J. Ecol. Field Biol. 32 (1): 47～53, 2009

Estimating the Soil Carbon Stocks for a *Pinus densiflora* Forest Using the Soil Carbon Model, Yasso

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ABSTRACT: The soil carbon stock for a *Pinus densiflora* forest at Gwangneung, central Korea was estimated using the soil carbon model, Yasso. The soil carbon stock measured in the forest was 43.73 t C ha^{-1}, and the simulated initial (steady state) soil carbon stock and the simulated current soil carbon stock in 2007 were 39.19 t C ha^{-1} and 38.90 t C ha^{-1}, respectively. Under the assumption of a 0.1℃ increase in mean annual temperature per year, the decomposition and litter fractionation rates increased from 0.28 to 0.56 % $year^{-1}$ and the soil carbon stock decreased from 0.03 to 0.12 % $year^{-1}$. Yasso is a simple and general model that can be applied in cases where there is insufficient input information. However, in order to obtain more accurate estimates in Korea, parameters need to be recalibrated under Korean climatic and vegetation conditions. In addition, the Yasso model needs to be linked to other models to generate better litter input data.

Key words: Litter decomposition process, *Pinus densiflora*, Soil carbon model, Yasso

INTRODUCTION

After the UNFCCC (1997) demanded that all sources and sinks of carbon dioxide be reported in the Kyoto protocol, people realized the possibility of including soils as credited carbon sinks. Measuring the soil carbon stock and its changes is difficult because the carbon density varies considerably depending on spatial difference (Morisada et al. 2004). In addition, the analysis requires enormous resources of time, capital and researchers. Therefore, the measured values for the soil carbon stock are lacking in many regions (Liski et al. 2002). In this circumstance, a soil carbon model will be useful for predicting the soil carbon dynamics (Powlson et al. 1996), and exploring the consequences of different environmental and forest management scenarios (Paul et al. 2003). Furthermore, simulated estimates will also be useful in approximating the number of samples needed when one decides to measure the changes in soil carbon (Liski et al. 2005).

Among the many soil carbon models, CENTURY (Kelly et al. 1997) and RothC (Coleman and Jenkinson 1996) are the most widely used and validated soil carbon models in many countries. Although both models were developed for grasslands (CENTURY) and arable lands (RothC), they have recently been applied to forest soils (Falloon and Smith 2002). On the other hand, DocMod (Currie and Aber 1997) and ROMUL (Chertov et al. 2001) were originally developed for forest soils. However, these models are difficult to apply to general forestry because they would require variety of input data that is usually unavailable in basic forestry information (Liski et al. 2005).

The soil carbon model, Yasso, is simple because it requires limited input data but, still can account for the dynamics of carbon in forest soils giving reliable results under variety of climatic and spatial conditions (Liski et al. 2005). The Yasso model has already been applied as a soil carbon module in CO2FIX (Masera et al. 2003), MOTTI (Hynynen et al. 2005) and EFISCEN (Karjalainen et al. 2002). Overall, Yasso is a feasible alternative to other soil carbon models because of the simple input data, general structure, and easy application (Palosuo et al. 2005).

In Korea, there have been very few studies on soil carbon modeling as well as its applications (Lim et al. 2003). Consequently, we are in the initial stages of developing a soil carbon model, particularly for forests. The objectives of this study were 1) to apply soil carbon model Yasso for a *P. densiflora* forest to estimate the soil carbon stock, and 2) to present implications of applying this for forests in Korea.

MATERIALS AND METHODS

Soil Carbon Model Yasso

The Yasso model estimates the soil carbon stock as a function of the litter input and requires the annual climatic and litter input data for operation. The model consists of a non-woody litter com-

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partment (nwl), two woody litter compartments (fine woody litter (fwl) and coarse woody litter (cwl)) and five decomposition compartments (extractives (ext), celluloses (cel), lignin-like compounds (lig), faster decomposing humus (hum1) and slower decomposing humus (hum2)) (Fig. 1). The materials cascade from the compartments with a rapid decomposition rate to the ones with a slow decomposition rate (Faubert et al. 2005). In Yasso, these dynamics are represented by several equations. A detailed description of the model was reported by Liski et al. (2005).

