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〈종설〉

Method for Assessing Forest Carbon Sinks by Ecological Process-Based Approach - A Case Study for Takayama Station, Japan

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ABSTRACT : The ecological process-based approach provides a detailed assessment of belowground compartment as one of the major compartment of carbon balance. Carbon net balance (NEP: net ecosystem production) in forest ecosystems by ecological process-based approach is determined by the balance between net primary production (NPP) of vegetation and heterotrophic respiration (HR) of soil (NEP = NPP − HR). Respiration due to soil heterotrophs is the difference between total soil respiration (SR) and root respiration (RR) (HR= SR − RR, NEP = NPP − (SR − RR)). If NEP is positive, it is a sink of carbon. This study assessed the forest carbon balance by ecological process-based approach included belowground compartment intensively. The case study in the Takayama Station, cool-temperate deciduous broad-leaved forest was reported. From the result, NEP was estimated approximately 1.2 t C ha^{-1} yr^{-1} in 1996. Therefore, the study area as a whole was estimated to act as a sink of carbon. According to flux tower result, the net uptake rate of carbon was 1.1 t C ha^{-1} yr^{-1}.

Key words : Carbon, Ecological process-based approach, Forest ecosystem, NEP, Root respiration, Soil respiration

INTRODUCTION

Since the increased emission of greenhouse gases, especially carbon dioxide (CO_2), into the atmosphere become a serious environmental problem in the world; quantitative studies on the carbon cycle are essential to predict the CO_2-induced warming effect on the earth (IPCC 2001). For nearly 30 years, it has been clear that carbon emissions by human activities are greater than the annual increase in atmospheric CO_2, implying that sinks in the ocean or on land are storing the difference, at least temporarily (Bacastow and Keeling 1973). Prior to 1990, the evidence for a terrestrial component to this sink was convolved with estimates of a carbon source from deforestation. Model estimates of ocean carbon uptake accounted more-or-less completely for the difference between carbon emissions from fossil fuel combustion and the increment in the atmosphere (Post *et al.* 1990). Evidence for additional sources from deforestation (Woodwell *et al.* 1983) automatically implied the existence of a terrestrial sink.

Beginning about 1990, other kinds of information reinforced the evidence for terrestrial sinks, partially resolving the convolution with sources. Atmospheric inverse analyses pointed to terrestrial sinks in the temperate and boreal latitudes of the Northern Hemisphere (Tans *et al.* 1990). This is a distinctly different location than the dormant deforestation sources, which are primarily in the tropics. Inverse studies with atmospheric ^{13}C (Francey *et al.* 1995), as well as studies on the growth of the intra-annual oscillation of CO_2 (Randerson *et al.* 1997), helped confirm the terrestrial component and provide further evidence for a temperate/boreal forest location. Therefore, understanding carbon cycling in a forest ecosystem is critical for estimating the future global carbon budget.

The Kyoto protocol agreement of December 1997 has focused the attention of the public and policymakers on the earth's carbon budget. It has fostered a continuing search for a more accurate quantification of global terrestrial C sources and sinks to mitigate global climate change by conserving or increasing C sequestration (Bachelet *et al.* 2001). It was requested that developed countries cut down their total CO_2 emission by 2008~2012 to 92~95% of the levels in 1990, taking the balance of CO_2 in their forest ecosystems into consideration. Thus, carbon balance in forest ecosystems should be measured or estimated more correctly in the near future (Nakane 2001).

Terrestrial carbon sink can be estimated by two approaches: top down (e.g. atmospheric inverse modeling, satellite observations), and bottom up (e.g. flux tower-based measurement, ecological process-based method). Top down approach largely depends on under-

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standing and simulation global and continental atmospheric and oceanic transport as well as carbon distribution in the atmosphere and oceans. In the bottom up approach, eddy covariance techniques of flux tower-based measurement are a unique data source for analyzing temporal variability over a small (≈ 1 km^2) region. The ecological process-based approach provides a detailed assessment of belowground compartment as one of the major compartment of carbon balance. The multi approaches can be understood as complimentary by inter comparison and can provide insight as to the contribution of various processes to carbon cycle. However, the assessment method of forest carbon balances for ecological process-based approach is not yet fully understood.

The primary objective of this study is to assess the forest carbon balance by ecological process-based approach included belowground compartment intensively. The case study in the Takayama Station, cool-temperate deciduous broad-leaved forest in central Japan was reported.

