Biogeosciences Discuss., 11, 5023–5052, 2014
www.biogeosciences-discuss.net/11/5023/2014/
doi:10.5194/bgd-11-5023-2014

Biogeosciences Discussions
Open Access

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

J. Lee[1], T. K. Yoon[1], S. Han[1], S. Kim[1], M. J. Yi[2], G. S. Park[3], C. Kim[4], R. Kim[5], and Y. Son[1]

[1]Department of Environmental Science and Ecological Engineering, Graduate School, Korea University, Seoul, Korea
[2]Department of Forest Resources, Kangwon National University, Chuncheon, Korea
[3]Department of Environment and Forest Resources, Chungnam National University, Daejeon, Korea
[4]Department of Forest Resources, Gyeongnam National University of Science and Technology, Jinju, Korea
[5]Department of Forest and Climate Change, Korea Forest Research Institute, Seoul, Korea

Received: 28 February 2014 – Accepted: 11 March 2014 – Published: 31 March 2014

Correspondence to: Y. Son (yson@korea.ac.kr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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 in the South Korean forests over the past decades. However, a retrospective long-term study including biomass and dead organic matter (DOM) C and validating DOM C is still insufficient. Accordingly, we estimated the C stocks and balances of both biomass and DOM C during 1954–2012 using a process-based model, the Korean Forest Soil Carbon model, and the 5th 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 and sequestered C at a rate of 7.0 $\mathrm{Tg\,C\,yr^{-1}}$ during 1954–2012. The DOM C stocks increased from 386.0 to 463.1 Tg C and sequestered C at a rate of 1.3 $\mathrm{Tg\,C\,yr^{-1}}$ during the same period. The estimates of biomass and DOM C stocks agreed well with observed C stock data. The annual net biome production (NBP) during 1954–2012 was 141.3 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, which increased from −8.8 to 436.6 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in 1955 and 2012, respectively. Compared to forests in other countries and global forests, the annual C sink rate of South Korean forests was much lower, but the NBP was much higher. Our results could provide the forest C dynamics in South Korean forests before and after the onset of reforestation programs.

1 Introduction

Forests contain about 1146 Pg carbon (C), which consists of 359 Pg C in the vegetation and 787 Pg C in soils, and the global C sink of the forests was estimated to be 2.4 ± 0.4 $\mathrm{Pg\,C\,yr^{-1}}$ (Dixon et al., 1994; Pan et al., 2011). The Kyoto Protocol established

BGD
11, 5023–5052, 2014
Estimating the carbon dynamics of South Korean forests from 1954 to 2012
J. Lee et al.

the function of forests as a C sink and their role in the global C dynamics has been recognized (IPCC, 2003; UNFCCC, 1997). Consequently, studies on the C budget of forest biomass and dead organic matter (DOM) 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 or 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 DOM C, and limitation on extrapolation due to high spatial variability (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 has 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 in South Korean forests over the past decades 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, DOM C stocks were excluded due to the lack of observed DOM 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, less than 20 years, (2) estimating C fluxes, not stocks, and (3) insufficient validation of DOM C.

The primary objective of this study was to estimate the C stocks and annual C balance of South Korean forests, including biomass and DOM 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 C dynamics before and after the onset of those programs. The estimated biomass and DOM C stocks were validated by comparing with the observed data in 5th NFI and Statistical Yearbook of Forestry. Furthermore, we compared the estimated annual C sink and NBP of South Korean forests with those of major countries and global forests.

2 Materials and methods

2.1 5th NFI data

We used the 5th South Korean NFI data to prepare input data for the KFSC model and to validate the estimated DOM C stocks. The latest 5th NFI applied systematic cluster sampling for surveys and obtained data from about 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. As we excluded denuded and bamboo forests in the simulation, 3890 plots (5 870 300 ha) were selected from the entire South Korean forests (6 368 843 ha). Each sampling plot represented 100, 400, or 1600 ha of forest grid cell, which is a simulation unit.

BGD
11, 5023–5052, 2014

2.2 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 (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 three secondary DOM compartments (aboveground humus (AHUM), belowground humus (BHUM), and soil organic C (SOC)) 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 soils as litter and woody debris, litter and woody debris are decayed to humus (HUM), HUM is decayed to SOC, and SOC is decayed to CO_2 (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

BGD
11, 5023–5052, 2014

describes the growth modifier used:

$$\text{Growth modifier} = \frac{\text{Vol}_{\text{obs}}}{\text{Vol}_{\text{est}}} \quad (1)$$

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 roots has been poorly studied for these species in Korea, Yi et al. (2013) used the ratio of fine roots to foliage described by Vanninen et al. (1996) as shown in Eq. (2):

$$\text{Fine roots : foliage ratio } 0.0016 \cdot \text{Stand age} + 0.0012 \; (r^2 = 0.67) \quad (2)$$

For the needleleaf species, this ratio was multiplied with the C stocks of the foliage to estimate the C stocks of fine roots. For the broadleaf species, we used the ratio of fine roots to coarse roots as 11 : 89 (Millikin and Bledsoe, 1999). By multiplying this ratio with the estimated C stocks of the coarse roots, we estimated C stocks of the fine roots for broadleaf species. The DOM C dynamics are the same as described by Yi et al. (2013); the detailed description of the DOM 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 stand 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 (Lee et al., 2007; Choi et al., 2011). The turnover rates of biomass C pools and decay rates of DOM C pools are required to simulate forest C processes (Table 1). The decay rate of ALT 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, 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, specifically those that experienced severe deforestation due to exploitation and war.

