

Estimating carbon dynamics in forest carbon pools under IPCC standards in South Korea using CBM-CFS3

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The main objective of this study was to estimate past and future dynamics of forest carbon pools in South Korea, as classified by the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance (GPG) and to test the Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3). Inventory data required in CBM-CFS3 were extracted from Korea's 3rd Forest Type Map. The site index in the inventory data was estimated through regression models developed using 5th National Forest Inventory (NFI) data with 4000 plots. Necessary yield tables to a stand age of over 100 years, stratified by species, were prepared through the estimation of volume per ha with tree species, site index and stand age. We considered thinning and cutting regulations for sustainable forest management announced by the Korean Forest Service and that the forest area was constant over from 1992 to 2092. We estimated the carbon stocks and their changes of aboveground (AGB) and belowground (BGB) biomass, litter (L), dead wood (DW), and soil organic matter (SOM). Validation was conducted based on the 5th NFI and statistical data. Our results showed that the carbon content of the total forest area increased from 509.7 Tg C to 1007.3 Tg C at a rate of 11.8 Tg C yr⁻¹ during 1992-2034. Results also showed that AGB, BGB, DW, L and SOM changed from 54.6, 30.2, 15.9, 43.6, and 373.9 Tg C in 1992 to 455.6, 100.77, 32.89, 65.46, and 369.2 Tg C in 2034, respectively. However, the amount of forest carbon was projected to decrease due to large increases in harvest rates as most of the forest reaches the legislated cutting age during 2035-2045. Our simulation estimated that by 2045 AGB, BGB, and SOM decreased to 347.8, 78.2, and 368.9 Tg C, respectively, while DW and L increased to 46.8 and 89.1 Tg C, respectively. The carbon content of the total forested area starts to stabilize after 2045 as the annual stand growth gradually decreases. Finally in 2092, the carbon content of AGB, BGB, DW, L, and SOM was estimated as 422.3, 93.9, 31.2, 63.0, and 365.1 Tg C, respectively. Through harvesting, over the 100 year period more than 200 Tg C were transferred from South Korea's forests to meet demands for timber, fiber and energy. Good agreement between model results, NFI data and independent studies, demonstrates the applicability of CBM-CFS3 for estimating past and future forest carbon budgets in South Korean forests and for exploring forest management activity impacts in managed forests.

Keywords: CBM-CFS3, Carbon Dynamics, Forest Management, National Forest Inventory, Forest Type Map

Introduction

Climate change has led to the global regulation of industrial development in an effort to restrict carbon dioxide (CO₂) emis-

sions, in both advanced and developing countries. Globally, forests are a major carbon (C) sink responsible for removing from the atmosphere 29% of anthropogenic C

emissions between 2004 and 2013 (Pan et al. 2011). Concerns about global climate change have highlighted the importance of finding efficient ways to quantify forest carbon dynamics on regional, landscape, national and global scales (Kurz et al. 2013). Measurement of forest biomass provides an indication of C sequestration in trees, as the amount of forest C stock can be estimated from forest biomass, but additional information is required to estimate C stocks in litter, dead wood and soil C pools.

There are two model-based approaches in quantifying forest C dynamics: (i) empirical models, driven by field-based inventory data; and (ii) process-based models, driven by the simulation of photosynthesis (Kurz et al. 2009, Pilli et al. 2013). Process-based models, such as 3-PG (Landsberg & Waring 1997), CENTURY (Metherall et al. 1994), and VISIT (Ito 2008), require extensive

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input datasets of vegetation, climate and soil variables, and fluxes which can be measured by eddy covariance flux towers. In South Korea, the data from flux towers are insufficient for informing process-based models. On the other hand, empirical models, such as EFISCEN (Nabuurs et al. 2000), CO₂FIX (Nabuurs & Schelhaas 2002), FORMICA (Böttcher et al. 2008), and CBM-CFS₃ (Kurz et al. 2009), are better suited than process-based models to utilize merchantable wood volume data collected from small scale investigations at plots in the field for or from large-scale surveys at the national level. The Korea Forest Service has conducted a National Forest Inventory (NFI) from 2005 over all South Korean forests (Korea Forest Research Institute 2011). This NFI contains sufficient information to estimate tree volume at the stand level. Therefore, for estimating the forest C dynamics in South Korea, it is more feasible to use an empirical model rather than a process-based model.

Most empirical forest C dynamic models can only provide estimates starting from the reference year of the NFI, and cannot consider uneven-aged stands or natural disturbances such as forest fires, insect outbreaks, and storms (Lindroth et al. 2009). However, the Carbon Budget Model for Canadian Forest Sector 3 (CBM-CFS₃) can represent impacts of natural disturbances (Kurz et al. 2008), past and future carbon dynamics (Metsaranta et al. 2011), and uneven-aged stands (Pilli et al. 2013). Furthermore, the CBM-CFS₃ implements Tier 3 approaches for estimating C stocks and stock changes following the guidelines of the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance (GPG) for the Land Use, Land-use Change, and Forestry (LULUCF – IPCC 2003) sector (Kurz et al. 2009). Reporting C stocks and changes at the Tier 3 level may be required because it is anticipated that South Korea will have a future obligation to reduce greenhouse gas (GHG) emissions. In this study, we tested CBM-CFS₃ for estimating past and future dynamics of forest carbon pools in South Korea as classified by the IPCC GPG and for supporting the establishment of a national-scale forest carbon budget in compliance with international reporting guidelines.

Materials and methods

CBM-CFS₃

The Carbon Budget Model of Canadian Forest Sector (CBM-CFS₃) is an inventory-based, yield-data driven model that simulates the stand- and landscape-level C dynamics of above- and belowground biomass, and dead organic matter (DOM) including soil (Kurz et al. 2009). The spatial framework conceptually follows the Reporting Method 1 (IPCC 2003), in which, for the purpose of estimating and reporting, the spatial units are defined by their geographic boundaries and all forest stands