CONCEPT OF CARBON BALANCE IN FOREST ECOSYSTEMS

The carbon cycle in a forest ecosystem involves the circulation of carbon among the atmosphere, vegetation, and soils as carbon pools. Therefore, relevant discussions about the carbon cycle require information on the carbon flux between soil and the atmosphere or between soil and vegetation (Koizumi 2001).

The absorption through photosynthesis of CO_2 in the atmosphere is the gross production (Fig. 1). Some of the carbon produced during the gross primary production (GPP) is used by plants for autotrophic respiration (AR). The gross primary product minus the carbon respired is the net primary production. The NPP is, however, further converted into other trophic levels, such as predators and decomposers. The carbon balance of the soil relates to the inputs, organic materials such as litter and root of plants, to output consisting of respiration caused by the decomposition of organic matter in the soil.

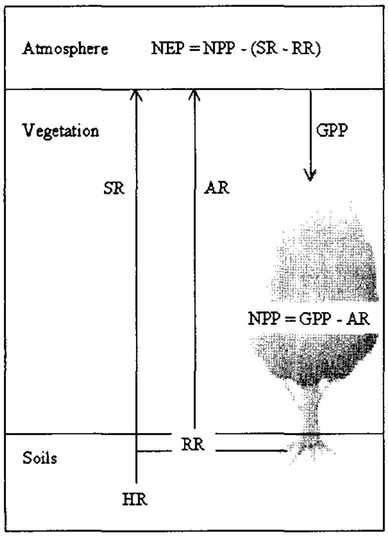

Fig. 1. The diagram of concept of carbon balance in forest ecosystems.

Carbon net balances (NEP: Net Ecosystem Productivity) in forest ecosystems were determined by the balance of net primary production (NPP) of vegetation and heterotrophic respiration (HR) of soil.

$$NEP = NPP - HR \tag{1}$$

These heterotrophic bacteria and fungi active in the organic and mineral soil horizons, and soil faunal activity (HR: heterotrophic respiration) are difference between forest soil respiration (SR) and the activity of autotrophic roots and associated rhizosphere organisms (RR: root respiration) (Edwards and Harris 1977).

$$HR = SR - RR \tag{2}$$

$$NEP = NPP - (SR - RR) \tag{3}$$

Therefore, the role of forests in the global carbon cycle is quantified by the NEP (Net Ecosystem Productivity). If NEP is positive, there is an increase in the net C storage of the ecosystem among the three large fluxes, atmosphere, vegetation and soil (C sink; Saxe *et al.* 2001).

It is important that these components need to precise assessment for quantifying the NEP. However, information about soil respiration and/or root respiration is limited surrounding methods, especially in forest ecosystems of the world. Although total and/or heterotrophic respiration has received considerable attention in recent decades, much less is known about the contribution of autotrophic respiration, or root respiration, to total respiration.

ASSESSING FOREST SOIL RESPIRATION

Carbon stored in soil is released into the atmosphere through the decomposition of the organic materials by soil microorganisms. CO_2 flux from soil surface to atmosphere is commonly referred to as soil respiration, which provides a useful parameter of biological activity and nutrient mineralization in the soil (Koizumi 2001).

Soil respiration is a more important component of the carbon balance in northerly latitudes (Valentini *et al.* 2000). Accurate measurements of soil respiration are crucial in ecosystem carbon balances, but are difficult to obtain (Lund *et al.* 1999). There are many methods for measuring soil respiration, with large differences in accuracy, spatial and temporal resolution, and applicability.

Several techniques have been used to measure soil respiration rates, including soil CO_2 concentration profiles, eddy-covariance, and chamber methods. The former two methods avoid confounding chamber effects, but their applicability has been limited by their methodological requirements (e.g., de Jong and Shappert 1972, Baldocchi and Meyers 1991). The many different chamber methods for measuring soil respiration exhibit large differences in applicability, spatial and temporal resolution, and to a large extent, accuracy (Britta and Lindroth 2003).

Measurement of soil respiration rates on a small scale is commonly made by chamber-based methods (Table 1, Norman *et al.* 1992, Fang and Moncrieff 1996, Janssens *et al.* 2000). Depending on the presence or absence of air circulation, chamber methods have been categorized as either static or dynamic (Witkamp and Frank 1969).

