of estimated stocking volume showed a similar trend to that of observed stocking volumes on a national scale ($r^2 = 0.98$; Fig. 4). According to Statistical Yearbook of Forestry (Korea Forest Service, 2000, 2011), the stocking volume in South Korean forests increased from 51.8 to 800.0 Mm^3 between 1954 and 2010. The simulation result showed that it increased from 78.4 to 798.0 Mm^3 during that period. This implied the successful reconstruction of age distribution on a national scale, while it was still uncertain on a stand scale.

Our finding was consistent with other studies showing a large increase in biomass C stocks after the onset of reforestation programs. However, the mean biomass C density, biomass C stock, and annual C balance in this study were estimated higher than other studies (Table 2). There were two possible reasons explaining these differences. As shown in Fig. 4, the stocking volume simulated by the model in recent years was an overestimate compared to the observed stocking volume. This caused the higher estimates of recent mean biomass C density and stocks, and annual C balance. The other possible reason was a difference in the methods of biomass C stock estimation. We estimated the biomass C stocks with species-specific growth functions and BCFs. In contrast, Li et al. (2010) and Choi and Chang (2004) estimated the biomass C stocks by multiplying stemwood volume with forest type-specific (coniferous, deciduous, and mixed) and constant biomass expansion factors (BEFs). Variable BEFs could overestimate biomass C of a young forest compared to constant BEFs (Guo et al., 2010). As South Korean forests are relatively young, the estimated biomass C stocks of South Korean forests with BCFs could be higher than the estimates with constant BEFs. As the ratio of each compartment in biomass varied with stand age, our estimates were considered more realistic.

3.2 The C stocks and annual C balances of dead organic matter

An increase in the C stock of dead organic matter in South Korean forests was also observed, with the data increasing from 386.0 Tg C in 1954 to 463.1 Tg C in 2012, respectively (Fig. 3). Before the onset of reforestation programs, the C stock of dead organic matter was C source releasing C at a rate of 0.7 Tg C yr^{-1}. As the forest vegetation had been almost denuded, the decomposition of the dead organic matter C exceeded the dead organic matter input during that period. Until around 1980, the dead organic matter C stocks were a C source. After the onset of reforestation programs and the recovery of litter input, the C stocks of dead organic matter changed from a C source to a C sink sequestering C at a rate of 2.3 Tg C yr^{-1}. Averaged over the entire 1954–2012 period, the annual C balance of dead organic matter was 1.3 Tg C yr^{-1}, which was approximately 20% of that of biomass (7.0 Tg C yr^{-1}).

The model estimates and NFI inventories for dead organic matter C stocks were in partial agreement (Fig. 5). The RMSE of the estimates were 26.9 and 49.2 Mg C ha^{-1} for needleleaf species and broadleaf species, respectively, on a regional scale. The underestimation of dead organic matter C stocks could be partially explained by the mean air temperature used as input data. As recent air temperature has been higher than that of past centuries (Aizebeokhai, 2009), the decay rates of dead organic matter C pools might be overestimated for initialization process. Accordingly, the initial dead organic matter C stocks were probably underestimated and uncertainties in estimating dead organic matter C stocks occurred (Peltoniemi et al., 2006; Wutzler and Reichstein, 2007).

Soil type also could affect the decay rate of humus, ultimately the dead organic matter C dynamics. Because of difference in dominant soil type, the dead organic matter C stocks of Jeju province might be especially highly underestimated (Fig. 5). Separated from the mainland provinces, Jeju province is a volcanic island and the representative soil type of Jeju is Andisol (Ahn and Chon, 2010). Andisol soils contain more C stocks than other soil types for two reasons: the properties of soil organic matter derived from charred plant materials (Shindo et al., 2004) and low decay rates of soil organic matter caused by the strong combination with allophane (Calabi-Floody et al., 2011; Theng and Yuan, 2008). As the input of these materials by volcanic activities and the low decay rates were not considered in the KFSC model, the dead organic matter C stocks in Jeju province may be underestimated. Excluding Jeju province, the RMSE improved to 12.8 and 21.9 Mg C ha^{-1} in needleleaf and broadleaf species, respectively. As Jeju province accounts for only 1.8% of South Korean forests, the estimated C stocks in South Korean forests might be reliable.

3.3 The total C stocks, annual C balances, and NBPs of South Korean forests

Increasing total C stocks were observed. The C stocks in South Korean forests increased from 422.4 Tg C in 1954 to 903.5 Tg C in 2012. As the C emission from dead organic matter C stocks overwhelmed C sequestration by biomass C stocks in the first two decades (1954–1973), South Korean forests were a C source and released C at a rate of 0.5 Tg C yr^{-1} during the period. From 1974, South Korean forests changed from C source to C sink sequestering C at a rate of 12.6 Tg C yr^{-1}. Averaged over the entire 1954–2012 period, the annual C balance was 8.3 Tg C yr^{-1}. Compared to the national fossil fuel-based C emissions data during 1954–2008 (Boden et al., 2012), South Korean forests annually offset 13.4% of the South Korean fossil fuel C emissions during that period.