are geographically referenced to a spatial unit. Within a spatial unit, each forest stand is characterized by age, area, and up to 10 classifier types that provide administrative and ecological information, including species or forest type and link to appropriate yield curves, and parameters defining the silvicultural system. During the model run, a library of yield tables defines the gross merchantable volume production by age and class for each tree species and site index. These yield tables represent the volume in the absence of natural disturbances and management practices. The CBM applies the net annual increment (i.e., the periodic increment minus mortality from self-thinning) during the model run. Species-specific stand-level equations (Boudewyn et al. 2007) convert merchantable volume into aboveground biomass, partitioned into merchantable stemwood, other material (tops, branches, sub-merchantable size trees), and foliage components. The belowground biomass (coarse and fine roots), its increment, and annual turnover are calculated using the equations provided by Li et al. (2003). Annual dead wood and foliage input is estimated as percentages (i.e., turnover rates) applied to the standing biomass stock. To estimate the decomposition rate of each DOM pool, the CBM adjusts the base decomposition rates, defined at 10 °C, by a temperature modifier based on the mean annual air temperature in each spatial unit and a pool-specific Q^{10} value. DOM pools (dead wood, litter, and soil) are initialized using a procedure that considers site productivity (NPP), temperature-dependent decomposition rates, and disturbance history (Kurz et al. 2009). In the simulation of stand- and landscape-level carbon dynamics, the user can define natural and anthropogenic disturbances such as fire, insects, or storms, partial or clear-cut harvesting, or other disturbance types for which users define the impacts on C stocks (Kull et al. 2006). Users define the amount (area or C target), type, and intensity of each disturbance by the year and spatial unit (or groups of spatial units). Eligibility criteria, such as forest type, age, or other classifier values, can be used to define the eligible stands for each disturbance. Disturbance impacts are defined using a “disturbance matrix” that describes the proportion of C transferred between pools, transferred to the forest product sector, or released to the atmosphere for each disturbance type (Kurz et al. 2009). Post-disturbance dynamics can be specified in considerable detail, allowing for successional pathways and rates of regeneration. Afforestation and deforestation also can be represented as disturbance types with their own disturbance matrices and transitions to and from forestland. The model provides annual estimates of C stocks and fluxes, such as annual C transfers between pools, from pools to the atmosphere, and to the forest product sector. In this study, projections were

limited to 2092 and the effects of possible environmental changes over 100 years have been excluded. CBM input data, including forest area by age class and yield tables, are described below.

National Forest Inventory data

NFI data were used to develop forest growth models for estimating present and future forest volumes by major tree species based on forest type and stand age. In South Korea, the 5th NFI was conducted for the entirety of South Korean forests from 2006 to 2010 (Korea Forest Research Institute 2011). The survey design consisted of systematic sampling at intervals of 4 km (longitude) × 4 km (latitude) across South Korea. Four circular sample plots were located at the intersection of each 4 × 4 km grid line. Each sample plot (31.6 m radius) covered 0.16 ha. Forest characteristics (tree species, age, height, diameter at breast height – *dbh*, and number of trees) and topographical factors (coordinates, elevation, slope, and aspect) were measured at all sites (Korea Forest Service 2011).

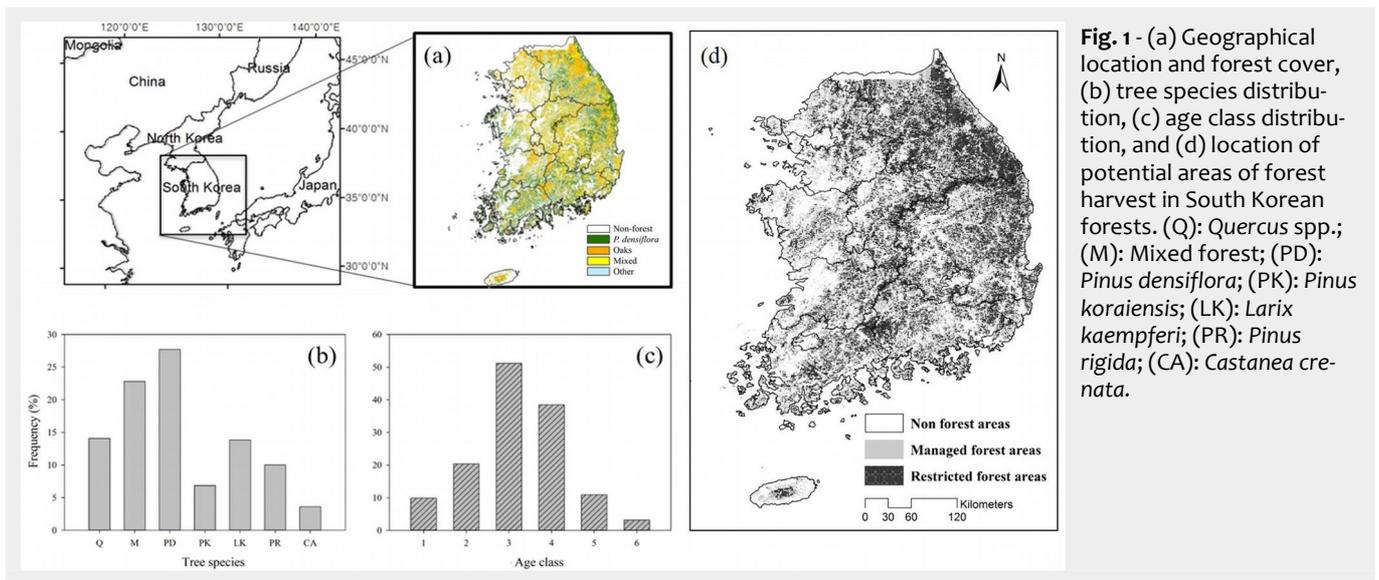
The plot data were used to estimate *dbh*, tree height (*h*), number of trees per hectare (*Nha*), and stand volume (*Vha*) using regression models developed by tree species.

Yield tables

The Korea Forest Service established stand yield tables for 10 major tree species, which provide information on tree volumes based on species, site index, and stand age (Korea Forest Service 2009). However, the Korean Map of Forests classifies the forest into 17 tree species, comprising more detail than is used in this study, which substitutes tree species recommended by the Korea Forest Service when certain species in the Forest Type Map (FTM) were not present in the yield tables. Moreover, there is no information on mixed forests in the stand yield index. According to NFI report (Korea Forest Research Institute 2011), most of mixed forests in South Korea were composed of red pine and Mongolian oak – the major species of coniferous trees and broadleaf in South Korea. Therefore, this research take into account that every mixed forest contains equal proportions of red pine and Mongolian oak. Consequently, C dynamics of mixed forests were estimated using both coefficients of red pine and Mongolian oak in this study.

Forest type map

The 3rd FTM was employed to predict the present forest volume. This map (scale 1:25,000) was produced from visual interpretation of aerial photographs and NFI data, and it outlined forest stands classified by tree species, *dbh*, age class, and canopy closure (Korea Forest Service 2000). Seventeen categories of tree species were specified. *dbh* and age of stands were expressed as “*dbh* class” (6-16 cm, 16-30 cm,



and over 30 cm), and 10-year “age class”. Canopy closure was classified into open, medium, and dense categories.