Traditionally, a majority of soil respiration studies has relied on the static chamber method because it is relatively inexpensive and easy to employ (Nakane 1975, Gupta and Singh 1981, Bowden *et al.* 1993). In static chamber method, CO_2 diffusing from the soil is absorbed inside a closed chamber using either an alkali solution (e.g. KOH, NaOH) or soda lime (Kirita 1971, Edwards 1982). Although, this method offers some practical advantages, several studies have shown that it tends to overestimate respiration rate at low respiration rates and severely underestimate respiration rate at high respiration rates (Koizumi *et al.* 1991, Rochette *et al.* 1992, Nakadai *et al.* 1996, Nay *et al.* 1994, Jensen *et al.* 1996). The bias appears to be driven by the chamber' s impact on the CO_2 concentration gradient at the soil-atmosphere interface (Nay *et al.* 1994).

Dynamic chamber methods have also been used to measure soil respiration in numerous studies (Ewel *et al.* 1987; Norman *et al.* 1992, Luo *et al.* 1996). Dynamic chambers are generally considered more accurate than static methods (Cropper *et al.* 1985, Koizumi *et al.* 1991, Rochette *et al.* 1992, Nay *et al.* 1994, Fang and Moncrieff 1996) and can be operated as either closed or open-flow systems.

Table 1. Comparison of chamber-based methods for measuring soil respiration

	Methods	Advantage	Disadvantage
Static	Alkali Absorption	inexpensive easy to employ	overestimate or Underestimate discontinuous measuring
Dynamic	Closed chamber	portable	need to operator value fluctuation by operator sunny day only
	Open-flow chamber	continuously (daily or weekly)	relative short-term monitoring

See detail the text description.

In closed dynamic chamber systems, air is circulated in a closed loop between the chamber head space and an infrared gas analyzer (IRGA). Soil respiration rate is then calculated using the difference in CO_2 concentration between the beginning and end of the measurement period. Potable closed chamber IRGA systems are accurate and suited to assess spatial variability, but need the presence of an operator during the night-time whenever daily totals are required.

The open-flow dynamic systems, ambient air is passed continuously through the chamber head space, and soil respiration rate is calculated using difference in CO_2 concentration between air entering and leaving the chamber. Open-flow dynamic systems are typically preferred for continuous measurements over the hours to days because the flow of outside air into the system maintains near ambient chamber temperature and CO_2 concentration. Thus, soil respiration rate are commonly measured using the open-flow dynamic chamber method.

In particular, early studies using static chamber and closed dynamic chamber have not measured soil respiration rate on condition of rainfall events because there are limitations associated with chamber system. On the other hand, open-flow dynamic chamber methods are allowed for continuous measurements of forest floor soil respiration rate, even rainfall conditions. Lee *et al.* (2002) reported that the post-rainfall increase in soil respiration represents approximately 16~21% of the annual soil carbon flux. Therefore, automatic open-closed dynamic chambers are used to continuously measure soil respiration at an IRGA connected to multichamber, recently.

Several comparisons among methods have been made (Rochette *et al.* 1992, Bekku *et al.* 1997, Norman *et al.* 1997, Rochette *et al.* 1997, Janssens *et al.* 2000, Longdoz *et al.* 2000). However, no method has yet been recognized as standard. Therefore, Britta and Lindroth (2003) recommend the need of calibrating systems used for measuring soil respiration rates is measured against a known flux, to elucidate the limits and applicability of each system.

ASSESSING FOREST ROOT RESPIRATION

The contribution of root respiration to total soil respiration is difficult to determine, as reflected by the wide range of published estimates for forest soils (10 to 90%). Although some of this variability reflects differences among types of ecosystems, a considerable proportion of it probably originates from the variety of measurement techniques used, each with a unique set of limitations (Rochette *et al.* 1999). Methods for separating root respiration from total soil respiration have been reviewed by Si,ngh and Gupta (1977) and Hanson *et al.* (2000) in detail.

The quantification of contribution of root respiration has been addressed using a variety of approaches that can be subdivided into three broad categories: component integration, root exclusion, and isotopic approaches (Table 2).

Component integration involves separation of the constituent soil components contribution to respiration rate (i.e., roots, sieved soil and litter) followed by measurements of the specific respiration rates from each component part (e.g. Ryan *et al.* 1996). A common, but less rigorous, variation on the component integration approach is to measure *in situ* soil respiration and the litter and root components, but to solve for the other soil heterotrophic activity by subtraction. The disadvantage of the component integration approach is the impact of physically separating the component parts of the soil (i.e., litter, roots, and mineral soil).