The time series of NBP increased over the simulation period and the change in NBP showed an upward trend (Fig. 6). The NBP during 1954–2012 was 141.3 g C m^{-2} yr^{-1} and that in 1955 and 2012 were estimated to be -8.8 and 436.6 g C m^{-2} yr^{-1}, respectively. The onset of reforestation programs influenced the mean NBP and the averaged NBP was -8.7 and 214.4 g C m^{-2} yr^{-1}, during 1954–1973 and 1974–2012, respectively. These high NBP values of South Korean forests were attributed to rapid increment of C stocks in biomass. As two-thirds of the South Korean forests are less than 40 years old (Korea Forest Service, 2013), the C stocks in biomass could rapidly increase. For example, the annual growth of biomass C stocks in the forests that are 20–40 years old ranged from 144.0 to 401.4 g C m^{-2} yr^{-1} for *P. densiflora* and from 174.5 to 588.3 g C m^{-2} yr^{-1} for *Q. variabilis*, based on the yield tables and BCFs. Considering that the dead organic matter C input from biomass also contributed to the NBP, those values could explain the high NBP of South Korean forests. In addition, the empirical study conducted in the mature South Korean forest also indicated a high rate of C sequestration by forests (418 g C m^{-2} yr^{-1}; Noh et al., 2013).

As the forest vegetation recovered, the contribution of biomass to NBP increased over the simulation period and became higher than that of dead organic matter over that period. The contribution of biomass to NBP increased from 22.9 to 76.1% during 1954–2012, and dead organic matter accounted for the remainder. Although the C stock of dead organic matter was also a C sink, that of biomass became more important C sink recently in South Korean forests.

We compared the annual C balance and NBP of South Korean forests with those of forests from other countries and global forests (Table 3). Global forests annually sequestered about 3.8 Pg C yr^{-1} (Pan et al., 2011) and South Korean forests accounted for less than 1% of that (8.3 Tg C yr^{-1}). However, the NBP of South Korean forests exceeded that of foreign forests, and the global average significantly. The NBP of global forests was around 100 g C m^{-2} yr^{-1} during 1990–2007 and that of South Korean forests during 1990–2007 was 365.2 g C m^{-2} yr^{-1}. The NBP of other major countries was also lower than that of South Korean forests. This large difference in NBP might be attributed to extensive reforestation program in a national scale.

3.4 Uncertainties

Although we estimated the C stocks and their changes of South Korean forests including biomass and dead organic matter C, there are still uncertainties in the estimation. A site index, which is important input data for determining the productivity of a forest, seemed to be responsible for the uncertainty. In the KFSC model, the site index is determined by the forest age and observed stemwood volume, based on the yield table. While, in other process-based models, physiological processes were coupled to simulate the growth of biomass and various input data (e.g. temperature, CO_2 concentration, solar radiation, or precipitation) are required (Chen et al., 2000; Ito et al., 2005; Krinner et al., 2005; Sitch et al., 2003). Using yield tables for a regional scale (Kurz et al., 2009) or quantifying the site index based on environmental factors (Nothdurft et al., 2012; Wang and Klinka, 1996) will help constrain the uncertainties associated with estimating a site index. To enable more precise and comprehensive assessment of South Korean forest C cycles, some important influences on C balance, such as CO_2 fertilization (Bellassen et al., 2011; Luyssaert et al., 2010), N deposition (Luyssaert et al., 2010), leaching (Luyssaert et al., 2010; Piao et al., 2012), forest area changes (Liski et al., 2006; Nabuurs et al., 2003), and management and other disturbances (Jandl et al., 2007; Kurz et al., 2009; Liu et al., 2002; Luyssaert et al., 2010; Zhou et al., 2013) need to be considered.

4 Conclusions

Using a model, we estimated the C dynamics of South Korean forests between 1954 and 2012. During this period, the total C stocks of South Korean forests increased from 422.4 to 903.5 Tg C. South Korean forests changed from a C source to a C sink because of the extensive reforestation. The average annual C balance during this period was 8.3 Tg C yr^{-1} and the NBP was 141.3 g C m^{-2} yr^{-1}. From 1954–2008, 13.4% of the fossil fuel C emission from Korea was offset by C accumulation in forest ecosystems. Because of the small forested area, South Korean forests had a comparatively lower contribution to the total C sequestration by global forests. However, the NBP of South Korean forests was much higher than those of other countries. The high NBP is a result of the implementation of extensive reforestation programs after the severe deforestation; thus, extensive reforestation activities after severe deforestation events would contribute to C sequestration for global climate change mitigation.