Climate data

The Korea Meteorological Administration (KMA) provided climate data, including monthly mean temperature, mean daily minimum temperature, and total precipitation, from 75 weather stations across South Korea from 1971 to 2000. The data were interpolated with a 0.01° grid size (≈ 1 km) using Kriging and Inverse Distance Squared Weighting (IDW), considering the absolute temperature and precipitation lapse rate by elevation (Lull & Ellison 1950). In this study, future climatic data were predicted under the A1B scenarios from the IPCC Special Report on Emission Scenarios (IPCC 2000). These datasets were resampled into 0.01° spatial resolution with the Geographic Coordinate System (GCS) and World Geodetic System 1984 (WGS 84).

Study area

The Korean peninsula is located in East Asia and shares overseas borders with China to the west and Japan to the east. The study area is contained within South Korea, and is located at $124^\circ 54' - 131^\circ 06' E$ and $33^\circ 09' - 38^\circ 45' N$ (Fig. 1a). Forest area covers about 63.7% (6,369,000 ha) of the total land area of South Korea, and evergreen forests (mainly *Pinus densiflora*), deciduous broad-leaved forests (mainly *Quercus* spp.), and mixed forests occupied approximately 40.5%, 27%, and 29.3% of the total forest area in 2010, respectively (Korea Forest Service 2011 – Fig. 1b). These are the major tree species in South Korea, and they have important ecological, economical, and socio-cultural value (Kwak et al. 2012).

South Korea’s once-rich forests were degraded in the 20th century due to unmanaged logging for timber and fuel during the Japanese occupation (1910-1945) and the Korean War (1950-1953 – Tak et al. 2007). Since 1973, following periods of serious

deforestation, the South Korean government has implemented the National Greening Program for the recovery of forests (Bae et al. 2012). After about 30 years of effort, South Korean forests have successfully recovered, and the stocking volume increased from $8.2 \text{ m}^3 \text{ ha}^{-1}$ in 1954 to $125.6 \text{ m}^3 \text{ ha}^{-1}$ in 2010 (Korea Forest Service 2011). Today, over 70% of South Korean forests are less than 40 years old (Fig. 1c).

Overview of analytical process

The overall process used in this study can be summarized as follows: (1) design of Spatial Units (SpUs) using various classifiers; (2) estimation of initial stand age and stand average *dbh* using NFI and FTM; (3) estimation of stand height, dominant tree height, site index, and stand volume based on stand age and stand average *dbh* using the Korean yield tables; (4) estimation of future changes of stand average *dbh* and stand average height based on aging of stand; (5) estimation of forest volume in SpUs considering forest management; and (6) using the information in the previous five steps to estimate each forest carbon pool, defined by IPCC GPG, using the CBM-CFS3 model.

Preparation of inventory data on present forest status

The CBM-CFS3 model input inventory is

based on forest stand information. In previous research (Lee et al. 2014), plot-level data of the 5th NFI were converted to be representative for the entire forest area. The total forest area (6.34 M ha) in Korea was divided into 3890 stands. This approach has advantages: it reduces the data processing time and uses field survey data directly at the national level. However, extreme variation in stand characteristics of Korean forests was not captured, because the average size per stand was large (1600 ha). To overcome the limitations of previous studies, this study overlaid four layers (administrative district map, map sheet, FTM, and management type map – Tab. 1) to divide the forest of Korea into 1,134,800 stands, which were on average 5.6 ha in size. Classifiers and stand age were assigned to each stand (Fig. 2). These stands were distributed within the 2250 spatial units recognized in this analysis.

No harvest activities were simulated in areas where forestry practices are restricted. These areas were identified using thematic maps such as FTM, forest site digital maps, and ecological zoning maps. Areas where forestry practices are restricted were defined as special forests (reserved forests, seed production forests, experimental forests, water conservation forests, natural reserve forests, landscape protection areas, and areas for protecting forest

Tab. 1 - Description of classifiers for running CBM-CFS3 in South Korean forests.

Classifier	Summary	Data used
Province	Administrative districts	Administrative district map of Korea
Map sheet	1:25,000 scale map sheets	Map index of Korea
Forest type	Definition of tree species for each stand	3 rd forest type map
Age class	Definition of stand age for each stand	3 rd forest type map
DBH class	Definition of average DBH for each stand	3 rd forest type map
Management type	Definition of restricted or manageable forest	Forest legislation and geographical features

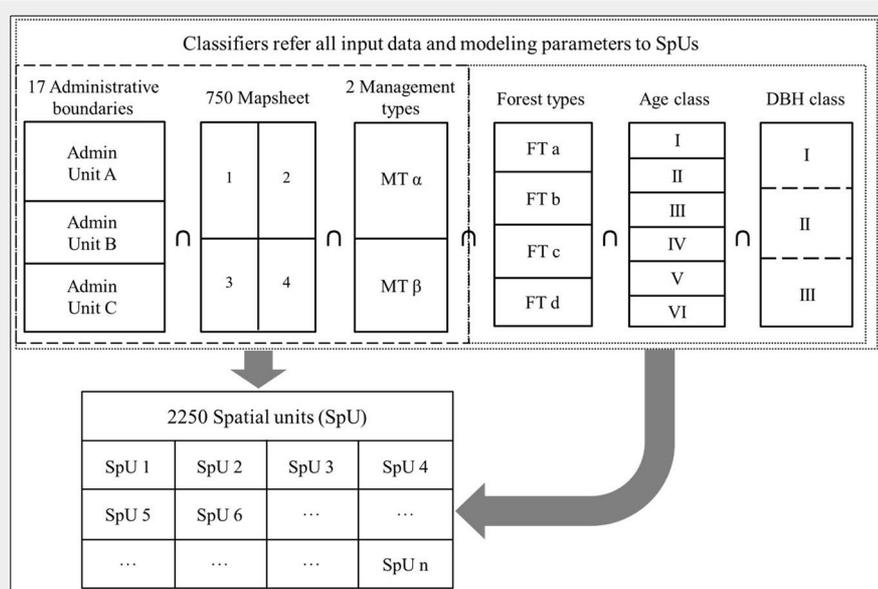


Fig. 2 - Schematic representation of the main input data required by CBM in order to define the Spatial Units (SpUs). The dashed line identifies the general classifiers and the dotted line delimits the information provided by the forest inventory, split between each SpU.

genetic resources) and management zones (green belt zones, national parks, wildlife sanctuaries, and protected areas including wetlands and cultural assets). In addition, impractical working conditions such as slopes of more than 25°, bedrock outcrops covering more than 30% of the surface, and mountain areas with altitudes of more than 900 m above sea level were categorized as restricted area.

The forest area with harvest activities, based on consideration of forest legislation and geographical conditions, occupied about 3,138,000 ha, which is approximately 51.7% of the whole forest area (6,067,400 ha – Fig. 1d). The whole forest areas was included in the analyses of carbon dynamics. We considered that the forest area was constant in the analysis. Therefore, we do not include deforestation and afforestation (land-use changes) in this analysis.