Both woody-litter compartments have fractionation rates (a_i), that determine the proportions of their contents released to the decomposition compartments. Each decomposition compartment has a decomposition rate, k_j, that determines the proportional loss of its contents at each time step, and a share of the mass, *p,* that is transferred to the subsequent compartments. The rates of decomposition and fractionation are affected by the temperature (T) and summer drought (D) (Eqs. (1) and (2)) (Liski et al. 2005, Peltoniemi et al. 2004).

$$a_i\ (T,\ D) = a_{i0}\ (1+\beta\ (T-T_0)+\gamma\ (D-D_0)) \quad (1)$$

$$k_j\ (T,\ D) = k_{j0}\ (1+S_j\ \beta\ (T-T_0)+\gamma\ (D-D_0)) \quad (2)$$

where the subscript zero represents the climatic values under standard condition, which were used to develop and calibrate Yasso in Europe, β and γ are the temperature and summer drought effects, respectively, and S_j is a variable reflecting the difference in temperature sensitivity in each compartment.

Study Area

The model was applied to a 55 to 75 year-old *P. densiflora* forest at Gwangneung Experimental Forest (37° 47' 01" N, 127° 10' 37" E, 425 m a.s.l.) near Seoul, Korea from January through December, 2007 (Fig. 2). The climate represents a central continental climate (You et al. 2000). The mean annual temperature and precipitation are 11℃ and 1,335 mm respectively. Approximately 79% of the annual precipitation falls during the growing season (May to September). Six 20×20m plots were located within the study site. Stem density (number of trees per ha) and diameter at breast height (cm) were 425 and 33.1 for plot 1, 400 and 31.1 for plot 2, 675 and 30.0 for plot 3, 1,200 and 21.6 for plot 4, 650 and 31.3 for plot 5, and 875 and 22.2 for plot 6, respectively.

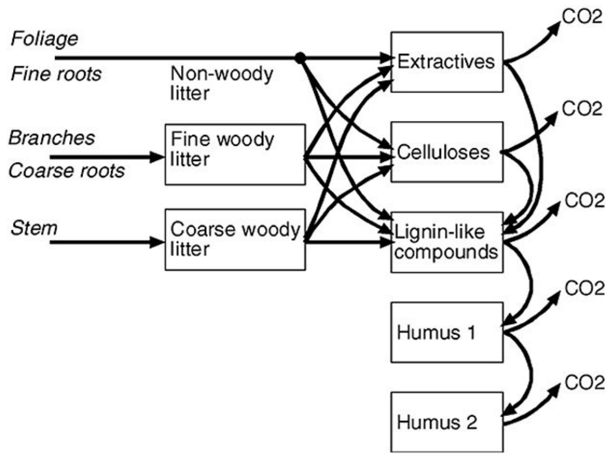

Fig. 1. Flow chart of the soil carbon model Yasso. The boxes indicate carbon compartments and the arrows indicate carbon fluxes (Liski et al. 2005).

Preparation of Input Data Needed to Run Yasso

Climatic Data

The climatic data needed to run the model include temperature and drought. The thirty-year (1971~2000) normals and 7-year (2001~2007) annual climatic data (i.e., mean monthly temperature, precipitation (Ppt.) and potential evapotranspiration (PET) were used for the weather stations nearest the study site. This means that the effect of yearly variations in climate was not considered (Palosuo et al. 2005). From the climatic data, the drought index and mean annual temperature (MAT) were calculated (Table 1). The reason why two sets of climatic data were chosen from different periods was to reflect the latest trend of climate change.

Yasso was calibrated using the Priestley-Taylor equation (Liski et al. 2003). However, unlike Europe, in Korea, PET could not be calculated using this method because of the lack of long-term radiation data. Therefore, the Thornthwaite method was used to estimate the PET, even though it is less accurate, because it provides effective estimates of the soil carbon stock and is calculated easily (Palosuo et al. 2005).