The forest grid cells simulated by the spin-up scenario were initialized by a spin-up process until the iteration of a quasi-steady-state, such that the difference between

SOCs at the end of two successive clear-cut rotations was < 1 % (Fig. 2a). After that, the model simulated forest C processes by forest age in 2012. In forest recovery scenario, those grid cells that experienced severe deforestation were also initialized by the spin-up process, while all DOM C pools, except SOC, 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. SOC continued to decay slowly until the vegetation recovered sufficiently. As the vegetation recovered, biomass and DOM 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 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 stocks and NBP

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

$$\text{C stock(MgC)} = \sum_{k=1}^{3890} \text{mean C density}_k \ \text{MgC ha}^{-1} \cdot A_k(\text{ha}) \tag{3}$$

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

The NBP ($\text{g C m}^{-2}\,\text{yr}^{-1}$) of South Korean forests was also calculated. The NBP equals the net primary production minus the heterotrophic respiration minus the disturbance (fire, harvest, pests, land-use change, and other disturbances). As harvest was assumed to be the only disturbance and land-use change was not considered in this study, the KFSC model could simulate the net change of C stocks in the forest biome. To calculate the NBP of South Korean forests, the annual change of C stocks in South Korean forests was divided by the total simulation area (5 870 300 ha).

2.3.3 Model validation

We validated the estimated biomass and DOM C stocks by comparing the estimated data to observed data 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 Yearbooks of Forestry (Korea Forest Service, 2000, 2011) to indirectly validate the estimated biomass C. Since observed data for DOM C from the past does not exist, the DOM C stocks in the 5th NFI data were used to validate the estimates. The estimates of soil C (BHUM + SOC) 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 DOM values, those other than AWDS, BWD, and BLT (data is unavailable in the 5th NFI), were added to those of soil C for validation. The performance of the model in predicting DOM 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, respectively (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). When averaged over the entire 1954–2012 period, the annual C balance of biomass was 7.0 Tg C yr^{-1}.

BGD
11, 5023–5052, 2014

The estimated stocking volumes simulated by the KFSC model were compared with observed stemwood volume data to indirectly validate the 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 implies 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 are 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 biomass C density and stocks, and annual C sink. The other possible reason is a difference in the methods of biomass C stock estimation. We estimated the biomass C stock with 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 constant biomass expansion factors (BEF). 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 DOM

An increase in the C stock of DOM in South Korean forests was also observed, with the data increasing from 386.0 Tg C in 1954 to 463.1 Tg C and in 2012, respectively (Fig. 3).

BGD
11, 5023–5052, 2014

Before the onset of reforestation programs, the C stock of DOM was C source releasing C at a rate of $0.7\,\mathrm{Tg\,C\,yr^{-1}}$. Until around 1980, the DOM C stocks were a C source. As the forest vegetation had been almost denuded, the decomposition of the DOM C exceeded the organic matter input during that period. After the onset of reforestation programs and the recovery of litter input, the C stocks of DOM changed from a C source to a C sink sequestering C at a rate of $2.3\,\mathrm{Tg\,C\,yr^{-1}}$. Averaged over the entire 1954–2012 period, the annual C balance of DOM was $1.3\,\mathrm{Tg\,C\,yr^{-1}}$.

The estimates and NFI inventories for DOM C stocks were in partial agreement (Fig. 5). The RMSE of the estimates were 26.9 and $49.2\,\mathrm{Mg\,C\,ha^{-1}}$ for needleleaf species and broadleaf species, respectively, on a regional scale. The underestimation of DOM 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 DOM C stocks might be overestimated for initialization process. Accordingly, the initial DOM C stocks were probably underestimated and uncertainties in estimating DOM C stocks occurred (Peltoniemi et al., 2006; Wutzler and Reichstein, 2007).

Soil type also could affect the decay rate of HUM, ultimately the DOM C dynamics. Because of difference in dominant soil type, the DOM 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). Because of the strong association with allophane, DOM in Andisol soil is more stable and the decay of DOM C pools is suppressed (Calabi-Floody et al., 2011; Theng and Yuan, 2008). The overestimated decay rate of DOM C pools could underestimate the DOM C stocks in Jeju province. Excluding Jeju province, the RMSE improved to 12.8 and $21.9\,\mathrm{Mg\,C\,ha^{-1}}$ in needleleaf and broadleaf species, respectively. As Jeju province accounts for only 1.8 % of South Korean forests, the estimated C stocks might be reliable.