Volume estimation

The Korean FTM contains information about species, age class, and dbh class. The FTM is classified into 17 species, 4 dbh classes, and six 10-year age classes, but it is difficult to fully describe stand characteristics of each species using only this information. Therefore, in this research NFI data were used to subdivide the stand. NFI is based on 4000 permanent sample plots throughout forests of South Korea. These data from the NFI are considered highly reliable and can be used as model data for each forest type.

We sorted dbh information for each species in each stand from the NFI data based on the information related to age class and dbh class obtained from the FTM. Moreover, we estimated the average dbh of the stand of all species, based on each age class and dbh class, matching the dbh value of the corresponding age class and

dbh class (Fig. 3). In addition, information on age class in FTM was derived and equated to match the stand age of each age class. To estimate average height, height of dominant trees, site index, and stand volume of each stand, we used the matched values of stand age and dbh values to replace the information on dbh class and age class in the FTM (Fig. 3).

In general, the volume of an individual tree in a stand can be estimated by the tree height and dbh (Segura & Kanninen 2005, Cutini et al. 2013). Moreover, the number of trees in one hectare (*Nha*) is essential to expand the volume of an individual tree to the total volume of a stand or forest. However, tree height and *Nha* information are not found in the FTM. To simulate the volume of stands in each SpU, it is necessary to estimate the relationship between: (i) mean tree dbh of stand (*dbh*) and mean tree height of stand (*hm*); (ii) *hm* and dominant tree height (*ho*); (iii) age, *ho*, and site index (*SI*); (iv) age, *ho*, and *dbh*; and (v) *dbh*, *hm*, and volume (*V*). Considering relationships and growth characteristics, a growth model formula such as $hm = f(dbh)$ could be developed with NFI data and the optimal nonlinear regression forms (Tab. S1 in Supplementary Material). All basic forms of regression equations were obtained from Sit & Poulin-Costello (1994). Four different types of regression forms were applied to estimate mean tree height for reflecting the growth characteristics of each tree species. Nonlinear regression analyses were performed for 12 tree species using SAS® 9.1 (SAS Institute Inc. 2003) and NFI data. For this study, the regression forms with the highest accuracy were applied to each species (Tab. S2 in Supplementary Material). The every coefficients of growth model formula such as $hm = f(dbh)$ were significant at the relative lower 0.05 (Tab. S3 in Supplementary Material). Other regression equations and coefficients for $hm = f(ho)$, $SI = f(age, ho)$, $dbh_{i+1} = f(dbh_i, age_{i+1}, ho_{i+1})$, and $V = f(dbh, hm)$ were applied to tree species developed by the Korea Forest Service (2009) (Tab. S1 in Supplementary Material).

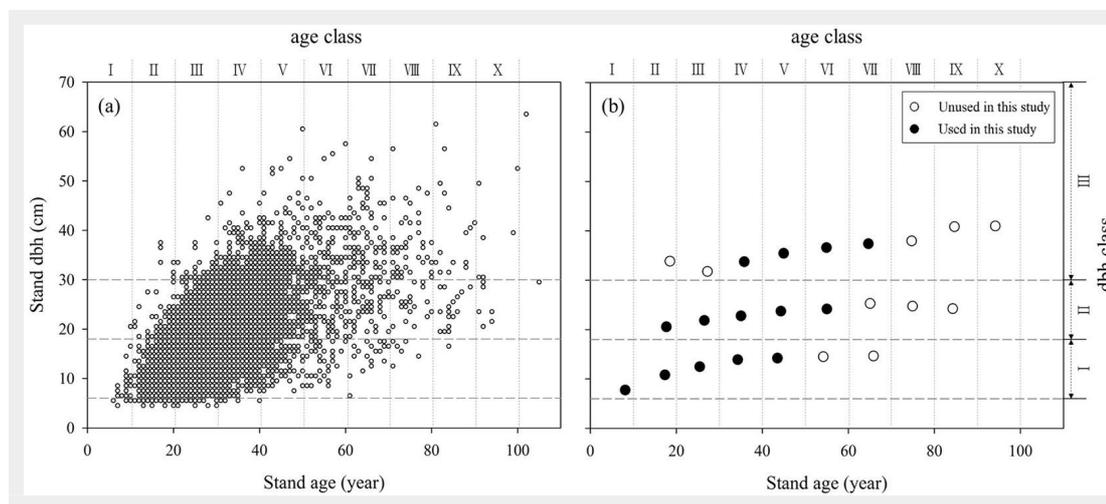


Fig. 3 - Definition of initial age and dbh value in the FTM based on NFI data. (a) Range of age class and dbh class in NFI data and (b) definition of equated values of age class and dbh class.

The SI is defined by the Korea Forest Service as the height of the dominant tree at 30 years of age. Therefore, to estimate the SI of each stand, a functional formula can be used (eqn. 1):

$$SI = f(h_o, age)$$

This research applied equations by either Chapman-Richards (Mitscherlich 1919) or Schumacher (1939) for each tree species to estimate the site index of stands (Tab. S4 in Supplementary Material). Coefficients proposed by the Korea Forest Service (2009) are shown Tab. S5 in Supplementary Material.

The future *dbh* (dbh_{i+1}) was computed by adding one year to the present age (age_i) of target tree species in the regression model. However, the direct application of age_{i+1} to the regression model forces all the dbh_{i+1} to fit the regressed *dbh* value corresponding to age_{i+1} on the regression curve, even though dbh_{i+1} can be estimated higher or lower than the regressed *dbh* value according to the *dbh* value of the previous year. Such forced fitting to the regression curve might lead to an underestimation in *dbh* in $i+1$ years in sites with high SI. On the other hand, poor sites (low SI) might lead to an overestimation of *dbh* in $i+1$ years. To solve such fitting problems, the regression models of $dbh_{i+1} = f(dbh_i, age_{i+1}, SI)$ were transformed into the form of algebraic differences (see Tab. S1 in Supplementary Material – Bailey & Clutter 1974, Jordan et al. 2006) and coefficients proposed by the Korea Forest Service (2009 – see Tab. S6 in Supplementary Material). Thereby, it is possible to estimate the future *dbh* based on the current *dbh* distribution of each stand.

As information about stand density is not included in the FTM, we used the following growth model (eqn. 2) to estimate the volume of stands. The coefficient of each tree species for eqn. 2 is derived from the Korea Forest Service (2009 – see Tab. S7 in Supplementary Material).

$$V_i = a \cdot dbh_i^b \cdot h_i^c$$

where *V* is stand volume ($m^3 ha^{-1}$), *dbh* (cm) is the tree average diameter, and *hm* (m) and *a*, *b*, *c* are species-specific coefficients.

