Development of a forest carbon and nitrogen model: Pilot application for a Pinus densiflora forest in Central Korea

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ABSTRACT
This study aimed to develop a forest carbon (C) and nitrogen (N) model, known as the Forest Biomass and Dead organic matter Carbon And Nitrogen (FBDCAN), which can be useful under limited input data availability. An N module was designated with three N pools (biomass, dead organic matter, and soil inorganic N) and ten N cycle processes (N deposition, biological N fixation, N mineralization, immobilization, root N uptake, retranslocation, nitrification, N leaching, denitrification, and turnover), and then integrated into an existing forest C model. A pilot application was carried out for a Pinus densiflora forest in Gwangneung Experimental Forests (PGEF), to verify the performance and reliability of the model. The simulated net N mineralization in 2010 (69.91 kg N ha⁻¹yr⁻¹) was within the observed range in PGEF. Furthermore, the simulated N stock (3.91 Mg N ha⁻¹) based on the FBDCAN model was consistent with the observed N stock (4.13 Mg N ha⁻¹) in PGEF ($r^2 = 0.96$ to 0.99). The newly developed forest C and N model could be used for the estimation of N cycle processes, N stock, and C stock, even in regions where the input data availability is low.

Introduction
Nitrogen (N) is a fundamental element in living organisms, and the N cycle is tightly connected to the carbon (C) cycle in forests (Binkley and Fisher 2013). For example, higher N concentration in foliage leads to higher rate of tree biomass C sequestration (Binkley and Fisher 2013), and soil N stocks have been suggested as indicators of C sequestration in soils (Akselsson et al. 2005). Meanwhile, forest C cycle also affects the forest N cycle. C in dead organic matter (DOM) is the main energy source of microbes involved in N transformation, and therefore, the amount of C supply to the microbes can accelerate or decelerate N mineralization and immobilization processes (Nilglgard 2012; Wang et al. 2018). Moreover, the relative fraction of C and N in DOM controls the decomposition rate, affecting CO₂ emission and mineralization rate (Berg and McClaugherty 2008; Högberg et al. 2017). Therefore, the study of forest N cycle needs to be conducted in conjunction with that of the forest C cycle, and vice versa.

Modeling is a cost-effective tool that can simulate forest C and N cycles for broad spatial and temporal scales. In particular, review articles have shown that development of models that consider the interaction between C and N can increase the simulation accuracy for both C and N cycles (Medlyn et al. 2011; Zaehle and Dalomech 2011; Drewniak and Gonzalez-Meler 2017). Accordingly, many models have been modified to combine C and N cycles. For example, the VISIT model uses soil respiration rate to estimate N₂O emission, and the Forest-DNDC model simulates nitrification and denitrification by using the concentration of dissolved organic C as input data (Li et al. 2000; Gilhespy et al. 2014; Ito et al. 2018).

However, there are some caveats in this modeling approach. First, these models are not feasible for countries where input data availability is limited (Yi et al. 2013; Han et al. 2014), as they typically require data such as hourly mean air temperature, net radiation, precipitation, relative humidity, wind speed, and soil texture at the national scale (Kim et al. 2018). Second, although N models can simulate N flows among the atmosphere, forests, and water systems, modeling studies that consider the N stocks are still rare compared to the ones that consider C stocks (Lo et al. 2015).

This study aimed to develop a forest C and N model, called the Forest Biomass and Dead organic matter Carbon and Nitrogen (FBDCAN), to enable the estimation of forest C and N dynamics under limited input data availability. For the development of this model, an N module was designated and integrated with a previously developed forest C model, known as the Forest Biomass and Dead organic matter Carbon...
Furthermore, a pilot application of the FBDCAN model was conducted to evaluate the reliability and limitation of the FBDCAN model in a *Pinus densiflora* forest, which is a representative species in Korea (Kim et al. 2017; Baek et al. 2018).