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Table 1. Standard input parameter values for model simulation. The other parameters are the same as described by Yi et al. (2013).

Parameters	Values	Notes
Turnover rate (yr^{-1})		
Stem	0.002^{abc}	Noh (2011)
	0.0045^{def}	Kurz et al. (1992)
Branch	0.061^{abc}	Lee et al. (unpublished)
	0.057^{def}	Lee et al. (unpublished)
Foliage	0.385^{ab}	Lee et al. (unpublished)
	0.934^{cdef}	Lee et al. (unpublished)
Coarse root	0.02	Kurz et al. (1992)
Fine root	1.23^{abc}	Park et al. (2010)
	0.695^{e}	Park et al. (2006)
	1.195^{df}	Park et al. (2006)
Decay constant (yr^{-1})		
AWDS and AWDB	0.137^{abc}	Noh (2011)
	0.058^{def}	Yoon et al. (2011)
ALT	0.317^{abc}	Lee et al. (unpublished)
	0.402^{def}	Lee et al. (unpublished)
BWD	0.137^{abc}	Assumed to be equal to the decay constant of AWD
	0.058^{def}	Assumed to be equal to the decay constant of AWD
BLT	0.462	Kim (2002)
AHUM and BHUM	0.012^{abc}	Liski et al. (2005): standard value for fast HUM pool
	0.02^{def}	Liski et al. (2005): maximum value for fast HUM pool
SOC	0.0012^{abc}	Liski et al. (2005): standard value for fast HUM pool
	0.0017^{def}	Liski et al. (2005): maximum value for fast HUM pool

(a: *Pinus densiflora*, b: *P. rigida*, c: *Larix kaempferi*, d: *Quercus variabilis*, e: *Q. mongolica*, f: *Q. accutissima*)

Table 2. Comparison of the biomass carbon (C) density, biomass C stocks, and annual C balance of South Korean forests in this study with those in two previous studies.

Category	Year or period	Estimate	Reference
Mean C density	1954	4.3	Li et al. (2010)
(Mg C ha^{-1})	1954	6.2	This study
	2001	34.4	Choi and Chang (2004)
	2001	39.7	This study
Biomass C stock	1954	20.6	Li et al. (2010)
(Tg C)	1954	36.4	This study
	2001	221.0	Choi and Chang (2004)
	2001	233.3	This study
	2007	239.9	Li et al. (2010)
	2007	341.1	This study
Annual C balance	1993–2007	9.1	Li et al. (2010)
(Tg C yr^{-1})	1993–2007	15.5	This study
	1997–2001	9.6	Choi and Chang (2004)
	1997–2001	15.6	This study

Table 3. The estimates of annual carbon (C) balance and net biome production (NBP) compared to those in past studies.

Region	Period	Annual C balance (Tg C yr^{-1})		NBP (g C m^{-2} yr^{-1})		Reference
		Biomass	dead organic matter	Biomass	dead organic matter	
Canada	1929–1989	14.8	50.7	12.4	36.0	Kurz and Apps (1999)[a]
Europe	1950–1999	49.0	30.0	35.0	21.4	Nabuurs et al. (2003)[b]
	1995–2005	80.0	29.0	53.0	22.0	Luyssaert et al. (2010)
Unites States	1990–1999	118	28	47	11	Pan et al. (2011)[c]
	2000–2007	147	64	58	25	
China	1990–1999	60	68	43	48	
	2000–2007	115	60	77	40	
Global forests	1990–1999	2991	868	76	22	
	2000–2007	2941	887	76	23	
South Korea	1954–2012	7.0	1.3	116.7	22.6	This study

[a] To calculate the NBP, the total change in biomass and dead organic matter stocks with 404 Mha.

[b] To calculate the NBP, the annual C balance was divided by forest area in 1999.

[c] To calculate the NBP, harvested wood product was excluded in C stock change.

Table A1. Parameter estimates of the Gompertz function for stem volume (m^3 ha^{-1}) for six dominant species by site index in Korea.

