B-1.6 Quantitative Analysis of Carbon Cycling and Balance in the Boreal Forest

Contact person Kaneyuki Nakane
Professor
Department of Environmental Studies, Faculty of Integrated Arts and Sciences,
Hiroshima University, Higashi-Hiroshima 739, Japan
Tel: +81-824-24-6510 Fax: +81-824-24-0758
E-mail: knakane@ipc.hiroshima-u.ac.jp

Total Budget for FY1993-FY1995 10,585,000 Yen (FY1995; 3,954,000 Yen)

Abstract: The flow rates and amounts of soil carbon were measured simultaneously with soil environmental condition, periodically during the growing seasons from 1994 to 1995 at the two plots (Plot A: drier soil condition, B: wetter condition) in a black spruce forest stand in the Candle Lake area, Saskatchewan, Canada. The seasonal trend of litterfall and accumulation of A_0 layer were not observed while the total and mineral soil respiration rates changed seasonally with soil temperature. There was no significant relationship between soil moisture content and any flow rates or accumulations of soil. Soil respiration and loss of litter might ceased during the winter because of the frozen soil. The annual soil carbon cycling was analyzed by a compartment model, based on the data obtained in this study. The relative decomposition rate of A_0 layer and humus in the mineral soil were estimated at 0.0616 and 0.0039 y^{-1} for Plot A, and 0.0275 and 0.0017 y^{-1} for Plot B, respectively. These values indicate that the cycling of soil carbon in Plot A was twice as fast as in Plot B. The slower cycling in Plot B might be caused by the lower soil temperature and per-humid soil condition due to higher ground water level in Plot B. The soil in both plots function as the sink of CO_2 in atmosphere(0.1-0.2 tC ha^{-1} y^{-1}). The soil carbon cycling in the boreal forest stand was slower than those reported in the cool- and warm-temperate forests owing to the lower soil temperature in the former than in the latter. The cycling in the boreal forest was conducted concentrately in or on the surface of mineral soil, suggesting that the decomposition of soil organic matter in the boreal forest will be facilitated strongly more than in forests developed in any other climate zone under global warming.

Key Words Boreal forest, Carbon balance, Carbon cycling, Missing sink

1. INTRODUCTION

Intergovernmental Panel on Climate Change (IPCC) [1990][1] has indicated an imbalance of about 1.6 Gt C y^{-1}, i.e. a "missing sink", in global carbon budget, and four years later it was suggested by IPCC [1995][2] that most of an unknown 1.6 Gt C y^{-1} might be sunk in terrestrial ecosystems, particularly in the Northern Hemisphere. However, no clear scientific evidence for this has yet been shown in the report. The CO_2 uptake by the ocean may be limited to less than 2.0 - 3.0 Gt C y^{-1}, which had been already accounted by IPCC [1990][1]. The most of imbalance, therefore, should be sunk into forest ecosystems, in particular, temperate and boreal forests in the Northern Hemisphere[3], which assimilate huge volume of carbon (ca. 50 Gt C y^{-1}) [Whittaker and Likens , 1973][4] as a net primary production.

On the other hand, the soil carbon cycle is a main component of the decomposition process and also usefull standard of other material cycles in forest ecosystems, suggesting that to study the carbon cycling gives the important knowledges about the mechanism involved in development and maintenance of forest ecosystems.

However, few study of carbon cycling and carbon budget, in particular, soil carbon cycling and budget in the boreal forests has been reported, although many fragmentary studies of soil carbon flows or reservoirs were reported for the boreal forests. Thus, in this study an attempt was made to measure and analyze the soil carbon cycling synthetically and quantitatively at the stand scale in a black spruce forest, which is most common type of forest in the boreal region in Canada. This study was conducted as a part of research project "BOREAS".

We express our thank to Dr. Ray L. Desjardins, Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada, for his management as our project team leader and offering useful data to us.

2. STUDY SITE

The study site was black spruce forest (BS Old Wet) stands about 30 km northeast from the Candle Lake, Saskatchewan (53° 55' N, 105° 5' W), where was one of the Southern Boreas Forest Super Site in Prince Albert area for BOREAS project. This region has a subarctic climate. The annual mean air temperature and annual precipitation in 1991 - 1993 observed in Prince Albert were 1.5 °C (degree centigrade) and 389 mm, respectively. The monthly air temperature showed a maximum (16.7 °C) in July and a minimum (-16.9 °C) in January.