BGD
11, 5023–5052, 2014

3.3 The total C budget and the NBP 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, respectively. As the C emission from DOM 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 $TgCyr^{-1}$ during the period. From 1974, South Korean forests changed from C source to C sink sequestering C at a rate of 12.6 $TgCyr^{-1}$. Averaged over the entire 1954–2012 period, the annual C balance was 8.3 $TgCyr^{-1}$. 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 $gCm^{-2}yr^{-1}$ and that in 1955 and 2012 were estimated to be −8.8 and 436.6 $gCm^{-2}yr^{-1}$, respectively. The onset of reforestation programs influenced the mean NBP and the averaged NBP was −8.7 and 214.4 $gCm^{-2}yr^{-1}$, during 1954–1973 and 1974–2012, respectively. As the forest vegetation recovered, the contribution of biomass to NBP increased over the simulation period and became higher than the that of DOM over that period. The contribution of biomass to NBP increased from 22.9 to 76.1 % during 1954–2012, and DOM accounted for the remainder. Although the C stock of DOM 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 overall global forests (Table 3). Global forests annually sequestered about 3.8 $PgCyr^{-1}$ (Pan et al., 2011) and South Korean forests accounted for less than 1 % of that (8.3 $TgCyr^{-1}$). 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 $gCm^{-2}yr^{-1}$ during 1990–2007 and that of South Korean forests during 1990–2007 was 365.2 $gCm^{-2}yr^{-1}$. 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 budget and balance of South Korean forests, including biomass and DOM 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, 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 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 taken into consideration to understand comprehensive forest C dynamics.

4 Conclusions

In summary, using a model, we estimated the C dynamics of South Korean forests between 1954 and 2012. During this period, the C stocks of South Korean forests increased from 422.4 to 903.5 Tg C. South Korean forests changed from a C source

BGD
11, 5023–5052, 2014

to a C sink because of the extensive reforestation. The average annual C sink rate during this period was 8.3 $TgC\,yr^{-1}$ and the NBP was 141.3 $gC\,m^{-2}\,yr^{-1}$. From 1954–2008, 13.4 % of the fossil fuel C emission from Korea was offset by C accumulation in forest ecosystems. Although South Korean forests sequestered less C than other countries, the NBP was much higher. The high NBP is a result of extensive reforestation programs; thus, global-scale reforestation would contribute to C sequestration for the mitigation of global climate change.

Acknowledgements. Support for this research was provided by the Korea Forest Service (S111313L100120). We thank the Korea Forest Service and Korea Forest Research Institute for providing the 5th NFI data. We also thank Moonil Kim from Korea University for technical support.

References

Ahn, J. S. and Chon, C. M.: Geochemical distributions of heavy metals and Cr behavior in natural and cultivated soils of volcanic Jeju island, Korea, Geosystem Engineering, 13, 9–20, 2010.

Aizebeokhai, A. P.: Global warming and climate change: realities, uncertainties and measures, Int. J. Phys. Sci., 4, 868–879, 2009.

Bellassen, V., Viovy, N., Luyssaert, S., Maire, G., Schelhaas, M. J., and Ciais, P.: Reconstruction and attribution of the carbon sink of European forests between 1950 and 2000, Glob. Change Biol., 17, 3274–3292, 2011.

Boden, T. A., Marland, G., and Andres, R. J.: Global, regional, and national fossil-fuel CO_2 emissions, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN, doi:10.3334/CDIAC/00001_V2011, 2012.

Calabi-Floody, M., Bendall, J. S., Jara, A. A., Welland, M. E., Theng, B. K. G., Rumpel, C., and Mora, M. L.: Nanoclays from an Andisol: extraction, properties, and carbon stabilization, Geoderma, 161, 159–167, 2011.

Chen, W., Chen, J., Liu, J., and Cihlar, J.: Approaches for reducing uncertainties in regional forest carbon balance, Global Biogeochem. Cy., 14, 827–838, 2000.

BGD
11, 5023–5052, 2014

Choi, S. D. and Chang, Y. S.: Factors affecting the distribution of the rate of carbon uptake by forests in South Korea, Environ. Sci. Technol., 38, 484–488, 2004.
Choi, S., Lee, W. K., Kwak, D. A., Lee, S., Son, Y., Lim, K. H., and Saborowski, J.: Predicting forest cover changes in future climate using hydrological and thermal indices in South Korea, Clim. Res., 49, 229–245, 2011.
Dixon, R. K., Brown, S., Houghton, R. A., Solomon, A. M., Trexler, M. C., and Wisniewski, J.: Carbon pools and flux of global forest ecosystems, Science, 263, 185–191, 1994.
Fang, J., Guo, Z., Hu, H., Kato, T., Muraoka, H., and Son, Y.: Forest biomass carbon sinks in East Asia, with special reference to the relative contributions of forest expansion and forest growth, Glob. Change Biol., doi:10.1111/gcb.12512, 2014.
Guo, Z., Fang, J., Pan, Y., and Birdsey, R.: Inventory-based estimates of forest biomass carbon stocks in China: a comparison of three methods, Forest Ecol. Manag., 259, 1225–1231, 2010.
Intergovernmental Panel on Climate Change (IPCC): Good practice guidance for land use, land-use change and forestry, available at: http://www.ipcc-nggip.iges.or.jp/, 2003.
Ito, A., Saigusa, N., Murayama, S., and Yamamoto, S.: Modeling of gross and net carbon dioxide exchange over a cool-temperate deciduous broad-leaved forest in Japan: analysis of seasonal and interannual change, Agr. Forest Meteorol., 134, 122–134, 2005.
Jandl, R., Lindner, M., Vesterdal, L., Bauwens, B., Baritz, R., Hagedorn, F., Johnson, D. W., Minkkinen, K., and Byrne, K. A.: How strongly can forest management influence soil carbon sequestration?, Geoderma, 137, 253–268, 2007.
Kang, Y.: Japan's exploitation of Korean forests and Korean resistance, Forests Culture, 7, 6–19, 1998 (in Korean) .
Kim, C.: Mass loss rates and nutrient dynamics of decomposing fine roots in a sawtooth oak and Korean pine stands, J. Ecol. Field Biol., 25, 235–239, 2002 (in Korean).
Korea Forest Research Institute: Study on the basis of forest carbon accounting in Korea, Korea Forest Service, Korea, 2010 (in Korean).
Korea Forest Research Institute (KFRI): The 5th national forest inventory report, KFRI, Korea, 2011 (in Korean).
Korea Forest Service: Forestry statistics, Korea Forest Service, Korea, 1974 (in Korean).
Korea Forest Service: Forestry statistics, Korea Forest Service, Korea, 1988 (in Korean).
Korea Forest Service: Statistical yearbook of forestry, Korea Forest Service, Korea, 2000 (in Korean).