Dead organic matter (DOM) estimation

As the volume or biomass of a living tree grows each year, some parts of the tree (such as fine roots, foliage, branches, etc.) are transferred to DOM carbon pools. This process is quantified by turnover rates that are specific to each biomass component in each ecozone of CBM-CFS3 (Kull et al. 2006). We used default turnover rates of Pacific Maritime ecozone in the CBM-CFS3 to estimate the amount of biomass that annually turns into DOM (Tab. 2).

The decay or decomposition rate of each DOM pool varies with temperature based on a pool-specific base decay rate (at 10

Tab. 2 - Biomass turnover and litterfall transfer rates (Kurz et al. 2009). (1): % of turnover transferred to each DOM pool.

CBM-CFS3 pool	Turnover rates (% C yr ⁻¹)	DOM pool receiving turnover	Litterfall transfer rate ¹
Merchantable stemwood (SW or HW)	0.6	Snag stems	100
Other wood (SW or HW)	4	Snag branches AG fast	25 75
Foliage (SW)	15	AG very fast	100
Foliage (HW)	95	AG very fast	100
Fine roots (SW or HW)	64.1	AG very fast BG very fast	50 50
Coarse roots (SW or HW)	2	AG fast BG fast	50 50

°C), Q₁₀ value, and scaling factor that can adjust decay rates based on the degree of canopy closure (not used in this study – Kurz et al. 2009). Therefore, for application of the CBM to Korea, average air temperature data are required for each spatial unit. This study used the default decay parameters (Kurz et al. 2009), but with temperature data for Korea.

Application of thinning and cutting schedule

Under the sustainable forest management law established by the Korea Forest Service, Korean forest cover needs to be thinned out by 25% at stand age 25 years. Therefore, this study reflected this legal requirement. Furthermore, a clear cut harvest at the final age of maturity for each tree species is implemented. These management activities affect the future carbon budget of the forests of South Korea. The simulations in this study did not include any natural disturbances and changes in land-use such as afforestation or deforestation.

Model validation

In this study, the carbon budget of the five carbon pools defined in the IPCC GPG in South Korean forests from 1992-2092 was estimated by applying the CBM-CFS3 model and validated using the 5th NFI, statistical data, and other research. For biomass, we compared model values to those of the statistical yearbook of forestry in South Korea between 1992 and 2010 and estimated R² and RSME to indirectly validate the estimated biomass C stocks. For soil and litter C, 5th NFI data were used to validate the estimates. Estimates of soil and litter C were not included in earlier NFI versions.

Results and discussion

Aboveground and belowground biomass

Changes in the C stock density of Total Aboveground Biomass (TAB) between 1992-2092 are depicted in Fig. 4a. Typically, the amounts of C stocks of TAB show a pattern of increase or decrease due to growth and thinning and cutting activities (thinning every 25 years and cutting by final maturity age – Fig. 4a). The C stocks of TAB showed rapid growth rates until 2034, fol-

lowed by variations in C density that reflect forest management activities to 2050, and stable densities after 2050. The C stock density of TAB in South Korean forests increased from 8.86 Mg C ha⁻¹ in 1992 to 73.96 Mg C ha⁻¹ in 2034 (Fig. 4a). Averaged over the period 1992-2034, the annual increase in C density of TAB was 1.55 Mg C ha⁻¹ yr⁻¹.

The projected C stocks of TAB decreased drastically from 73.96 Mg C ha⁻¹ in 2034 to 56.46 Mg C ha⁻¹ in 2045 due to forest management activities. Following the management instructions of the Korea Forest Service, many forests will reach a final cutting and reforestation age in 2040, which results in the decrease of TAB at that time. This decline is caused by the imbalanced age structure of Korean forests; in 2009, about 67% of forests in Korea was between 30 and 40 years old (Korea Forest Service 2011) and thus will require that large areas are cut and replanted in 2040, as provided by the forest management practice guide in Korea.

The C stock density of TAB slowly increased thereafter from 56.46 Mg C ha⁻¹ in 2045 to 68.55 Mg C ha⁻¹ in 2092. Averaged over the 2045-2092 period, the annual increase in C density of TAB was 0.25 Mg C ha⁻¹ yr⁻¹. This reflects the decreased growth rates of the aging forests of South Korea and the increasing amount of biomass carbon removed through thinning and final clear cutting.

This increasing and decreasing pattern of the C stocks of TAB reflects the impacts of thinning and final cutting practices as well as forest regrowth (Fig. 4a). Thinning and cutting can reduce the amount of aboveground biomass but enhance the forest growth rate. Over the period 1992 to 2092, thinning and cutting transfer a cumulative 206 Tg C from forests to meet society's demands for timber, fiber and energy (Fig. 4c). The C stock of foliage is relatively low compared to other aboveground C pools, but it also shows a small increase.

The C stock density of Total Belowground Biomass (TBB) follows the pattern of TAB (Fig. 4b), because TAB and TBB are closely related and C stocks of live coarse roots are also affected by the thinning and cutting schedule. The C stock of fine roots shows a relatively small increase similar to foliage. The C stock of belowground bio-