The soil are sandy, which was predominantly derived from Glacial Lake Agassiz sediments and consist of sandy deposit, clay and organics. The topography is terrain of low relief, and so the drainage is poor.

The predominant species is black spruce (Picea mariana) which occurs in stands of varying density. There are some jack pine (Pinus banksiana) stands on the higher part of the terrain. White spruce, jack pine and larix (Larix laricina) are scattered within black spruce stands. Forest stands are mature with some being over 100 or 150 years old, the floor of which are covered with deep moss or lichens. Heights vary from stunned black spruce in bog area to stands as tall as 15 m, according to the level of ground water table.

The two plots were established on black spruce stands in June 1994, one (25 m x 25 m) was set up on drier soil condition (ground water table: 40 cm depth beneath the soil surface) and

another (15 m x 15 m) was on the wetter condition (ground water table: 10 cm depth).
The present study was carried out from June 1994 to August 1995.

3. METHODS

3.1 Tree census and biomass estimation : A census of tree dimensions was made in September 1994. The aboveground biomass of individual trees was calculated by the allometric correlation equations [Research Group of Forest Productivity of the Four Universities 1960][5]. For the estimation of belowground (root) biomass, soil block sampling was made vertically in two pits at the two plots. After the washing, dug up roots were divided into two size classes, fine (ϕ < 1cm) and big ones (ϕ >1cm). Root sample were dried at 85 °C for one week and weighed. The stand age was determined by a dendrochronological method.

3.2 Soil temperature and soil moisture content: Soil temperature at the surface of mineral soil (T_0) was observed continuously using thermistors and data logger (KADEC-U, KONA system Co. Ltd.). Moss and woody litters (L layer), F+H layer and surface soil core samples for the estimation of their moisture content were collected at five points at the time of soil respiration measurement in the two plots. The moisture content of these samples were calculated on a dry weight basis .

3.3 Litterfall: Eight (for Plot A) or four (for Plot B) plastic funnel-type litter traps of 1 mm mesh and with a 0.2 m^2 'mouth' were placed at random 1 m above the ground. Litters of trees (woody litter) were collected three times a month from June to September 1994 and May 1995 and sorted into leaf, fine branch and bark, seeds (cone), and others, and oven-dried to obtain the dry weight and subsequent measurement of the carbon content. Large branch litter (1< f <10cm) on the ground in the quadrat (50m x 50m) including the plot (Plots A or B) was marked with yellow paint at the beginning of the study (June 1994) and further addition of large branch litter were collected and weighed on May and August 1995. Their wet weight was measured in the field and dry weight was later estimated based on subsamples dried 85 °C for 1 week. The amount of supply of moss litter from moss layer to A_0 layer (moss turnover) was estimated from the annual turnover of standing crop (above-ground biomass) of living moss.

3.4 Amount of moss and woody litters, F+H layer and humus in mineral soil: The amount of moss and woody litters, and F+H layer was separately measured in five quadrats (50cm x 50cm) at the time of soil respiration measurement. The wet weight of moss + woody litters and F+H layer was measured in the field, and partial samples were taken for dry weight and carbon content determination. Two profile pits for mineral soil sampling were dug in the two plots. Soil samples were collected at each layer at 5 cm depth intervals along the profile by a cylindrical steel sampler. All samples were air-dried and weighed, and excluded duff and roots for carbon content determination, which was repeated twice for each sample. The total amount of humus in mineral soil was calculated by summing the carbon content from the surface to bottom of each pit.

3.5 Soil respiration: Evolution of CO_2 from the ground surface was measured using Kirita' s [1971] method[6]. A piece of plastic sponge wetted with NaOH solution is used to absorb CO_2 released from the ground surface into a space covered by an inverted cylindrical box placed on the forest floor. Two sets of Kirita 's apparatus, with and without moss + woody litters and F+H layer was set on the floor, to measure total and mineral soil respiration rates. Eight (for Plot A) or four (for Plot B) pairs of the apparatus were placed fixedly in the plots in June 1994. A measurement of soil respiration over a 24 hours period was made three times a month from June to September 1994 and twice on May or once on August 1995.