BGD
11, 5023–5052, 2014

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

J. Lee et al.

Korea Forest Service: Statistical yearbook of forestry, Korea Forest Service, Korea, 2005 (in Korean).
Korea Forest Service: Table of tree volume/mass and yield table, Korea Forest Service, Korea, 2009 (in Korean).
Korea Forest Service: Statistical yearbook of forestry, Korea Forest Service, Korea, 2010 (in Korean).
Korea Forest Service: Statistical yearbook of forestry, Korea Forest Service, Korea, 2011 (in Korean).
Korea Forest Service: Statistical yearbook of forestry, Korea Forest Service, Korea, 2012 (in Korean).
Krinner, G., Viovy, N., Noblet-Ducoudré, N., Ogée, G., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cy., 19, 1–33, doi:10.1029/2003GB002199, 2005.
Kurz, W. A. and Apps, M. J.: A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector, Ecol. Appl., 9, 526–547, 1999.
Kurz, W. A., Apps, M. J., Webb, T. M., and McNamee, P. J.: Carbon budget of the Canadian forest sector: phase I (Inf. Rep. NOR-X-326), Northern Forestry Centre, Canada, 1992.
Kurz, W. A., Dymond, C. C., White. T. M., Stinson, G., Shaw, C. H., Rampley, G. J., Smyth, C., Simpson, B. N., Neilson, E. T., Trofymow, J. A., Metsaranta, J., and Apps, M. J.: CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards, Ecol. Model., 220, 480–504, 2009.
Lee, M. A., Lee, W. K., and Song, C. C.: Spatio-temporal change prediction and variability of temperature and precipitation, J. GIS Assoc. Korea, 15, 1–12, 2007 (in Korean).
Lee, A. R., Noh, N. J., Yoon, T. K., Lee, S. K., Seo, K. W., Lee, W. K., Cho, Y., and Son, Y.: Estimation of forest soil carbon stocks with Yasso using dendrochronological approach, J. Korean For. Soc., 98, 791–798, 2009 (in Korean).
Li, X., Yi, M. J., Son, Y., Jin, G., and Han, S. S.: Forest biomass carbon accumulation in Korea from 1954 to 2007, Scand. J. Forest Res., 25, 554–563, 2010.
Liski, J., Palosou, T., Peltoniemi, M., and Sievänen, R.: Carbon and decomposition model Yasso for forest soils, Ecol. Model., 189, 168–182, 2005.

BGD
11, 5023–5052, 2014

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

J. Lee et al.

Liski, J., Lehtonen, A., Peltoniemi, M., Eggers, T., Muukkonen, P., and Mäkipää, R.: Carbon accumulation in Finland's forests 1922–2004 – an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil, Ann. For. Sci., 63, 687–697, 2006.
Liu, J., Peng, C., Apps, M., Dang, Q., Banfield, E., and Kurz, W.: Historic carbon budgets of Ontario's forest ecosystems, Forest Ecol. Manag., 169, 103–114, 2002.
Luyssaert, S., Ciais, P., Piao, S. L., Schulze, E. D., Jung, M., Zaehle, S., Schelhaas, M. J., Reichstein, M., Churkina, G., Papale, D., Abril, G., Beer, C., Grace, J., Loustau, D., Matteucci, G., Magnani, F., Nabuurs, G. J., Verbeeck, H., Sulkava, M., van der Werf, G. R., Janssens, J. A., and members of the Carboeurope-IP Synthesis Team: The European carbon balance. Part 3: forests, Glob. Change Biol., 16, 1429–1450, 2010.
Millikin, C. S. and Bledsoe, C. S.: Biomass and distribution of fine and coarse roots from blue oak (*Quercus douglasii*) trees in the northern Sierra Nevada foothills of California, Plant Soil, 214, 27–38, 1999.
Nabuurs, G. J., Schelhaas, M. J., Mohren, G. M. J., and Field, C. B.: Temporal evolution of the European forest sector carbon sink from 1950 to 1999, Glob. Change Biol., 9, 152–160, 2003.
Noh, N. J.: Carbon and nitrogen dynamics in a natural *Pinus densiflora* forest with different stand densities, Ph.D. thesis, Korea University, Korea, 2011.
Nothdurft, A., Wolf, T., Ringeler, A., Böhner, J., and Saborowski, J.: Spatio-temporal prediction of site index based on forest inventories and climate change scenarios, Forest Ecol. Manag., 279, 97–111, 2012.
Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., and Hayes, D.: A large and persistent carbon sink in the world's forests, Science, 333, 988–993, 2011.
Park, C. W., Lee, J., Yi, M., Kim, C., Park, G. S., Kim, R. H., Lee, K. H., and Son, Y.: Estimation of change in soil carbon stocks of *Pinus densiflora* forests in Korea using KFSC model under RCP 8.5 climate change scenario, Clim. Change Res., 4, 77–93, 2013 (in Korean).
Park, G. S., Lim, J. G., Kim, D. H., and Ohga, S.: Net fine root carbon production in *Quercus* natural forest ecosystems of Korea, J. Fac. Agr. Kyushu Univ., 51, 57–61, 2006.
Park, G. S., Kang, G. N., Lee, S. J., Lee, H. G., Lee, S. Y., Chae, H. M., and Ohga, S.: Net fine root carbon production in *Pinus densiflora*, *Pinus koraiensis*, *Larix kaempferi* and *Quercus*