The root exclusion method is any procedure that indirectly estimates the contribution of root respiration by measuring soil respiration with and without the presence of roots (Table 3, i.e., no direct measurements of bare root tissue are made). Existing root exclusion techniques may be categorized into three broadly defined areas, (1) root removal: roots are removed, soil is placed back in reverse order of removal (e.g. Bowden *et al.* 1993), and further root growth is prevented by barriers (alternatively, roots may be removed after a series of soil respiration measurements), (2) trenching: existing roots are severed by trenching at a plot boundary but not removed, and a barrier is installed to inhibit future root growth, and (3) gap analysis: aboveground vegetation is removed from relatively large (e.g., clear cutting in forests; Nakane *et al.* 1996) compared to soil respiration data for a forested area. One of the biggest concerns with the root removal approach is the impact of extremely changing the moisture conditions of soil by physiological disturbance (Edwards 1975, Hanson *et al.* 1993). The disadvantage of the trench approach is the influence of residual decomposing roots left in the trenched plots and their contribution to soil respiration rate. Gap studies have same problems as trenching, but with appropriate precautions the technique is attractive in terms of labors.

Table 2. Comparison of methods for quantification of root contribution to total soil respiration measuring soil respiration

Methods	Advantage	Disadvantage
Component integration	relatively sample	impact of physically separating, less regorous
Root exclusion	relatively sample most common in forest ecosystem	impact of changing the moisture conditions of soil by physiological disturbance
isotopic	avoid the disturbance effects and the assumption of equilibrium in soil C pools	complexity of experimental setup and/or the added difficulty and cost of analytical measurements

See detail the text description.

Table 3. Comparison of root exclusion methods for quantification of root contribution to total soil respiration measuring soil respiration

Methods	Advantage	Disadvantage
Root removal	simple	biggest disturbance
Trenching	relatively simple most common use in forest ecosystems	influence of residual decomposing roots left in the trenched plots
Gap analysis	relatively large	this technique is attractive in terms of labors

See detail the text description.

Isotopic methods (Table 2) have an advantage over component integration and root exclusion methods because they allow partitioning of soil respiration rate between root respiration and soil organic matter decomposition *in situ*, and avoid the disturbance effects and the assumption of equilibrium in soil C pools common to the previously discussed methods (Rochette *et al.* 1999). The major disadvantage of isotopic methods over component integration and root exclusion methods is the complexity of experimental setup and/or the added difficulty and cost of analytical measurements for radioactive or stable C isotopes.

Trenching method can be modified using the root-bag method to eliminate the decomposition of the residual roots. Thus, Lee *et al.* (2003a, b) were examined by a trenching and root-bag method in Takayama station. The decomposition rate of dead roots was estimated by using a root-bag method to correct the soil respiration measured from the trenched plots for the additional decaying root biomass. In addition, to the contribution of root respiration to total soil respiration may change seasonally. Several studies have been differences between the growing season and the dormant season in the contribution of root respiration to total soil respiration (Edwards 1991, Rochette and Flanagan 1997). However, little information is available on seasonal changes in the contribution of root respiration to total soil respiration, especially for forest ecosystems. Lee *et al.* (2003a) reported that contribution of root respiration to total soil respiration was change seasonally by trench method. They estimated that the contribution of root respiration to total soil respiration in the growing season ranged from 27 to 71%. Therefore, the contribution of root respiration to total soil respiration was estimated 45 % entire annually (Lee *et al.* 2003b).

ESTIMATION OF NEP IN TAKAYAMA STATION

Several studies (Malhi *et al.* 1999, Valentini *et al.* 2000, Saxe *et al.* 2001) have suggested that forests can be either sources or sinks for atmospheric CO_2. Forest carbon balance, which is given by NEP, is the balance between CO_2 fixation by net photosynthesis occurring aboveground and CO_2 release from the belowground compartment through soil respiration. Of the two compartments, the belowground system is the most difficult to evaluate.

In this study, the NEP of the cool-temperate deciduous broad-leaved forest at Takayama Site was investigated (Fig. 2). The Takayama site is located in oak (*Quercus crispula* Blume) and beech (*Betula ermanii* Cham.) forest stand, in central Japan (36° 80' N, 137° 26' E, 1,430 m above sea level). In areas with brown forest soils, the forest floor vegetation consisted of a bamboo (*Sasa senanensis* Rehd.). The annual mean air temperature in 1980~2000 was +6.1℃ and the annual mean precipitation 2,175 mm. The site is covered with snow from December to April (annual mean 600 cm). The carbon pool in the site was 44 ton C ha^{-1} for aboveground biomass, 19 ton C ha^{-1} for belowground biomass, 5 ton C ha^{-1} for litter and 267 ton C ha^{-1} for organic matter in the mineral soil (Mariko *et al.* 2000).