**Materials and methods**

**Structure of the forest C and N model**

The N module in the FBDCAN model was designated by connecting three N pools (biomass, DOM, and soil inorganic N) with ten N cycle processes (N deposition, biological N fixation, N mineralization, immobilization, root N uptake, retranslocation, nitrification, N leaching, denitrification, and turnover) based on a previous study for the development of forest C and N models (Figure 1; Kim et al. 2018). This N module requires input data such as air temperature, precipitation, and N deposition. The main N flows in the three N pools were simulated as follows (Table 1): (1) biomass N stock was calculated using root N uptake, retranslocation, and turnover, (2) DOM N stock was calculated using turnover, immobilization, and N mineralization, and (3) soil inorganic N stock was calculated using N deposition, biological N fixation, N mineralization, immobilization, root N uptake, nitrification, N leaching, and denitrification. Finally, the change in total N stock can be summarized as the addition of N deposition and biological N fixation to the existing N stock and the subtraction of N leaching and denitrification from the existing N stock, as follows:

\[
\text{TotalN}(t+1) = \text{TotalN}(t) + N_{\text{dep}}(t)_{\text{NH4+}} + N_{\text{dep}}(t)_{\text{NO3-}} + N_{\text{NN}}(t) - N_{\text{leach}}(t) - N_{\text{denit}}(t)
\]  

(1)

* Total N(t): total N stock at time t
* \(N_{\text{dep}}(t)_{\text{NH4+}}\), \(N_{\text{dep}}(t)_{\text{NO3-}}, N_{\text{NN}}(t), N_{\text{leach}}(t), \) and \(N_{\text{denit}}(t)\): explained in Table 1
* More detailed information on the N cycle processes is presented in Table A1.

**Integration of the N module into the Forest C model**

The N module was integrated into the FBDC model, which simulates forest C dynamics with three C cycle processes: tree growth, turnover, and decay (Figure 1: process 10 to 12; Yi et al. 2013; Lee et al. 2014). The FBDC model requires air temperature, species, and stand age as input data. This model has been applied to the temperate, tropical, and alpine regions in various developing countries (Yi et al. 2013; Lee et al. 2014, 2016, 2017, 2018a, 2018b). The detailed description of the FBDC model can be found in the studies by Yi et al. (2013) and Lee et al. (2014).

A variable based on Mitcherlich’s Law was used in the FBDCAN model to integrate the C and N cycles. This variable was used to limit the tree biomass C sequestration when N availability is low, as follows (Mitchell and Chandler 1939; Aber et al. 1979; Schneeberger 2010):

\[
N_{\text{int}}(t) = (\text{int}_a - \text{int}_c) \times (1 - \text{exp}(-\text{int}_b \times (\text{SoilinorganicN}(t))) + \text{int}_c
\]  

(2)

* \(N_{\text{int}}(t)\): degree of N limitation effect on tree biomass C sequestration at time t
* Soil inorganic N(t): N stock in soil inorganic N pool at time t
* \(\text{int}_a, \text{int}_b, \text{int}_c\): constants (Table A2)

To apply this N limitation effect on tree biomass C sequestration, \(N_{\text{int}}(t)\) was integrated into the biomass...
### Table 1. The main equations in the FBDCAN model.

| Pool name | Equation |
|-----------|----------|
| Biomass \( N(t+1) \) | \( = \text{Biomass}\(N(t) + N_{\text{imm}}(t) - N_{\text{ru}}(t) \) |
| DOM \( N(t+1) \) | \( = \text{DOM}\(N(t) + N_{\text{imm}}(t) - N_{\text{ru}}(t) \) |
| Soil inorganic \( N(t+1) \) | \( = N_{\text{ru}}(t+1) + NO_3^-(t+1) \) |
| \( NH_4^+(t+1) \) | \( = NH_4^+(t+1) + \left[ N_{\text{ru}}(t+1) \right]_{\text{NH}_4^+} \) |
| \( NO_3^-(t+1) \) | \( = NO_3^-(t) \) |