acutissima stands, Gongju area, Chungnam province, Korea, J. Fac. Agr. Kyushu Univ., 55, 73–76, 2010.

Peltoniemi, M., Palosou, T., Monni, S., and Mäkipää, R.: Factors affecting the uncertainty of sinks and stocks of carbon in Finnish forests soils and vegetation, Forest Ecol. Manag., 232, 75–85, 2006.

Piao, S. L., Ito, A., Li, S. G., Huang, Y., Ciais, P., Wang, X. H., Peng, S. S., Nan, H. J., Zhao, C., Ahlström, A., Andres, R. J., Chevallier, F., Fang, J. Y., Hartmann, J., Huntingford, C., Jeong, S., Levis, S., Levy, P. E., Li, J. S., Lomas, M. R., Mao, J. F., Mayorga, E., Mohammat, A., Muraoka, H., Peng, C. H., Peylin, P., Poulter, B., Shen, Z. H., Shi, X., Sitch, S., Tao, S., Tian, H. Q., Wu, X. P., Xu, M., Yu, G. R., Viovy, N., Zaehle, S., Zeng, N., and Zhu, B.: The carbon budget of terrestrial ecosystems in East Asia over the last two decades, Biogeosciences, 9, 3571–3586, doi:10.5194/bg-9-3571-2012, 2012.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, Glob. Change Biol., 9, 161–185, 2003.

Stinson, G., Kurz, W. A., Smyth, C. E., Neilson, E. T., Dymond, C. C., Metsaranta, J. M., Biosvenue, C., Rampley, G. J., Li, Q., White, T. M., and Blain, D.: An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008, Ecol. Model., 222, 2333–2341, 2011.

Tak, K. and Wood, P. M.: The South Korean forest dilemma, Int. For. Rev., 9, 548–557, 2007.

Theng, B. K. G. and Yuan, G.: Nanoparticles in the soil environment, Elements, 4, 395–399, 2008.

United Nations Framework Convention on Climate Change (UNFCCC): Kyoto Protocol to the United Nations Framework Convention on Climate Change, available at: http://www.unfccc.int, 1997.

Vanninen, P., Ylitalo, H., Sievänen, R., and Mäkelä, A.: Effects of age and site quality on the distribution of biomass in Scots pine (*Pinus sylvestris* L.), Trees, 10, 231–238, 1996.

Wang, G. G. and Klinka, K.: Use of synoptic variables in predicting white spruce site index, Forest Ecol. Manag., 80, 95–105, 1996.

Wang, S., Chen, J. M., Ju, W. M., Feng, X., Chen, M., Chen, P., and Yu, G.: Carbon sinks and sources in China's forests during 1901–2001, J. Environ. Manage., 85, 524–537, 2007.

Wutzler, T. and Reichstein, M.: Soils apart from equilibrium – consequences for soil carbon balance modelling, Biogeosciences, 4, 125–136, doi:10.5194/bg-4-125-2007, 2007.
Yi, K., Park, C. W., Ryu, S. R., Lee, K. H., Yi, M. J., Kim, C., Park, G. S., Kim, R., and Son, Y.: Simulating the soil carbon dynamics of *Pinus densiflora* forests in central Korea, Scand. J. Forest Res., 28, 241–256, 2013.
Yoo, S., Kwak, D. A., Cui, G., Lee, W. K., Kwak, H., Ito, A., Son, Y., and Jeon, S.: Estimation of the ecosystem carbon budget in South Korea between 1999 and 2008, Ecol. Res., 28, 1045–1059, 2013.
Yoon, T. K., Chung, H., Kim, R. H., Noh, N. J., Seo, K. W., Lee, S. K., Jo, W., and Son, Y.: Coarse woody debris mass dynamics in temperate natural forests of Mt. Jumbong, Korea, J. Ecol. Field Biol., 34, 115–125, 2011.
Zhou, D., Zhao, S. Q., Liu, S., and Oeding, J.: A meta-analysis on the impacts of partial cutting on forest structure and carbon storage, Biogeosciences, 10, 3691–3703, doi:10.5194/bg-10-3691-2013, 2013.