Litter Input

The litterfall (foliage and branch) was collected from 30 litter traps of the 6 plots in the *P. densiflora* forest in 2007, and the mean annual litter input, which assumed a constant value under normal conditions (steady state), was determined as total average of 2.5 t C ha^{-1} (including 1.9 t C ha^{-1} of foliages and 0.6 t C ha^{-1} of

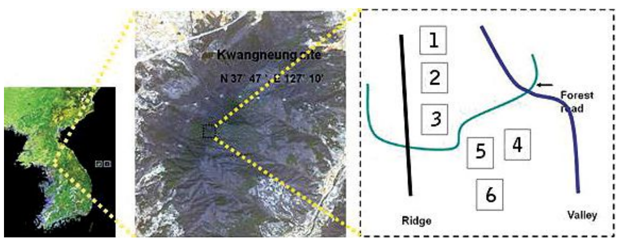

Fig. 2. Study site and plot location in central Korea.

Table 1. Climate data used as model input values for the *P. densiflora* site located in Gwangneung Experimental Forest

	MAT (℃)[a]	Ppt. (mm)[b]	PET (mm)[c]	D (mm)[d]
1971～2000 (for initial climate) data	10.80	989	584	0
2001～2007 (for current climate) data	11.84	1,209	603	0

[a] Mean annual temperature.
[b] Precipitation from May to September.
[c] Accumulated potential evapotranspiration from May to September calculated from mean monthly temperatures using the Thornthwaite method (Thornthwaite, 1948).
[d] Summer drought variable, Ppt. - PET if < 0.

branches). The stems and roots (coarse and fine) were not included in simulation due to the difficulty in measuring their annual input.

Model Initialization

The soil carbon stock was initialized by assuming them to be in a steady state by a spin-up run prior to the actual simulation run (Schmid et al. 2006). For initialization, climatic data (thirty-year normals) and the annual litter input data in 2007 were used. The resulting initial soil carbon stock was an average of 39.19 t C ha^{-1}, and it takes approximately 4,000 years until the stock reaches a steady state. Setting the initial soil carbon stock is important because the initial stock value strongly affects the estimation of the accumulation rate of soil carbon (Peltoniemi et al. 2004).

Model Parameterization

In the Yasso model, the standard values were first determined for climate conditions typical for southern Finland and middle Sweden, which were 3.3℃ for the MAT, −32 mm for the Drought index, 0.105 for β as the effect of MAT, and 0.00274 for γ as the effect of drought. The reference values were the default parameter values under standard conditions and were changed according to the forest type. For the fractionation and decomposition rates, the values were determined using the equations depending on the reference values and differences in the standard conditions. Their default values were used for the proportion of decomposed mass and, the values based on a *P. sylvestris* forest were used for the share of chemical compounds (Table 2).

Model Simulation

Current and Future Soil Carbon Stocks

The current and future soil carbon stocks were estimated using

Table 2. Parameter values of the model under the reference (Peltoniemi et al. 2004) and the current study

Parameter	Reference	Current study
Fractionation rates ($year^{-1}$)		Depending on climatic condition
Fine woody litter (a_{fwl})	0.54	
Coarse woody litter (a_{cwl})	0.030 or 0.077	
Decomposition rates ($year^{-1}$)		
Extractives (k_{ext})	0.48 or 0.82	Depending on climatic condition
Celluloses (k_{cel})	0.30	
Lignin-like compounds (k_{lig})	0.22	
Fast humus (k_{hum1})	0.012	
Slow humus (k_{hum2})	0.0012	
Formation of more complex compounds in decomposition (proportion of decomposed mass)		
Extractives to lignin-like compounds (p_{ext})	0.2	0.2
Celluloses to lignin-like compounds (p_{cel})	0.2	0.2
Lignin-like compounds to faster humus (p_{lig})	0.2	0.2
Faster humus to slower humus (p_{hum})	0.2	0.2
The share of chemical compounds, c_i in nonwoody, nwl, fine woody, fwl and coarse woody, cwl.		
$c_{nwl \to ext}$	0.27 or 0.06 or 0.38	0.27
$c_{nwl \to cel}$	0.51 or 0.54 or 0.36	0.51
$c_{fwl \to ext}$	0.03	0.03
$c_{fwl \to cel}$	0.66 or 0.61 or 0.65	0.66
$c_{cwl \to ext}$	0.03 or 0.01	0.03
$c_{cwl \to cel}$	0.69 or 0.71	0.69

Yasso. In particular, the future soil carbon stock was predicted assuming, the following: 1) there are no climate changes between the current and future, 2) there are no natural and anthropogenic disturbances such as fire, thinning, epidemics, etc, and 3) the *P. densiflora* forest is in a steady state. Therefore, the future litter input is the same amount compared with the current litter input.