\( N_{\text{ru}}(t) \): turnover of \( N \) in the pool names as \( k \) at time \( t \); \( N_{\text{ru}}(t) \): retranslocation at time \( t \); \( N_{\text{imm}}(t) \): immobilization at time \( t \); \( N_{\text{dep}}(t) \): deposition to the pool named as \( k \) at time \( t \); \( N_{\text{fix}}(t) \): biological \( N \) fixation at time \( t \); \( N_{\text{leach}}(t) \): leaching at time \( t \); \( N_{\text{uptake}}(t) \): uptakes of \( N \) by plant at time \( t \) and \( N_{\text{net}}(t) \): the net uptake rate of \( N \) by the planting at time \( t \).

\( V_{\text{FBDC}}(t) \): volume estimated by the FBDC model at time \( t \) (Yi et al. 2013)

\( W_d \): wood density (Table A2)

\( C_{\text{con}} \): concentration (assumed as 50%; Penman et al. 2003)

### Table 2. The observed \( C \) and \( N \) stocks in a 70-year-old \( P. \text{densiflora} \) forest in Gwangneung Experimental Forests (Noh et al. 2013).

| Plot number | 1 | 2 | 3 | 4 | 5 | 6 |
|-------------|---|---|---|---|---|---|
| C stocks (Mg C ha\(^{-1}\)) | 13.9 | 13.8 | 15.6 | 11.6 | 13.9 | 16.6 |
| Soil (0–30 cm) | 0.141 | 0.151 | 0.167 | 0.133 | 0.154 | 0.171 |
| N stocks (Mg N ha\(^{-1}\)) | 0.540 | 0.617 | 0.776 | 0.885 | 0.589 | 0.674 |
| Soil (0–30 cm) | 3.143 | 3.814 | 3.212 | 3.913 | 2.812 | 2.91 |

**Simulation procedures**

Due to the lack of empirical data on \( N \) stocks before the harvesting, an initialization was required for the FBDCAN model. We initialized the model with a spin-up process and took into account the effect of harvesting in 1912 on the \( C \) and \( N \) stocks (McGuire et al. 1992; Kurz et al. 2009; Ajami et al. 2014). After the initialization, we simulated the \( N \) cycle processes and \( N \) stocks in PGEF with the FBDCAN model from 1950 to 2010, using input data such as air temperature (Korea Meteorological Administration (KMA) 2019), precipitation (Korea Meteorological Administration (KMA) 2019), \( N \) deposition (Hegglin et al. 2016), species (Noh et al. 2013), and stand age (Noh et al. 2013). The ability of the FBDCAN model was assessed by tracking the major \( N \) cycle processes such as net \( N \) mineralization, \( N \) leaching, and tree \( N \) uptake, the latter assumed as the sum of \( N \) uptake and \( \Delta N \) retranslocation.

**Verification**

The simulated \( N \) stocks in 2010 were verified through comparison with the observed \( N \) stocks in PGEF. To investigate the consistency between the simulated and observed \( N \) stocks, a regression analysis \((n=6)\) was conducted using the PROC REG function in SAS 9.4 software (Statistical Analysis System Institute (SAS) 2014). Furthermore, the total \( C \) stock in 2010 was simulated to identify the effect of \( N \) module integration on the \( C \) stock estimation by the FBDCAN model, and was compared with the simulated \( C \) stock by the FBDC model and the observed \( C \) stock \((n=6)\) using the PROC ANOVA function in SAS 9.4 software (Statistical Analysis System Institute (SAS) 2014). A sensitivity analysis was also conducted for the FBDCAN model. As the \( C \) stock and \( N \) leaching are related to forest productivity and soil \( N \) availability, these values were selected as the targets of the sensitivity analysis. Although the sensitivity analysis followed the same simulation procedures for the \( N \) cycle processes and \( N \) stock, it was conducted by changing the \( N \) deposition rate by 40% to 160%, relative to the original \( N \) deposition data (Lee et al. 2018b).