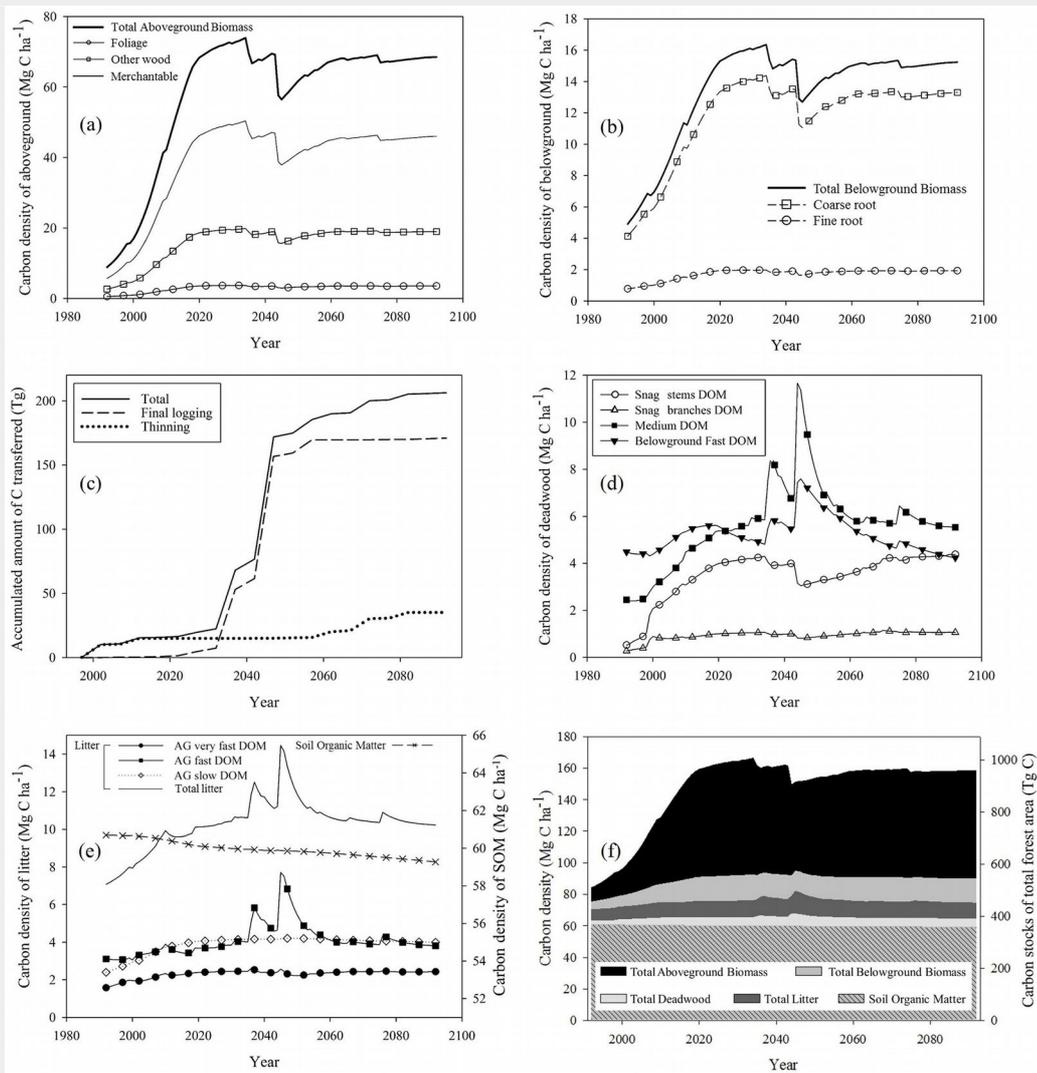


Fig. 4 - Average carbon density (Mg C ha^{-1}) (a) aboveground and (b) belowground biomass in South Korean forests. (c) The cumulative amount of carbon transferred from thinning and final logging. Mean carbon density (Mg C ha^{-1}) of (d) dead wood, and (e) litter, and soil in South Korean forests. (f) Time series of carbon density (left Y-axis) and total carbon (right Y-axis) for five carbon pools in South Korean forests during the simulation period.

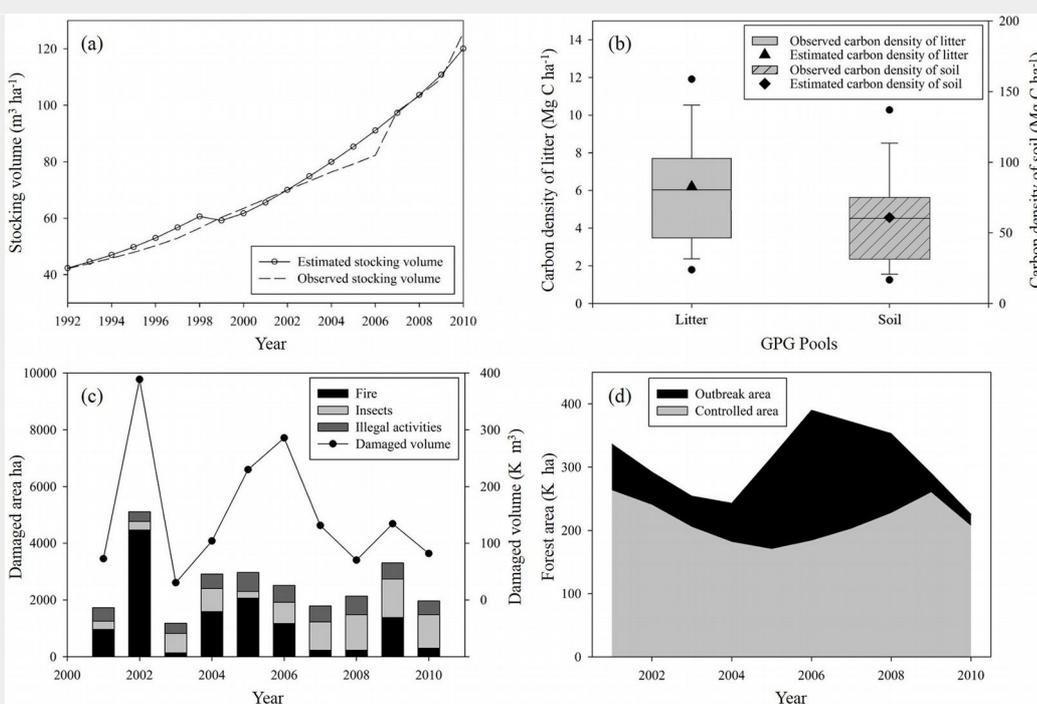


Fig. 5 - (a) The time series of the estimated and observed (statistical data) stocking volume in South Korean forests during 1992-2010. The observed stocking volumes for each year were compiled from those published by the Korea Forest Service in the Statistical Yearbook of Forestry. (b) Comparison between the estimated and observed carbon (C) densities of litter and soil. For each box plot, top circle is 95th percentile, lower circle is 5th percentile, top bar is 90th percentile, lower bar is 10th percentile, top of box is upper or third quartile, bottom of box is lower or first quartile, middle bar is median value. (c) Annual damaged area and volume from natural and artificial disturbances (Korea Forest Service 2011). (d) Annual forest pests and diseases outbreaks and controlled area (Korea Forest Service 2011). (Fire): burned forest area from forest fires; (Insects): clear cut area affected from pest damage by Korea Forest Service; (Illegal activities): area affected by illegal logging activities.

mass was analyzed to be about 23-27% of the C stock of aboveground biomass.

Dead wood

Changes in C stock density of dead wood are also affected by forest management activities (Fig. 4d). Within the four types of dead wood, medium DOM and belowground fast DOM (which includes dead coarse roots) tend to increase in the presence of forest management activities (Fig. 4d). Compared with the TAB and TBB C stocks, the C stock of medium DOM and belowground fast DOM showed an opposite pattern. Forest management activities include cutting standing trees, which decreases the C stock of total above- and belowground biomass, but increases the C stocks of DOM because the transfer of C to woody debris and dead roots adds more C than the loss from these pools during forest management activities. This effect is projected to be particularly significant in 2044, when the C stock of TAB will be reduced by about 11.6 Mg C ha⁻¹ yr⁻¹ (from 69.2 Mg C ha⁻¹ to 57.6 Mg C ha⁻¹, -16.7%), while the C stock of medium DOM and belowground fast DOM will increase by about 4.8 Mg C ha⁻¹ yr⁻¹ (from 6.9 Mg C ha⁻¹ to 11.7 Mg C ha⁻¹, +69.8%) and 1.9 Mg C ha⁻¹ yr⁻¹ (from 5.5 Mg C ha⁻¹ to 7.4 Mg C ha⁻¹, +34.7%), respectively (Fig. 4d).