$Volume(age) = a * \exp(b * \exp(c * age))$

Species	Site index	a	b	c
Pinus densiflora	10	182.8	-7.73	-0.0902
	12	231.5	-8.75	-0.0954
	14	285.6	-9.55	-0.0991
	16	345.0	-10.20	-0.1018
P. rigida	10	221.7	-4.30	-0.0593
	12	268.2	-4.85	-0.0642
	14	322.1	-4.74	-0.0637
	16	378.0	-4.81	-0.0644
	18	436.7	-4.85	-0.0649
Larix kaempferi	16	319.5	-2.78	-0.0423
	18	355.2	-2.79	-0.0439
	20	393.2	-2.77	-0.0450
	22	432.4	-2.75	-0.0461
	24	472.8	-2.73	-0.0470
Quercus variabilis	12	190.3	-3.81	-0.0883
	14	233.6	-3.90	-0.0903
	16	280.8	-3.96	-0.0918
	18	311.5	-4.01	-0.0930
Q. mongolica	12	268.7	-2.83	-0.0422
	14	295.9	-2.76	-0.0436
	16	350.7	-2.83	-0.0440
Q. accutissima	16	378.5	-3.48	-0.0397
	18	411.3	-3.40	-0.0406
	20	444.3	-3.36	-0.0417

Table B1. The biomass conversion factors (BCFs) for each species by site indices. Multiplying BCFs with C stocks of stemwood, C stocks of other compartments were estimated. The estimation method for the parameters is given in Yi et al. (2013).

$BCF(age) = a * age^{b}$

Species	Site index	Compartments					
		Branch		Foliage		Coarse root	
		a	b	a	b	a	b
Pinus densiflora	10	0.3574	-0.1397	0.8357	-0.6735	0.3962	-0.0545
	12	0.3515	-0.1397	0.7772	-0.6746	0.3936	-0.0545
	14	0.3462	-0.1396	0.7203	-0.6730	0.3912	-0.0545
	16	0.3419	-0.1401	0.6811	-0.6754	0.3893	-0.0547
P. rigida	10	3.1964	-0.7503	4.4212	-1.1445	0.9754	-0.1301
	12	2.9530	-0.7532	3.9561	-1.1507	0.9599	-0.1302
	14	2.7372	-0.7544	3.5568	-1.1543	0.9458	-0.1302
	16	2.5654	-0.7564	3.2363	-1.1576	0.9342	-0.1305
	18	2.4138	-0.7577	2.9642	-1.1602	0.9233	-0.1306
Larix kaempferi	16	1.3883	-0.5117	3.4449	-1.205	0.7175	-0.1823
	18	1.3124	-0.5084	3.0006	-1.1902	0.7033	-0.1815
	20	1.2623	-0.5090	2.8055	-1.1961	0.6922	-0.1815
	22	1.2219	-0.5105	2.6327	-1.2003	0.6832	-0.1819
	24	1.1854	-0.5119	2.4794	-1.2041	0.6750	-0.1824
Quercus variabilis	12	0.0458	0.4536	0.0907	-0.2120	0.8268	-0.1060
	14	0.0479	0.4529	0.0889	-0.2110	0.8181	-0.1060
	16	0.0500	0.4523	0.0871	-0.2110	0.8099	-0.1060
	18	0.0516	0.4537	0.0858	-0.2120	0.8039	-0.1060
Q. mongolica	12	0.0376	0.6848	0.1139	-0.1280	2.7366	-0.3750
	14	0.0392	0.6836	0.1130	-0.1280	2.6765	-0.3750
	16	0.0406	0.6835	0.1123	-0.1280	2.6259	-0.3750
Q. accutissima	16	0.0676	0.5064	0.0789	-0.0380	2.0183	-0.4200
	18	0.0659	0.5066	0.0788	-0.0380	1.9708	-0.4200
	20	0.0640	0.5074	0.0786	-0.0380	1.9293	-0.4190