**The pilot application**

**Study site**

The pilot application of the FBDCAN model was performed in a 70-year-old \( P. \text{densiflora} \) forest in Gwangneung Experimental Forests (PGEF; 37° 47’ 01” N, 127° 10’ 37” E), which had naturally regenerated following the harvesting in 1912 (Noh et al. 2013). PGEF belongs to temperate climate, and the mean annual temperature and precipitation from 1998 to 2018 was 11.4°C and 1,457 mm, respectively (Korea Meteorological Administration (KMA) 2019). Six \( 20 \text{ m} \times 20 \text{ m} \) plots were established in 2006, and \( C \) and \( N \) stocks, tree biomass \( C \) sequestration, litter fall, soil respiration, and \( N \) mineralization were continuously measured from 2006 to 2010. In particular, the \( C \) stocks observed in 2010 were used as comparable values to validate the prototype of the FBDC model (Yi et al. 2013). In this study, the newly developed model was validated using the \( N \) stocks observed in 2010 as comparable values.
Results

N cycle processes and N stocks

The net N mineralization and tree N uptake varied with time (Figure 2(a)). Net N mineralization decreased from 56.06 to 50.87 kg N ha\(^{-1}\) yr\(^{-1}\) until 1966, and then increased to 69.91 kg N ha\(^{-1}\) yr\(^{-1}\) until 2010. Tree N uptake increased from 10.86 to 55.62 kg N ha\(^{-1}\) yr\(^{-1}\) until 1986, and then decreased to 53.93 kg N ha\(^{-1}\) yr\(^{-1}\) until 2010. Overall, the net N mineralization was higher than the tree N uptake, except from 1973 to 1982. The difference in net N mineralization and tree N uptake decreased with time, but the difference began to increase after mid-1980s.

Although N deposition increased gradually from 1950 to 2010, N leaching dropped from 6.91 to 2.31 kg N ha\(^{-1}\) yr\(^{-1}\) until 1983, and then increased to 4.12 kg N ha\(^{-1}\) yr\(^{-1}\) in 2010 (Figure 2(b)). Until the mid-1960s, the N leaching was higher than N deposition, but N deposition exceeded the N leaching after mid-1960s. The cumulative difference in N deposition and N leaching from 1950 to 1965 and from 1966 to 2010 was 42.29 and 210.66 kg N ha\(^{-1}\), respectively.

During the simulation period, the mean annual N stock changes in biomass, forest floor, and soil were 9.86, 0.82, and 10.20 kg N ha\(^{-1}\) yr\(^{-1}\), respectively (Figure 3(a)). The N stock in biomass consistently increased during the simulation period. However, the N stocks in forest floor and soil decreased until 1956 and 1963, respectively, after which, they started to increase. Since the mid-1980s, biomass, forest floor, and soil, all contributed to the increase in total N stock, but the trend of overall increase gradually declined. Meanwhile, the total N stock in PGEF increased from 2.61 to 3.91 Mg N ha\(^{-1}\) during the simulation period (Figure 3(b)). Most of the total N stock was stored in soil (89%), followed by the biomass (9%) and forest floor (2%). In particular, the soil and biomass pool primarily led to the increase in total N stock (0.62 and 0.60 Mg N ha\(^{-1}\), respectively).

Verification

The results for simulated N stocks were consistent with the observed N stocks (Figure 4). The averages of the simulated and observed N stocks (average ± standard deviation; Mg N ha\(^{-1}\)) in soil were 3.17 ± 0.59 and 3.30 ± 0.42, respectively. The slope of the regression model for the soil was 0.96 (\(r^2 = 0.98\)). Meanwhile, the mean of the simulated and observed N stock in biomass (Mg N ha\(^{-1}\)) was 0.63 ± 0.12 and 0.68 ± 0.12, respectively. The slope of the linear
relationship of these biomass N stocks was 0.93 ($r^2 = 0.92$). However, the N stock in the forest floor was underestimated. The average of the simulated and observed N stocks in forest floor (Mg N ha$^{-1}$) was 0.10 ± 0.02 and 0.15 ± 0.01, respectively, and the slope of the linear relationship for these N stocks was 0.65 ($r^2 = 0.96$).