3.6 Loss rate of moss and woody litters, and dead roots: Moss and woody litters, and F+H layer collected from the forest floor were air-dried for 1 week and about 50-150g was carefully put into each nylon litter bag and weighed. One hundred litter bags for Plot A and fifty for Plot B were placed on the forest floor in June 1994, and another half of litter bags were collected in September 1994 and June 1995, respectively to measure the dry weight loss after air-drying for 1 week. Dug up roots were also air-dried for 1 week after washing to clean off soil and 500-1500 g was put into a nylon bag after separation into two diameter classes (ϕ <1 cm and 1< ϕ <5 cm). Ten bags were buried at 0-10 cm soil depth in the plots, and 1 year later their dry weight was measured again after carefully washing to clean off soil and air-drying for 1 week. The carbon content of moss and woody litters, F+H layer, mineral soil and roots were determined by C-N corder (Yanagimoto, Model MT-500).

4. RESULTS

4.1 Vegetation

The floristic composition of the two plots was very simple, e.g. only two species: Picea marina and Pinus banksiana for Plot A, or Picea marina and Larix laricina for Plot B. The most of total basal area and above-ground biomass were occupied by Picea marina in both plots. The above-ground biomass was estimated to be 133.9 t ha^{-1} for Plot A and 100.6 t ha^{-1} for Plot B.

The below-ground biomass was calculated at 30 t ha^{-1} (15 tC ha^{-1}) for Plot A and 22 t ha^{-1} (11 tC ha^{-1}) for Plot B based on the ratio (22 %) of root to total biomass. The stand age was also estimated to be 98±13 year-old for Plot A and 128±17 year-old for Plot B. The forest floor was covered with deep moss layer, which was composed mainly of Hylocomium splendens, Pleurozium schreberi and Ptilium crista-castrensis.

4.2 Soil temperature and soil moisture content

The soil surface temperature beneath the L layer increased from middle of May to early of

August, after melting of frozen soil, and decreased to autumn in Plot A.

The soil froze in winter (November to early of May), and the soil temperature ranged stationarily between 0 and -5 °C, regardless the very cold air temperature (-10 ~ -20 °C) for the period, because of the thick cover of moss layer. The daily mean temperature ranged from 0 to 5 °C for May and October, from 5 to 10 °C for June and September and from 10 to 15 °C for July and August. The annual mean soil surface temperature was estimated to be about 1.9 °C in Plot A. The surface soil temperature in Plot B changed seasonaly as same as in Plot A, but the degree was always lower in Plot B somewhat (0.5 ~ 1.0 °C) than in Plot A, which might be due to higher groundwater level in the former than in the latter.

The soil moisture content was relatively constant and ranged from 150 and 250 % in the both plots except for autumn (September), due to thick cover of moss layer. The soil moisture content was always higher in Plot B than in Plot A because of higher groundwater level in the former than in the latter.

4.3 Litterfall

The woody litterfall records for the studied year are given in Table 1. There was no clear seasonal tendency in the total litterfall rate at the both plots. The leaffall rate, however, increased in autumn (September) while fine branch & barkfall rate decreased from summer (July) to autumn (September). The averaged annual total fine litterfall rate (±S.D.) was estimated to be 1.34±0.11 t ha^{-1} y^{-1} for Plot A and 1.07±0.13 for Plot B. The big branchfall was also estimated to be 0.47 t ha^{-1} y^{-1} for Plot A and 0.03 for Plot B. Thus, total litterfall rate was calculated at 1.81 t ha^{-1} y^{-1} (0.91 tC ha^{-1} y^{-1}) for Plot A and 1.11 (0.54) for Plot B.

The moss turnover rate was estimated averagely to be 0.75±0.08 t ha y^{-1} (0.37 tC ha^{-1} y^{-1}) in the both plots, based on the data of new living moss biomass, which was easely identified.

4.4 Amount of A_0 layer and humus in mineral soil

There was no significant seasonal change in the amount of A_0 layer in the both plots. The averaged amount of L layer was 4.57±0.11 tC ha^{-1} (2.09 for moss litter, 2.48 for woody litter), 6.15 ± 0.16 tC ha^{-1} (2.99 for moss litter, 3.16 for woody litter) in Plots A and B, respectively. The amount of F+H layer was estimated to be averagely 19.60±3.52 tC ha^{-1} for Plot A and 36.11±5.89 for Plot B. The amount of humus in mineral soil was estimated at 30.9 tC ha^{-1} for Plot A and 58.3 for Plot B. About two-fold amount of soil humus in Plot B as much as in Plot A was due to too far high concentration of carbon in the surface soil layer in Plot B, which might derived from charcol.