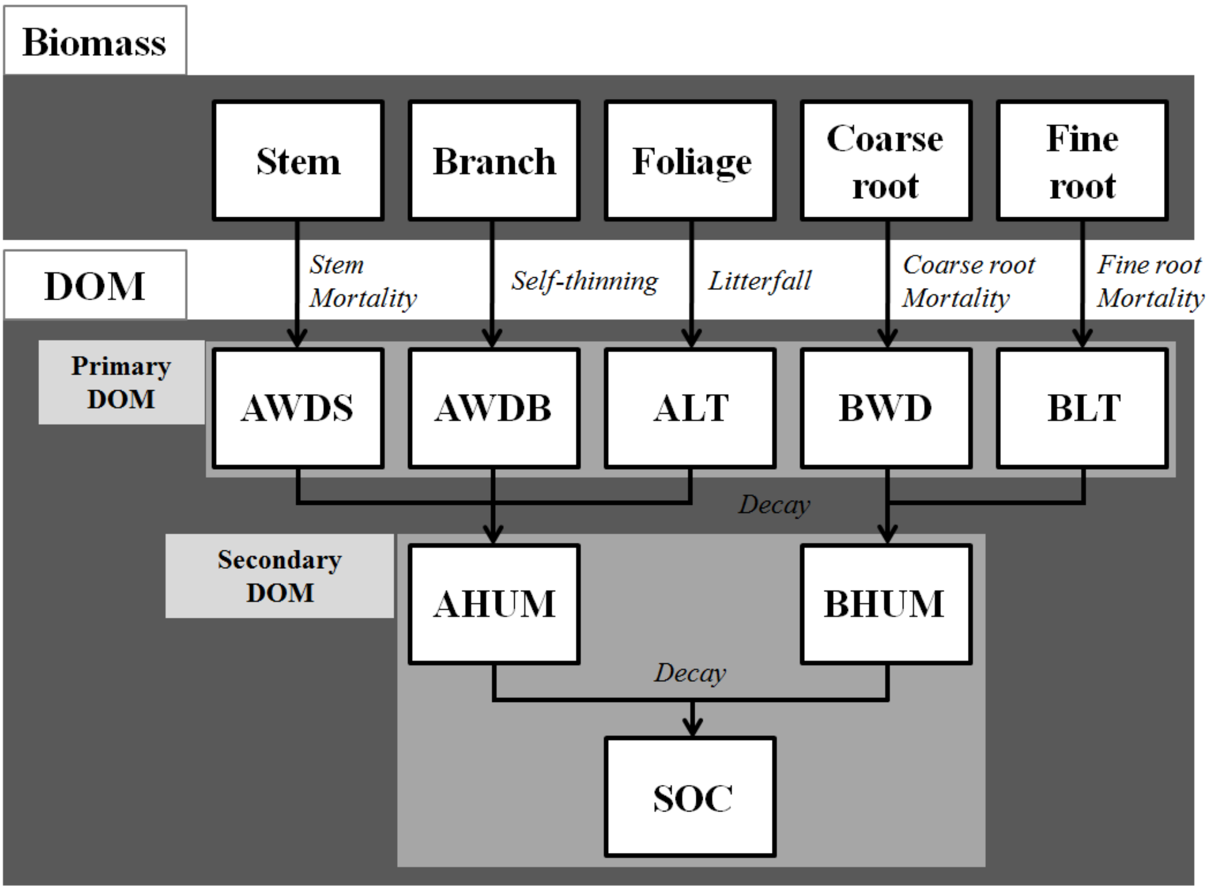

Figure 1. The schematic diagram of the modified forest soil dynamics model (KFSC) used in this study. The carbon pools consist of biomass compartments (stem, branch, foliage, coarse root, and fine root), primary dead organic matter (DOM) compartments (aboveground woody debris from stem (AWDS), aboveground woody debris from branch (AWDB), aboveground litter (ALT), belowground woody debris (BWD), and belowground litter (BLT)), and secondary DOM compartments (aboveground humus (AHUM), belowground humus (BHUM), and soil organic carbon (SOC)). The carbon flows are shown as solid arrows. In Yi et al. (2013), the AWDS and AWDB, as well as the AHUM and BHUM were united as aboveground woody debris (AWD) and humus (HUM), respectively.