The reliability of the FBDCAN model for C stock estimation was higher than that of the FBDC model (Figure 5(a)). The slopes of the linear regression for simulated C stock by the FBDCAN and FBDC model to the observed C stock were 0.97 ($r^2 = 0.99$) and 1.07 ($r^2 = 0.99$), respectively, showing a 4% increase in the reliability of estimation. There was no significant difference in the simulated C stocks and the observed C stocks (Figure 5(b)). The mean observed total C stock (average ± standard deviation; Mg C ha$^{-1}$) in PGEF was 151.80 ± 15.64, and the mean simulated total C stock by the FBDCAN and the FBDC model was 147.21 ± 11.55 and 162.84 ± 10.60, respectively. This demonstrates that the N module integration reduced the mean difference in the simulated and the observed C stock from 11.04 to 4.59 Mg C ha$^{-1}$.

Sensitivity analysis showed that the simulated C stock in 2010 was positively related with the N deposition (Figure 6). The C stock increased from 89.80 to 149.86 Mg C ha$^{-1}$, upon a change in N deposition by 40% to 160%, relative to the original value. Meanwhile, the N leaching increased from 3.04 to 6.51 kg N ha$^{-1}$ yr$^{-1}$, when N deposition increased from 60% to 160%. However, on the contrary, the N leaching decreased from 3.25 to 3.04 kg N ha$^{-1}$, upon an increase in the N deposition from 40% to 60%.

**Discussion**

**N cycle processes and N stocks**

The decrease in net N mineralization from 1950 to 1966 was due to a decrease in the DOM N stock...
(Figure 2(a)). Owing to young stand age, the N flow from biomass to DOM was smaller than the N flow from DOM to soil inorganic N, which led to the decrease in the DOM N stock. Platek and Allen (1999) had similarly reported that the net N mineralization decreased with time in young pine forests. Meanwhile, the net N mineralization increased after 1966, owing to the increase in the N flow from biomass to DOM with stand age. This pattern is in line with previous chronosequence studies; White et al. (2004) and Yermakov and Rothstein (2006) reported that the net N mineralization decreases during initial stage of forest regeneration, and then increases with stand age. Moreover, the simulated net N mineralization in 2010 (69.91 kg N ha\(^{-1}\) yr\(^{-1}\)) was within the range of the measured net N mineralization in PGEF (66.05–84.01 kg N ha\(^{-1}\) yr\(^{-1}\); Yoon et al. 2015), as well as within the general range for temperate pine forests (28.0–87.0 kg N ha\(^{-1}\) yr\(^{-1}\); Nadelhoffer et al. 1983; Binkley and Valentine 1991; Scott and Binkley 1997; Son and Lee 1997). Particularly, the net N mineralization was usually larger than the tree N uptake, but the tree N uptake was slightly larger than the net N mineralization from 1973 to 1982. This is because of the active tree growth during this period.

The simulated N leaching was about three times higher than the N deposition in 1950 (Figure 2(b)), which is uncommon for general pine forests (Dise and Wright 1995), which might be due to the young stand age. Low tree N demand in young forests led the net N mineralization to exceed the tree N uptake until late 1960s (Figure 2(a)), resulting in much of the inorganic N to remain in soil and in the unexpectedly high N leaching. A study conducted in Hubbard Brook Experimental Forest also reported similar results, with temporarily high N leaching during initial stage of forest regeneration (Valipour et al. 2018). The tree N uptake exceeded the net N mineralization when N leaching was the lowest (Figure 3(a,b)), reflecting the role of tree N uptake in controlling ecosystem N losses (Vitousek and Reiners 1975; Lovett et al. 2018).