However, snag stems DOM and snag branches DOM, which mainly occur naturally from dead trees, show a decreasing tendency in the 2045, because the clear cut disturbance matrix in CBM-CFS3 represents cutting of the snags which transfers C to the medium pool (Fig. 4d). The C stock density of snag stems DOM and snag branches DOM will decrease from 4.0 Mg C ha⁻¹ to 3.2 Mg C ha⁻¹ and 1.0 Mg C ha⁻¹ to 0.8 Mg C ha⁻¹, respectively, in 2045.

Litter

Similar to C stock changes in dead wood, the C stock change in total litter was primarily linked to changes in forest management activities, because of the relatively high amount of residue transferred to DOM during thinning and cutting activities.

Within the three types of litter, aboveground fast DOM tends to increase with forest management activities (Fig. 4e). The C stock density of aboveground fast DOM increases from 4.6 Mg C ha⁻¹ to 7.7 Mg C ha⁻¹ in 2045. However, aboveground very fast DOM and aboveground slow DOM gradually increase from 1.6 and 2.4 Mg C ha⁻¹ in 1992 to 2.4 and 4.0 Mg C ha⁻¹ in 2092, respectively, with almost no effect from forest management activities. The C stock density of total litter slowly increases from 7.1 Mg C ha⁻¹ in 1992 to 11.2 Mg C ha⁻¹ in 2034. In the years of extensive forest management activities the simulation results estimated two peaks, which reached 12.5 Mg C ha⁻¹ in 2037 and 14.4 Mg C ha⁻¹ in 2045. However, the C stocks of total litter start to gradually decrease and stabilize during 2046-2092.

Tab. 3 - Comparison of living biomass carbon (C) density and NEP of South Korean forests with those of previous studies.

Category	Year or period	Model	Estimate	Reference
Mean C density (Mg C ha ⁻¹)	2001	Statistical model	34.4	Choi & Chang (2004)
		KFSC	39.7	Lee et al. (2014)
		CBM-CFS3	34.1	This study
	2010	Statistical model	72.9	Nam et al. (2015)
CBM-CFS3		68.0	This study	

Soil organic matter

Soil organic matter density shows a very small decrease from about 60.7 Mg C ha⁻¹ to 59.3 Mg C ha⁻¹ (Fig. 4e). This changing pattern of soil organic matter C stocks could be partially explained by future climate data used as input data, as future air temperature is predicted to increase under the A1B scenario and the decomposition rates in the model increases with temperature (Kurz et al. 2009).

Total carbon stock

Simulation results showed that the carbon stocks of total forested areas nearly double from 509.7 to 1007.3 Tg C at a rate of 11.8 Tg C yr⁻¹ (1.96 Mg ha⁻¹ yr⁻¹) during the period 1992-2034, but then stabilize as the annual increment of carbon storage decreases (Fig. 4f). There are three causes for the decrease. First, the annual increment of carbon density declines as the 48.3% of reserved forests in Korea increase in average age, because they are not subject to forest management. Second, increasing biomass removals on managed forests through thinning and clear cutting decreases C density, and third, rising temperatures caused by climate change represented in the model result in greater annual losses of dead organic matter and soil organic horizon carbon through increased heterotrophic respiration in later decades. Temperature in general has an effect on soil respiration and the decay rates of dead organic matter C pools (Peltoniemi et al. 2009).

Results validation

The estimated stocking volumes simulated by the CBM-CFS3 model were compared with the observed stemwood volume data to indirectly validate the estimated biomass C stocks. The time sequence of estimated stocking volumes showed a trend similar to that of observed stocking volumes on a national scale ($R^2 = 0.93$, RMSE = 3.44 - Fig. 5a). According to the Statistical Yearbook of Forestry from NFI (Korea Forest Service 2011), the stocking volume in South Korean forests increased from 42.1 to 125.6 m³ ha⁻¹ between 1992 and 2010. The simulation result showed that it increased from 42.3 to 120.0 m³ ha⁻¹ during that period. As the results were similar, it could be inferred that the model successfully reflected the volume trends of Korean forests, which further

suggests successful reconstruction of age distribution at the national scale, while uncertainties remain for individual stands.

A comparison of model estimates and NFI inventory measurements for litter and soil C stocks showed partial agreement (Fig. 5b). According to NFI, mean carbon density of litter and soil in Korean forests were 6.03 (SD: 3.36) and 60.06 (SD: 44.69) Mg C ha⁻¹, respectively. Estimated values obtained from the CBM-CFS3 model in 2010 were 6.19 and 60.46 Mg C ha⁻¹.

Soil type could affect the decay rate of humus, and ultimately the dead organic matter C dynamics. Even though this research did not consider soil type, the outcome was similar to actual amounts of soil carbon. There were two possible explanations for these results. First, the spatial scale of forests in Korea is not too large to show differences between forest areas, and soil type does not vary by region. Research by Lee et al. (2014) used the Korean Forest Soil Carbon (KFSC) model to estimate the carbon amount of DOM and compared the outcome with NFI data, which proved to be highly accurate except for the Jeju province, even though the research did not consider soil type. The Jeju province is a volcanic island located far from the mainland, and its soil differs greatly from soils on the mainland (Ahn & Chon 2010).

In fact, most research on quantifying litter and soil carbon conducted in Korea has not considered soil type, and it has been proven that carbon stocks mainly differ not because of soil but because of forest type and age class. In addition, forest types are affected by soil types (Webb 1968). Each forest type requires different soil types; therefore, forest type data input into CBM-CFS3 could partially reflect the differences in soil types which can affect forest productivity.

We compared the living forest biomass (AGB and BGB), which have been compared in this study to previous research results from South Korean forests (Tab. 3). First, living biomass estimates of CBM-CFS3 showed a very similar pattern, but were slightly smaller than previous research (Choi & Chang 2004, Lee et al. 2014, Nam et al. 2015). Previous reports did not consider forest management under the Korea Forest Service law, but our research included a certain amount of timber harvest. Therefore, this study, as distinguished from the previous research that used a process-

based model, successfully reflected the changes in annual growing stock (Tab. 3).