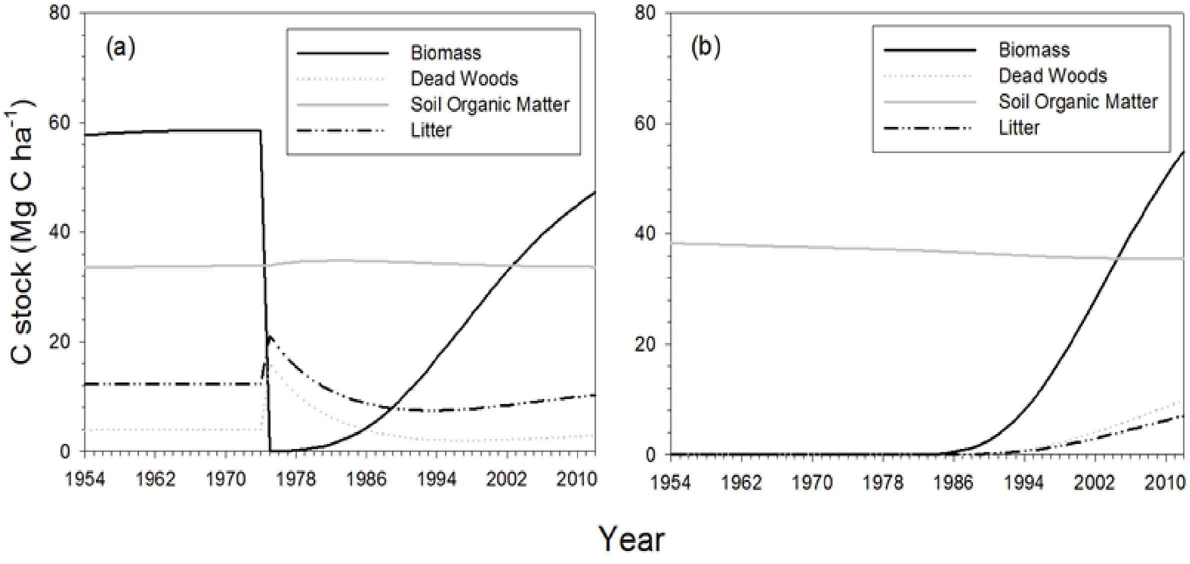

Figure 2. Examples showing the carbon dynamics (biomass, dead woods, soil organic matter, and litter) simulation for each scenario; spin-up scenario (a) and forest recovery scenario (b). The spin-up scenario simulates carbon dynamics under periodic harvesting. The forest recovery scenario simulates carbon dynamics from deforestation. In this scenario, forest carbon stocks start increasing as the forest stand regenerates.

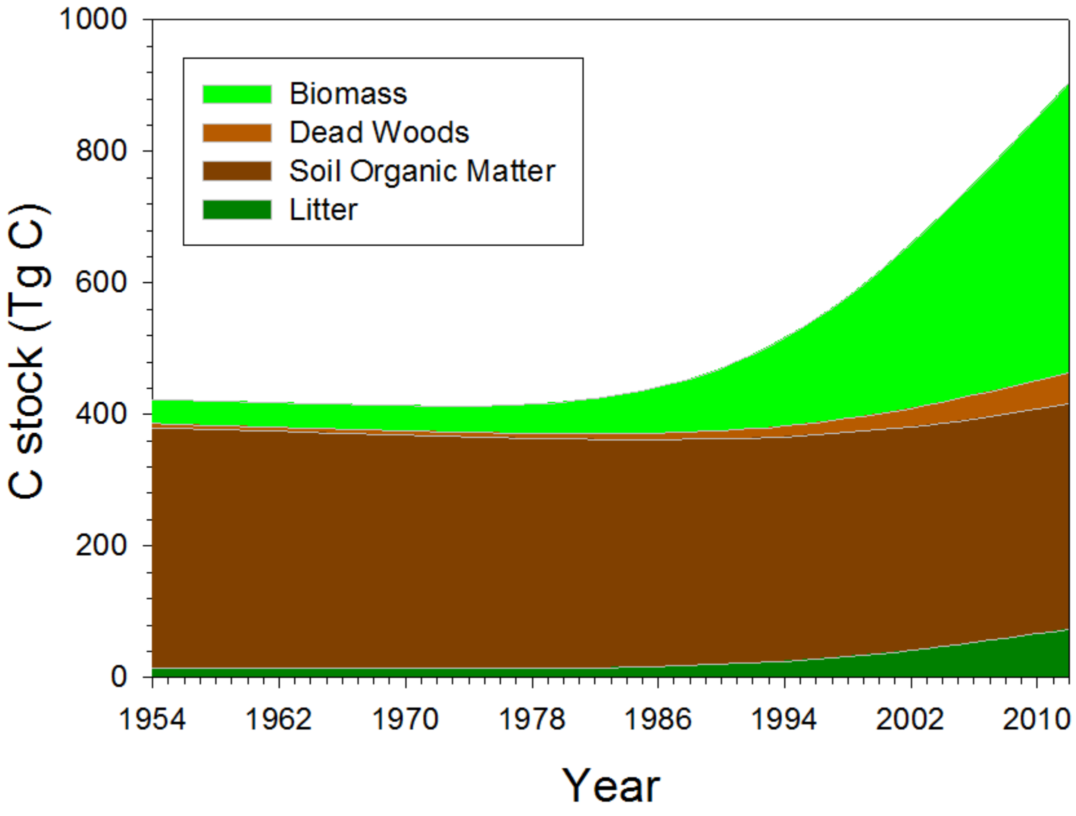

Figure 3. The time series of biomass and dead organic matter (dead woods, soil organic matter, and litter) carbon (C) stocks in South Korean forests during the simulation period. Total C stocks in South Korea have increased as forest vegetation has recovered.