BGD
11, 5023–5052, 2014

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[a,b,c]	Noh (2011)
	0.0045[d,e,f]	Kurz et al. (1992)
Branch	0.061[a,b,c]	Lee et al. (unpublished)
	0.057[d,e,f]	Lee et al. (unpublished)
Foliage	0.385[a,b]	Lee et al. (unpublished)
	0.934[c,d,e,f]	Lee et al. (unpublished)
Coarse roots	0.02	Kurz et al. (1992)
Fine roots	1.23[a,b,c]	Park et al. (2010)
	0.695[e]	Park et al. (2006)
	1.195[d,f]	Park et al. (2006)
Decay constant (yr^{-1})		
AWDS and AWDB	0.137[a,b,c]	Noh (2011)
	0.058[d,e,f]	Yoon et al. (2011)
ALT	0.317[a,b,c]	Lee et al. (unpublished)
	0.402[d,e,f]	Lee et al. (unpublished)
BWD	0.137[a,b,c]	Assumed to be equal to the decay constant of AWD
	0.058[d,e,f]	Assumed to be equal to the decay constant of AWD
BLT	0.462	Kim (2002)
AHUM and BHUM	0.012[a,b,c]	Liski et al. (2005): standard value for fast HUM pool
	0.002[d,e,f]	Liski et al. (2005): maximum value for fast HUM pool
SOC	0.0012[a,b,c]	Liski et al. (2005): standard value for fast HUM pool
	0.0017[d,e,f]	Liski et al. (2005): maximum value for fast HUM pool

[a] *Pinus densiflora*, [b] *P. rigida*, [c] *Larix kaempferi*, [d] *Quercus variabilis*, [e] *Q. mogolica*, [f] *Q. accutissima*.

BGD
11, 5023–5052, 2014

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

Category	Year or period	Estimate	Reference
Mean C density ($Mg\,C\,ha^{-1}$)	1954	4.3	Li et al. (2010)
	1954	6.2	This study
	2001	34.4	Choi and Chang (2004)
	2001	39.7	This study
Biomass C stock (Tg C)	1954	20.6	Li et al. (2010)
	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 ($g\,C\,m^{-2}\,yr^{-1}$)	1993–2007	9.1	Li et al. (2010)
	1993–2007	15.5	This study
	1997–2001	9.6	Choi and Chang (2004)
	1997–2001	15.6	This study

BGD
11, 5023–5052, 2014

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

Region	Period	Annual C sink ($Tg\,C\,yr^{-1}$)		NBP ($g\,C\,m^{-2}$)		Reference
		Biomass	DOM	Biomass	DOM	
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, C sink was divided by the total change in biomass and dead organic matter (DOM) stocks with 404 Mha.
[b] To calculate the NBP, the C uptake rate was divided by forest area in 1999.
[c] To calculate the NBP, harvested wood product was excluded in C stock change.

BGD
11, 5023–5052, 2014

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) = $a \cdot \exp(b \cdot \exp(c \cdot \text{age}))$.

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

BGD
11, 5023–5052, 2014

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) = $a \cdot \text{age}^b$.

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

BGD
11, 5023–5052, 2014

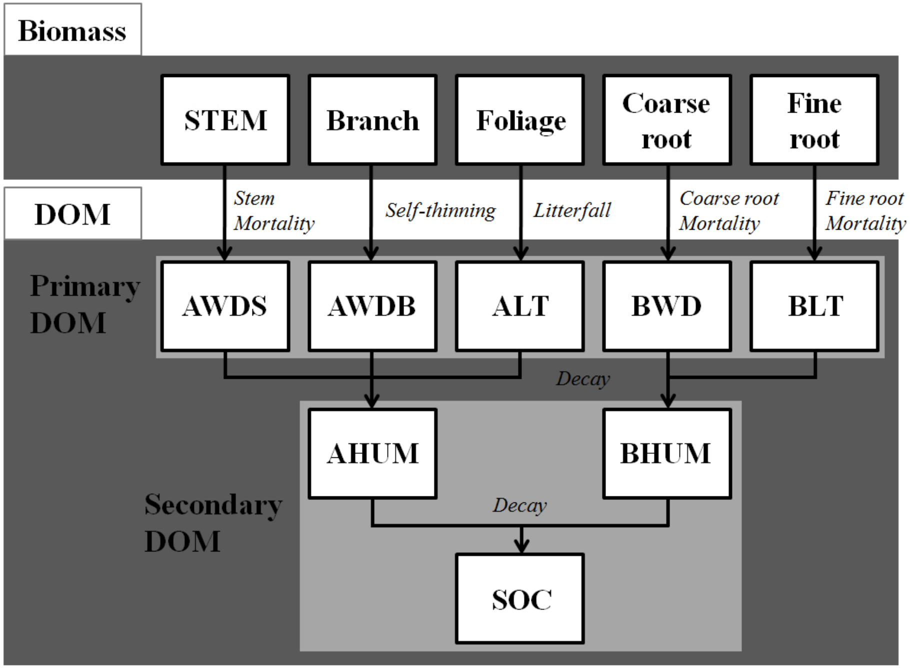

Fig. 1. The schematic diagram of the modified forest soil dynamics model (KFSC) used in this study. The carbon pools consists of biomass (BIO) compartments (stem, branch, foliage, coarse root, and fine root), primary dead organic matter (DOM) compartments (AWDS, AWDB, ALT, BWD, and BLT), and secondary DOM compartments (HUM and SOC). The abbreviations are shown in Sect. 2.3.1. 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 AWD and HUM, respectively.