Changes in Soil Carbon Stock Under Changing Climate

To examine the changes in the parameters and soil carbon stock in Yasso under a changing climate, it was assumed that there was a 0.1℃ increase in the MAT per year starting from same state with the initial (steady state) condition with a constant litter input.

Soil Carbon Measurements

Five soil samples up to 30 cm depth per plot were randomly collected in 2007. Soil samples were air-dried and sieved to pass through a 2 mm sieve. Soil carbon concentrations were analyzed using the vario MACRO analyzer (Elementar Analysensysteme GmbH, Germany), and soil carbon contents were calculated by multiplying soil depth, bulk density and soil carbon concentration.

RESULTS AND DISCUSSION

Parameter Estimation of Yasso for the *P. densiflora* Forest in Korea

First of all, the model overestimated the decomposition rates for the *P. densiflora* forest in Korea. Palosuo et al. (2005) reported an overestimation of the decomposition rates in Canada. The Yasso model was developed in European countries and was based on the parameters determined in Europe. However, there are considerable differences in the climatic and spatial conditions between Europe and Korea, which can affect the parameters and process of Yasso in an unknown way. Next, the reference parameters of *P. sylvestris* forest were used as a share of the chemical compounds in each soil compartment, because there was no related information in a *P. densiflora* forest available. This might increase the uncertainty of the estimates.

Soil Carbon Stock in the *P. densiflora* Forest

Measured and Simulated Current Soil Carbon Stock

The measured and simulated soil carbon stocks were 43.73 and 38.90 t C ha^{-1} on average in the *P. densiflora* forest (Table 3). Simulated current carbon stocks among soil components were presented in Fig. 3. Generally, the measured soil carbon stocks mostly exceeded the simulated stocks (Fig. 4). On the other hand, while the soil carbon stocks of Yasso represents the total carbon up to a 1 m depth (Peltoniemi et al. 2004), most of the forest soil depths in Korea were between 31 to 60 cm (Jung et al. 2004), and the total soil carbon contents were measured to 30 cm depth in the current study. More adequate comparisons can be made when the data is fitted the same standard depth. Consequently, the simulated current soil carbon stock can be underestimated due to 1) considerable omission of the litter inputs, such as stem, coarse and fine roots and understory vegetation because there is insufficient litter input data in Korea and 2) overestimation of the decomposition rates when simulating Yasso.

Table 3. Measured and simulated current soil carbon stocks for a *P. densiflora* forest

Plots	Simulated (0~100 cm)		Measured (0~30 cm)
	Total (litter + soil) (t C ha^{-1})	In soils (t C ha^{-1})	In soils (t C ha^{-1})
1	35.92	35.38	54.03
2	40.58	39.65	36.41
3	47.08	46.26	51.23
4	35.44	34.99	45.89
5	42.87	42.25	45.28
6	35.29	34.86	39.56
Average (SE)	39.53 (2.0)	38.90 (1.9)	43.73 (3.2)

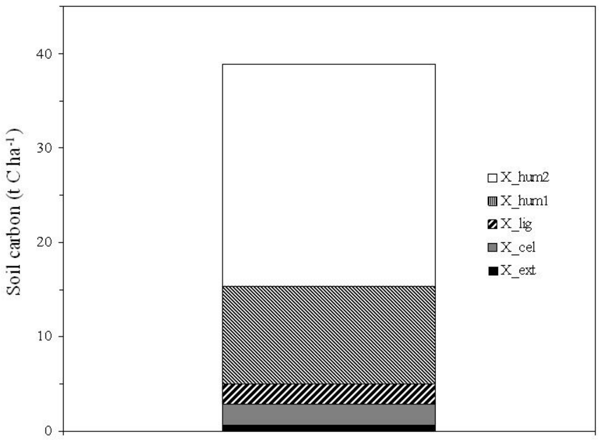

Fig. 3. Simulated current carbon stocks in soil components.