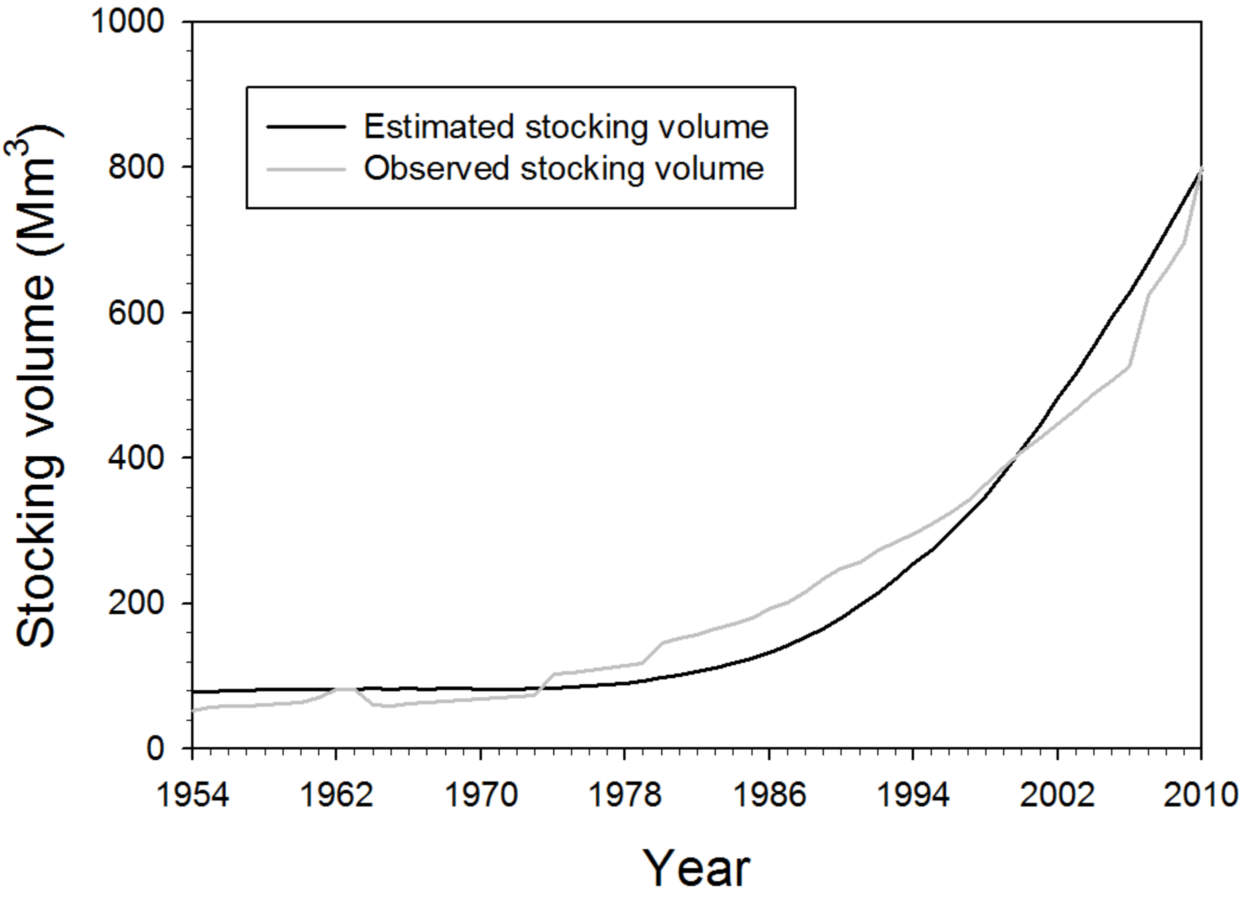

Figure 4. The time series of the estimated and observed (statistical data) stocking volume in South Korean forests during the simulation period. The observed stocking volumes of each year were compiled from those published by the Korea Forest Service in the Statistical Yearbook of Forestry.