BGD
11, 5023–5052, 2014

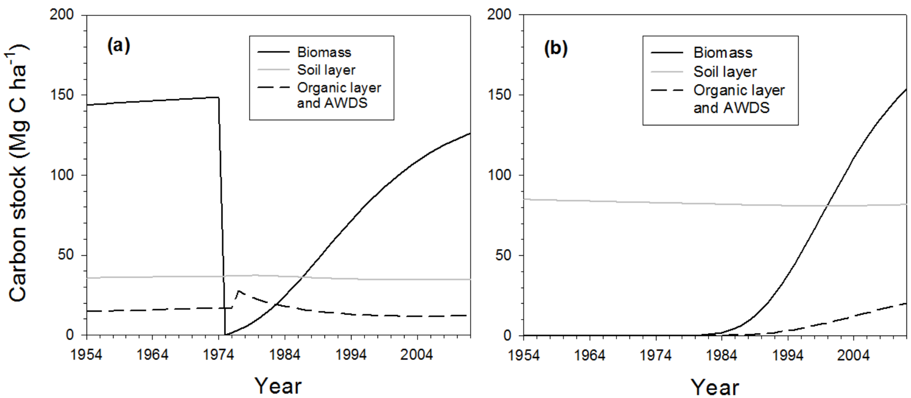

Fig. 2. Examples showing the carbon dynamics (biomass, soil layer, and organic layer and aboveground woody debris from stem (AWDS)) simulation for each scenario; spin-up scenario **(a)** and forest recovery scenario **(b)**. The spin-up scenario simulates carbon dynamics under periodic harvesting. The forest recovery scenario simulates carbon dynamics from deforestation. In this scenario, forest carbon stocks start increasing as the forest stand regenerates.

BGD
11, 5023–5052, 2014

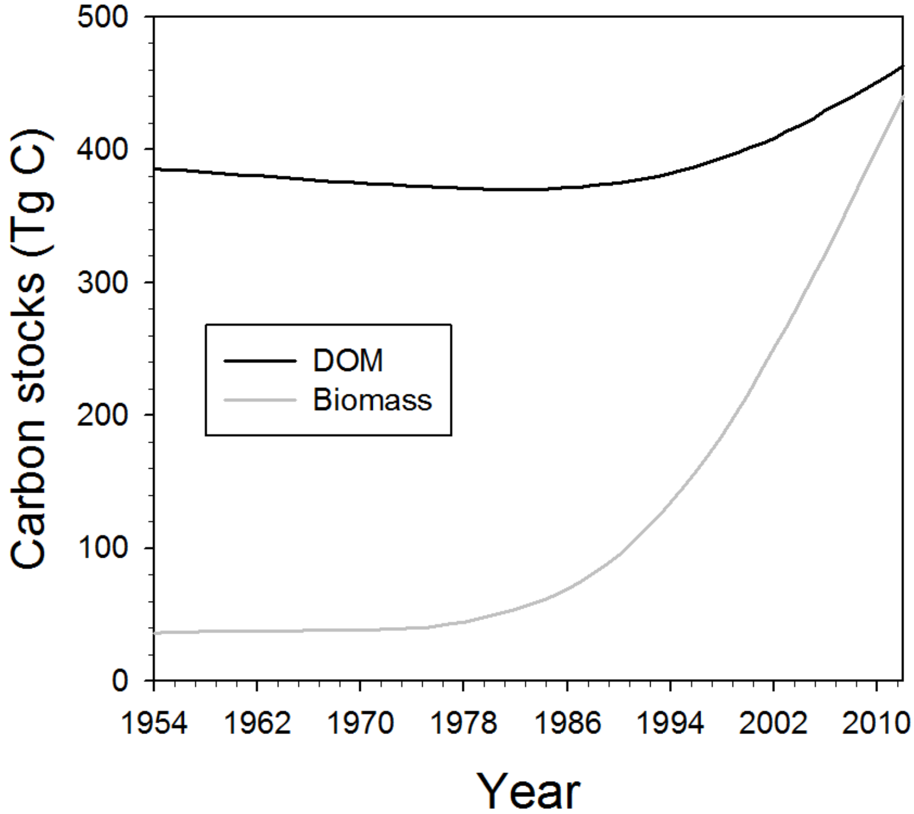

Fig. 3. The time series of biomass and dead organic matter (DOM) carbon (C) stocks in South Korean forests during the simulation period. Total C stocks in South Korea have increased as forest vegetation has recovered.