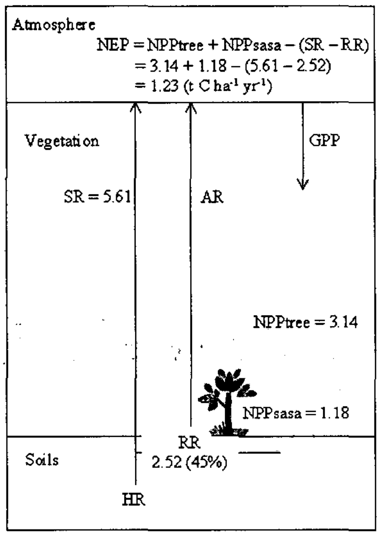

Fig. 2. The estimation of NEP of the cool-temperate deciduous broad-leaved forest at Takayama station.

According to Ohtsuka *et al.* (submitted) for this study area in the cool-temperate deciduous broad-leaved forest, the tree biomass of this study area was 129.6 t C ha^{-1} of aboveground and 26.8 t C ha^{-1} of belowground. The NPP was estimated as about 4.32 t C ha^{-1} yr^{-1} from tree (3.14 t C ha^{-1} yr^{-1}) and emitted it from *Sasa* (1.18 t C ha^{-1} yr^{-1}). Soil respiration was estimated as about 5.61 t C ha^{-1} yr^{-1} (average from 1994 to 1996), and root respiration was stimulated as approximately 2.52 t C ha^{-1} yr^{-1} (45% of total soil respiration). From the result (Fig. 2), NEP was estimated approximately 1.23 t C ha^{-1} yr^{-1} (Lee *et al.* 2003b). Therefore, the study area as a whole was estimated to act as a sink of carbon. According to flux tower result, the net uptake rate of carbon was 1.1 t C ha^{-1} yr^{-1} in 1994~1996 (Yamamoto *et al.* 1999).

Flux tower provides detailed information about annual details and remote sensing provides detailed spatial information. Ecological direct survey data provide realistic, verifiable estimates of carbon that can be used to check remote sensing and flux tower data (Martin *et al.* 2001). The advantages of each of the approaches, used in combination with the other ones, will allow not only for more accurate estimates but also for better understanding of forest carbon dynamics.

FUTURE PERSPECTIVE

It is considered likely that global warming will increase soil respiration, releasing more CO_2 that will further exacerbate warming (Raich and Schlesinger 1992, Townsend *et al.* 1992, Schimel *et al.* 1994, McGuire *et al.* 1995, Rustad *et al.* 2000). It is estimated that a global warming of 0.03℃ per year will enhance soil respiration, producing a net release of an additional 60 Gt C from soil to the atmosphere between 1990 and 2050 (Xu and Qu 2001). That amount of carbon would be equivalent to a 19% increase in fossil fuel combustion during the same period (Jenkinson *et al.* 1991). It is therefore critical to develop better understanding of the controls on soil respiration and its components. This should promote a better assessment component of the rate and direction of change of soil carbon, which is an essential component of developing and implementing policies and measure.

Increasing temperatures have the potential to increase the NPP of northern forests. Most models predict that likely scenarios of climate change and increasing [CO_2] will enhance global forest NPP over the next 50~100 yr, especially high latitudes (IPCC 2001). Climate change alone is often predicted to produce a carbon source (negative

NEP). Most models predict that this sink will persist for many decades in response to increasing [CO_2] and climate change, but they differ in regional and temporal detail (Saxe *et al.* 2001).

The carbon balance has considerable inter-annual change; therefore, an analysis of the carbon balance in other years is needed. For instant, long-term measurements of NEP in the artic tundra indicate that climatic warming and drying in the early 1980s resulted in substantial losses of carbon (Oechel *et al.* 1995). Saxe *et al.* (2001) reported that NEP may be increased in the boreal region by the spread of conifer forests but decreased in temperate regions by the loss of deciduous forests.

These results may provide to improve the precision of future forest carbon estimation of forest ecosystem. These studies, combined with modeling and measurements of respiration, photosynthesis, and carbon storage, and approaching the tower -based research, can help us to better understanding how ecosystem process are influenced by climate, age, and management, and how seasonal dynamics affect annual carbon balances. A mechanistic understanding allows us to provide insights on how management practices can be modified to improve C sequestration (Law *et al.* 2001).

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