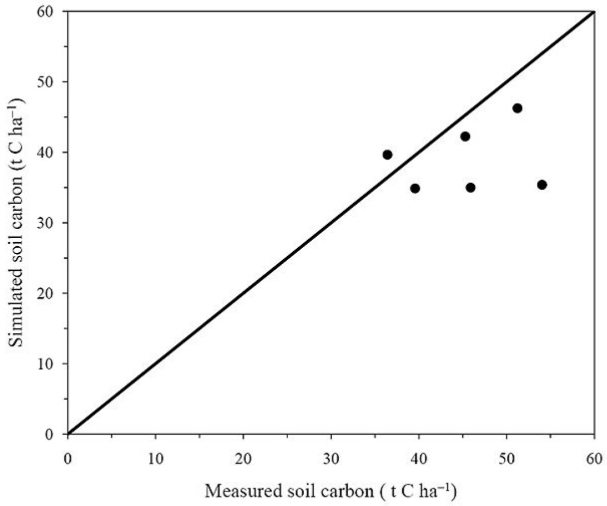

Fig. 4. Comparison of measured and simulated current soil carbon stocks. Each point represents a study plot.

Nakane et al. (1984) reported that the soil carbon stock was estimated to be about 47.0 t C ha^{-1} for a *P. densiflora* forest in Japan. Jeon et al. (2007) and Kim (2006) reported a soil carbon stock of 84.6 t C ha^{-1} 50 cm-$depth^{-1}$ and 102.6 t C ha^{-1} 30 cm-$depth^{-1}$ for *P. densiflora* forests in Korea, respectively. In this way, there can be considerable deviations in soil carbon stock according to the different climate and spatial characteristics (e.g. species, stand age, soil characteristics, etc.). On the other hand, in the present study, the simulated and measured soil carbon stocks were estimated to be 39～44% of the biomass values of the trees (Noh 2008, unpublished data). At the landscape scale in Finland, the potential carbon stock of soils was estimated to be 30～70% of the stock of trees, depending on forest management (Karjalainen et al. 1996). Therefore, the simulated soil carbon stock is probably within a similar range of estimates.

Estimating Future Soil Carbon Stock

The soil carbon stock for this region decreased each year compared to the current soil carbon stock and it was estimated to be 38.64 t C ha^{-1} at 2070 (Fig. 5). This estimate is related to the faster fractionation and decomposition rates as a result of the increasing MAT because the latest temperature (2001～2007 average) was approximately 1℃ higher than the long term normal temperature (1971～2000 average) and temperature generally has a positive effect on the carbon dynamics in soil, such as decomposition and fractionation rates (Peltoniemi et al. 2004).

Simulated Changes in the Soil Carbon Stock in Proportion as Climate Changes

When MAT increased 0.1℃ per year in Yasso, the parameters and resulting soil carbon stock changed in proportion to temperature (Table 4). The decomposition and litter fractionation rates increased up to 0.56% annually, because they are a function of the temperature and drought effects. Among the decomposition rates depending on the carbon compartment, the rates of the humus compartments increased less than the others, 0.40% for k_{hum1} and 0.28% for k_{hum2} annually. This is because humus is less sensitive to temperature (Liski et al. 2005). Consequently, the soil carbon stock decreased from 0.03 to 0.12 % annually (Fig. 6).

Improvement of Yasso Model for Forest Soils in Korea

In order to overcome the limitations and uncertainties of soil carbon simulations using Yasso, an attempt was made to improve the accuracy of the simulated estimates using following processes. First, correct climatic and litter input values are needed in Yasso.

Table 4. Annual changes of the parameters and soil carbon stock following the increase of 0.1℃ per year

	Annual changes (%)
The decomposition rate	
k_{ext}	+0.56
k_{cel}	+0.56
k_{lig}	+0.56
k_{hum1}	+0.40
k_{hum2}	+0.28
The litter fractionation rate	
a_{fwl}	+0.56
a_{cwl}	+0.56
Total soil carbon stock	−0.12 to −0.03