Second, the changing trend of C stocks of TAB with forest management showed a similar trend as previous research. Nam et al. (2015) analyzed the changes of carbon storage considering actual and potential forest cover, and the final cutting age in South Korea from 2010-2100 in 10-year periods. In their study, a decrease in the C stock of aboveground biomass in South Korean forests was also found to range from 74.8 Mg C ha⁻¹ in 2040 to 35.3 Mg C ha⁻¹ in 2060, because most forests are anticipated to reach a final cutting age between 2040 and 2060 and, hence, will be cut. Nam et al. (2015) assumed that forest management applies to an entire forest and estimated the changes of C stock in 10-year periods, so the result of the research differs slightly from ours, but the studies show similarities in the trend of changes in C stock.

Volume change through thinning and cutting schedule

According to the regulations of the Korea Forest Service, when the stand of any tree species reaches 25 years of age a thinning activity removing around 25% of its total stand volume should be undertaken. In addition, every tree species has its own final cutting age. In this analysis, therefore, every tree species was thinned by 25% of the total stand volume when the stand age reached 25 years. The thinning happens only once per stand, hence, thinned stands grow continuously until their cutting age and then regenerate to the same tree species. This process was repeated during the 100 years of the CBM-CFS3 simulation. Because most of the mountainous area in South Korea was afforested after the 1970s, a decrease in forest volume by thinning appeared during mid-to-late 1990s when many stands reached 25 years of age. In addition, a large decrease in volume is projected from early 2030 to mid 2040 (Fig. 4f), as most species have a final cutting age of 60 to 70 years.

Management implications for supply of carbon to Korean society

The rate of carbon transfer from Korea's forests to Korean society has changed over time. At the start of the simulation most stands are too young for the final cutting. The amount of carbon transferred out of the forest through thinning and clear felling increases over time and is highly variable (Fig. 4c). The cumulative amount of carbon removed from Korea's forests between 1992 and 2092 is 206.3 Tg C. This is carbon removed from the atmosphere and is available to meet Korea's needs for timber, fiber and energy. Note that despite these transfers of carbon to harvested wood products and bioenergy, ecosystem carbon stocks increased between 1992 and 2092. Sustainable forest management and the continuous supply of timber, fiber and

energy can help contribute to climate change mitigation objectives in Korea. Some of the carbon removed from forests will be transferred to long-lived wood products and will continue to store carbon for many years to come. Moreover, some of the long-lived wood products can displace other emissions-intensive products such as concrete, steel or plastics and further contribute to climate change mitigation objectives (Lemprière et al. 2013).

Uncertainties

Although we estimated C stock values and levels of change within South Korean forests, including biomass and dead organic matter, uncertainties remain. In this study, each C stock values were estimated using carbon emission factors proposed by the Korea Forest Research Institute (2014). According to this report, the average uncertainties of basic wood density, biomass expansion factor, root-shoot ratio were estimated 3.6, 7.0 and 14.9%. These factors to be used are usually species specific (Levy et al. 2004), however, they may also depend on site (Wirth et al. 2004), tree size and age (IPCC 2003, Levy et al. 2004), because these all affect the biomass allocation strategies of the trees. However, we considered that each carbon emission factors were hold value. Our results involved these uncertainties.

In addition, this research did not consider the natural (disease and insect pests, wind damage, landslide) and anthropogenic (forest fires, illegal activities, land cover change) disturbances that occur every year. The forests in Korea suffered an average loss of 152,900 m³ yr⁻¹ of stand volume in an average area of 2561 ha yr⁻¹ in a recent 10 year-span (2001-2010) due to forest fires, logging to address disease and insect pests, and illegal activities (Korea Forest Service 2011 – Fig. 5c). In other words, 0.4% of the total area of forest in Korea is affected by disturbances every year. Furthermore, during the same period, 307.2 K ha yr⁻¹ of forest has been stricken by diseases and pests (Fig. 5d). While most areas (69.6% – Korea Forest Service 2011) experiencing diseases and pests are treated to prevent the breeding of pests or to encourage their extermination, the ecosystem and carbon cycle within these areas is still affected. To enable a more precise and comprehensive assessment of South Korean forest C cycles, some important influences on C balance need to be considered, such as atmospheric CO₂ fertilization (Bellassen et al. 2011), N deposition (Fischer et al. 2011), leaching (Luyssaert et al. 2010), forest area changes (Liski et al. 2006), forest cover changes (Choi et al. 2011), forest growth changes (Byun et al. 2013), illegal activities, and other disturbances (Kurz et al. 2008, Oubrahim et al. 2015).

Conclusions

In this study, the five carbon pools defined in the IPCC GPG in South Korean

forests and their changes from 1992-2092 were estimated through the application of the CBM-CFS3 model using Korean NFI and other forest and climate data. Simulation results showed that the carbon stocks of the total forest area increased from 509.7 to 1007.3 Tg C at a rate of 11.8 Tg C yr⁻¹ during the period 1992-2034. However, forest carbon stocks were projected to decrease due to the thinning and end-of-rotation harvest, as most forested areas will reach the specified cutting age between 2035-2050. Among the four types of dead wood, medium DOM and belowground fast DOM tend to increase with the implementation of forest management practices. This results from the increase of woody debris and dead roots that are left behind after forest management activities, and demonstrates the carbon dynamics within ecosystem pools as affected by forest management. The forest carbon stocks were estimated to gradually increase from 2050-2090 with a low growth rate, because the growth rate of forests classified as restricted area not subject to forest management (approximately 47% of the total forest) decreases as stands age. The carbon dynamics within ecosystem pools according to climate change and forest management were also predicted. Through harvesting, over the 100 year period more than 200 Tg C were transferred from South Korea's forests to meet demands for timber, fiber and energy. A small gradual decrease in soil carbon stocks was predicted, as a temperature increase (according to the climate change scenario applied in this study) enhanced decomposition rates. The results of this study can support the establishment of a national-scale forest carbon budget compliant with international reporting guidelines.

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- Tab. S2** - The optimal regression forms to estimate mean tree height, dominant tree height, site index, mean tree *dbh*, and volume by tree species.
- Tab. S3** - Parameter estimates of the regression models for mean tree height (m) for each tree species.
- Tab. S4** - Site index model used in yield table (Korea Forest Service 2009).
- Tab. S5** - Coefficients for site index and dominant tree height equations by tree species developed by the Korea Forest Service (2009).
- Tab. S6** - Coefficients for mean *dbh* equations by tree species developed by the Korea Forest Service (2009).
- Tab. S7** - Coefficients for volume ($V \text{ ha}^{-1}$) equations by tree species developed by the Korea Forest Service (2009).

Link: Kim_2040@suppl001.pdf

Supplementary Material

Tab. S1 - The whole regression forms to estimate mean tree height, dominant tree height, site index, mean tree *dbh*, and volume.