BGD
11, 5023–5052, 2014

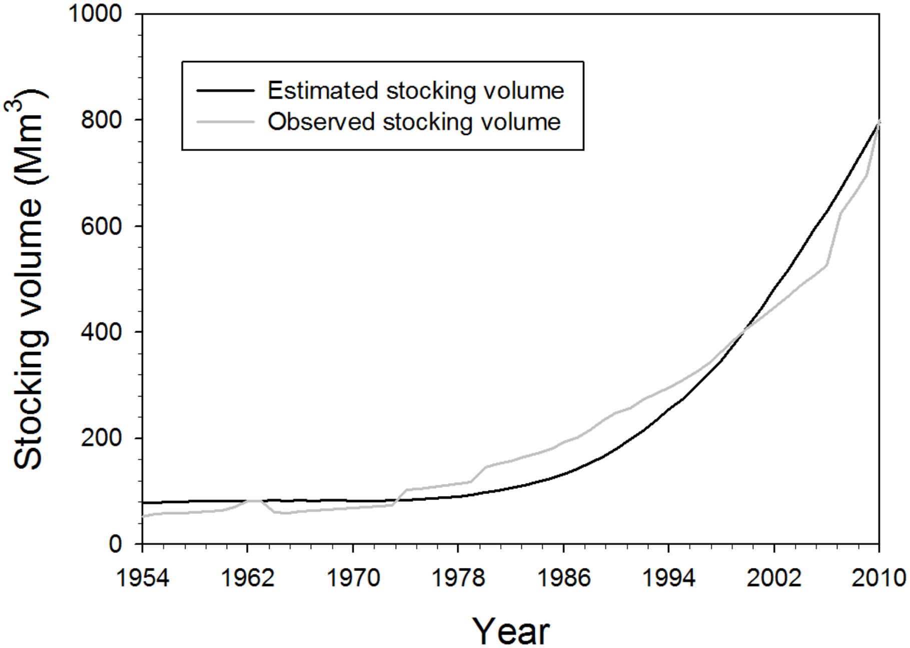

Fig. 4. The time series of the estimated and observed (statistical data) stocking volume in South Korean forests during the simulation period. The observed stocking volumes of each year were compiled from those published by the Korea Forest Service in the Statistical Yearbook of Forestry.

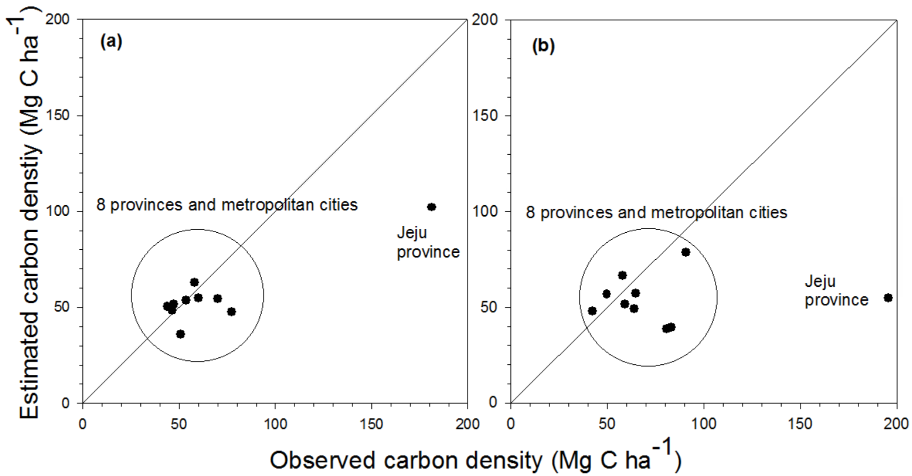

Fig. 5. Comparison between the estimated and observed carbon (C) densities of dead organic matter, excluding dead wood for needleleaf species **(a)** and broadleaf species **(b)**. The C densities of seven metropolitan cities were compiled as one unit.

BGD
11, 5023–5052, 2014

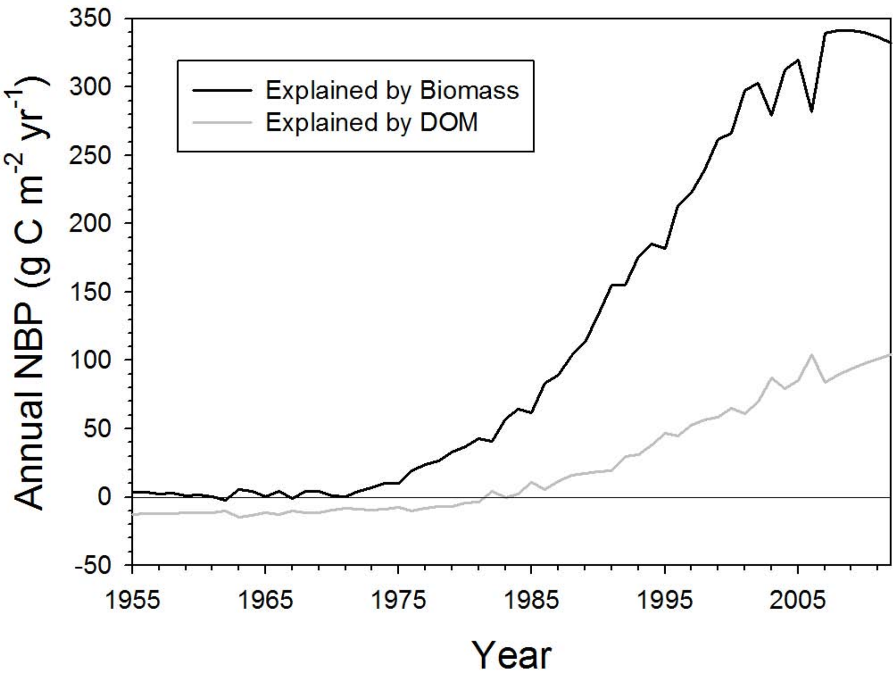

Fig. 6. The time series of net biome production (NBP) in South Korean forests during the simulation period. Carbon (C) sequestration by biomass and dead organic matter (DOM) C stocks in South Korean forests rapidly increased and showed an upward trend.

BGD
11, 5023–5052, 2014