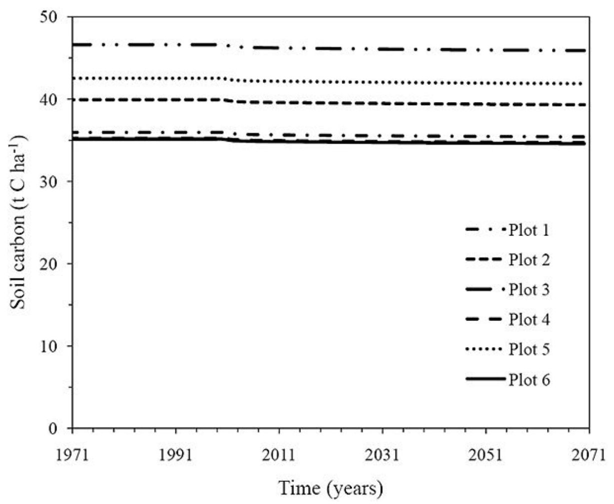

Fig. 5. Estimated soil carbon stocks from 1971 through 2070.

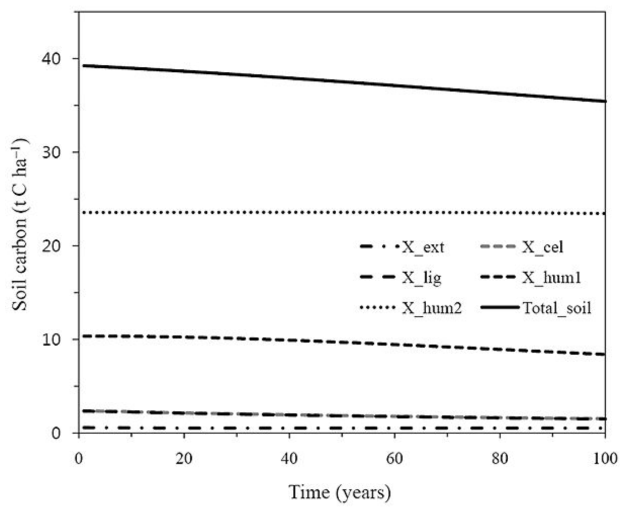

Fig. 6. Estimates of changing soil carbon stocks with time.

For this, the establishment of a long-term dataset (i.e. litterbag, measured soil carbon stock, forest inventory data and so on) is the highest priority for developing a model or applying existing models. On the other hand, the litter input data in future are needed to predict the changes in soil carbon stock, which can be calculated by multiplying the biomass estimates by the biomass turnover rates (Karjalainen et al. 2002, Masera et al. 2003) or simulated by linkage with other ecosystems or carbon models. In addition, it is useful to generate litter input when there is insufficient for modeling. Second, recalibration of the parameters in Yasso using the Korean data may improve the estimation accuracy of soil carbon stocks when applying the model outside of Europe (Palosuo et al. 2005). In particular, there is a need to recalibrate the decomposition rate of the extractive that was overestimated in Korea. Third, it is important to deal with a few criticisms of Yasso model. Although Yasso provides good estimates of the measured values in various climatic and spatial conditions and accounts for the decomposition cycle in soils (Liski et al. 2005, Peltoniemi et al. 2004), there are still problems that need to be overcome. For example, there is limited reliability on the litterbag experiment (Liski and Westman 1995), uncertain division between the organic and mineral soil layers (Peltoniemi et al. 2004) and the omission of the soil carbon contribution from ground vegetation.

CONCLUSIONS

The soil carbon model, Yasso, can be a useful method for estimating the soil carbon stock in Korea considering its compact characteristics and the status of modeling in Korea. Although there are several limitations, the simulated soil carbon stock using Yasso was similar to the measured one for the *P. densiflora* forest. In order to obtain more accurate estimates from Yasso and indicate the carbon dynamics in soils, Yasso needs to be recalibrated using the Korean data and past and future litter input values need to be generated from estimates of other ecosystems or carbon models. Linking Yasso to other models might help compensate for the insufficient input data. In further research, an attempt will need to generalize the Yasso model to many regions, such as different forests, countries or continents with various species.

ACKNOWLEDGEMENTS

This study was supported by the Korea Science and Engineering Foundation (KOSEF) (Grant No. R01-2006-000-10863-0; A307-K001) and Graduate School of Specialization to Specify Climate Change Project of the Ministry of Environment. The authors wish to thank Dr. M.S. Lee for her review and valuable comments.

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(Received February 9, 2009; Accepted February 15, 2009)