**Verification**

The simulated N stocks in biomass and soil were consistent with the observed N stocks (Figure 4). However, the simulated N stock in the forest floor was underestimated by 35%. This inconsistency might be attributed to the fact that the FBDCAN model considers the turnover of only the stem and foliage. However, various kinds of debris, such as understory vegetation and reproductive organs, also accumulate on the forest floor. In fact, about 27% of the litter production is from broadleaf or miscellaneous, according to a previous study in PGEF (Noh et al. 2013). Therefore, considering the production of other components besides stem, foliage, and branches is necessary to reduce this uncertainty in the simulations.

The N module integration increased the reliability of C stock estimation (Figure 5(a)). This increase resulted from the difference in C stock estimation equations between the FBDCAN and the FBDC models. The FBDC model used a growth equation based on yield tables without enough consideration of N limitation for tree growth (Korea Forest Service 2009; Korea Forest Research Institute 2010; Puettmann et al. 2012; Yi et al. 2013; Lee et al. 2014). However, such exclusion of the N limitation might result in an overestimation of the C stock, given that N is the most important factor governing tree growth (Binkley and Fisher 2013). Similarly, integration of N cycle into the C cycle model reduced the overestimated C uptake by 74% in the CLM model and by 28% in the TEM model (Thornton et al. 2007; Sokolov et al. 2008). Therefore, N module integration is necessary to avoid overestimation of the C stock.

The C stock increased with increase in N deposition by 40% to 160%, relative to the original value. This shows that the increase in N deposition is closely related to the increase in forest productivity, as reported in previous studies (Thomas et al. 2010; Schulte-Uebbing and de Vries 2018). However, the increasing trend for the C stock saturated with increasing N deposition. Although the increase in C stock was 57.48 Mg C ha\(^{-1}\), when N deposition increased from 40% to 100%, the increase in C stock was 2.66 Mg C ha\(^{-1}\) when N deposition increased from 100% to 160%. This could be attributed to the fact that inorganic N input from net N mineralization met the tree N demand without N deposition, considering that the net N mineralization was larger than tree N uptake, except for the period from 1973 to 1982 (Figure 2(a)). Moreover, although the mean difference in tree N uptake and net N mineralization from 1973 to 1982 was 0.75 kg N ha\(^{-1}\) yr\(^{-1}\) (Figure 2(a)), on an average, the N deposition was greater by 3.24 kg N ha\(^{-1}\) yr\(^{-1}\) than the N leaching (Figure 2(b)). This suggests that the N limitation effect on tree biomass C sequestration would not have appeared during the simulation period. Meanwhile, N leaching increased when N deposition increased by 60% to 160% relative to the original value, as reported in other studies (Figure 6; Dise and Wright 1995; Fang et al. 2009). However, on the contrary, the N leaching decreased from 3.25 to 3.05 kg N ha\(^{-1}\) yr\(^{-1}\), following a change in N deposition from 40% to 60%. This might be due to an assumption of the FBDCAN model, that the tree N uptake occurs before N leaching (Vitousek and Reiners 1975; Lovett et al. 2018). This resulted in a decrease in N leaching, even though the N deposition increased.

**Conclusions**

In this study, a forest C and N model, referred to as the FBDCAN model, was developed by integrating the N module into the existing FBDC model. The FBDCAN model simulated net N mineralization, tree N uptake, and N leaching within the reasonable range for temperate forests. Our study also found the N module integration increased the reliability of C stock estimation, reaffirming the importance of C and N.
integration in modeling studies. Furthermore, this study showed that a model using only a small amount of input data could achieve a high reliability for N stock estimation. Therefore, this newly developed model and the developmental process could contribute to the estimation of forest N stock in countries with limited input data availability.

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