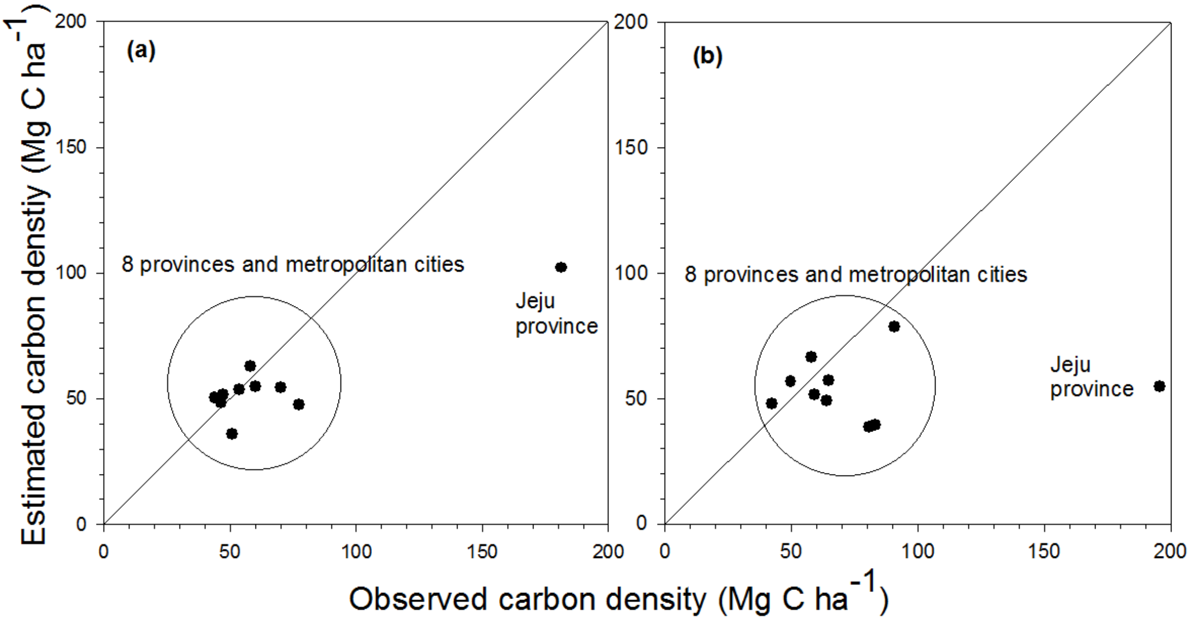

Figure 5. Comparison between the estimated and observed carbon (C) densities of dead organic matter, excluding dead woods for needleleaf species (a) and broadleaf species (b). The C densities of seven metropolitan cities were compiled as one unit.

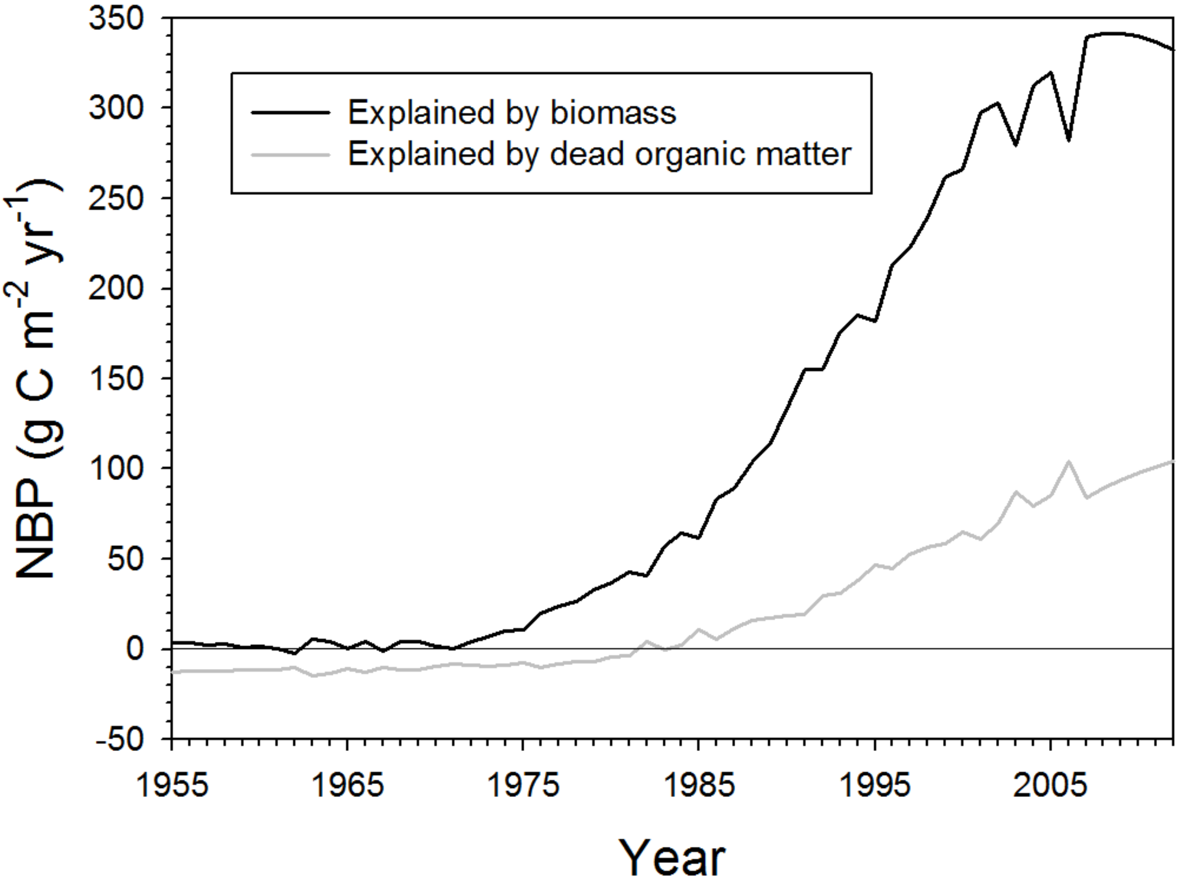

Figure 6. The time series of net biome production (NBP) in South Korean forests during the simulation period. Carbon (C) sequestration by biomass and dead organic matter C stocks in South Korean forests rapidly increased and showed an upward trend.