4.5 Amount of living and dead fine roots

The fine roots of <u>Picea mariana</u> penetrated densely into the F+H layer, and the root biomass in F+H layer was 4.42±0.78 tC ha^{-1} for Plot A and 3.69±0.76 for Plot B, while the biomass in the mineral soil was 2.61±0.33 tC ha^{-1} for Plot A and 1.59±0.14 for Plot B. The amount of dead fine roots in mineral soil was estimated at 2.83 tC ha^{-1} for Plot A and 0.96 for Plot B.

4.6 Soil respiration

All of S_R , S_{RM} and S_{RA} increased from May to July and decreased at September in response to the changes in the soil temperature. The S_R and S_{RM} increased swiftly from May 7 to 11, 1995, when freezed soil was beginning to melt. All of soil respiration rates on May 7 in Plot B was very low due to the presence of snow on the moss, which suggested moss, A_0 layers and mineral soil to be freezing, while S_R and S_{RA} in Plot A, where only mineral soil was freezing, was relatively high. The fact indicates that the soil respiration rates were nearly zero from November to April when the forest floor was covered with snow and mineral soil was frozen.

S_R and S_{RM} increased more or less exponentially with rising temperature at the surface of mineral soil, however the increasing gradient of soil respiration rates changed around T_0 = 5 °C. The relations, therefore, were expressed tentatively with the two separate exponential curves. Using daily mean temperature at the surface of mineral soil, annual values of S_R and S_{RM} were calculated to be 3.56 and 1.53 tC ha^{-1} y^{-1} for Plot A, and 2.72 and 1.10 tC ha^{-1} y^{-1} for Plot B, the value of S_{RA} , therefore, 2.03 tC ha^{-1} y^{-1} for Plot A and 1.62 for Plot B, respectively. The value of S_{RA} , however, included the respiration of roots invaded into A_0 layer and decomposition of fine roots litter in A_0 layer. On the above calculation, the all respiration rates were assumed to be zero from November to April because A_0 layer and mineral soil froze.

4.7 Loss rate of A_0 (L) layer and dead roos

The annual mean weight loss of A_0 layer was 0.071 y^{-1} for Plot A and 0.030 for Plot B, respectively. The relative loss rate of dead roots ($\varepsilon_R M_r$) measured by the root bag method was larger in Plot B than in Plot A, e.g. the value of dead fine roots was averagely 0.092 y^{-1} for Plot A and 0.163 y^{-1} for Plot B.

5. DISCUSSION

5.1 Analysis of soil carbon cycling in a compartment model

A compartment model for the analysis of soil carbon cycling, which was modification of the model [7] was proposed. In this model, pools of carbon (tC ha^{-1}) in various parts of the soil system were tentatively classified into the following four pools: A_0 layer (M_0), humus in mineral soil (M), dead roots (root litter, M_r), living fine roots (B_r). A_0 layer is divided into three parts, i.e., moss litter layer (moss Llayer), woody litter layer (woody L layer) and F+H layer. Arrows in a diagram correspond to the flux between pools. Each flux of carbon (tC $ha^{-1}y^{-1}$) is labeled as follows: litterfall (L = L_w (woody litter) + L_m (moss turnover)), supply of humus from A_0 layer to mineral soil (l_A) and from dead roots to mineral soil (l_R), root turnover (L_R), total soil respiration (S_R), which includes A_0 layer respiration (S_{RA}), root respiration (R_R)

and mineralization of dead roots and humus in mineral soil.

The decomposition and transportation processes taken in and on the mineral soil may be assumed as first order reaction as follows:

$$S_{RA} = \nu_A M_0 \qquad (1)$$

$$l_A = \kappa_A M_0 \qquad (2)$$

$$S_{RM} = \mu M + R_R + \nu_R M_r \qquad (3)$$

If S_{RA}, l_A and M_0 are known, we can obtain ν_A and κ_A (y^{-1}) from Eqs.(1) and (2), and if S_{RM}, R_R, $\nu_R M_r$ and M are measured or estimated, m (y^{-1}) can be derived from Eq.(3). As mentioned earlier, L, S_{RA} (including root respiration rate in the F+H layer), l_A and M_0 were measured on annual basis in the plots. Therefore, annual mean value of ν_A and κ_A can be obtained after subtracting respiration of roots in A_0 layer from S_{RA}. The annual mean value of μ can be also derived according to the following procedures. R_R can be assumed to be about half of total soil respiration rate (S_R) in mature forest ecosystems [8, 9, 10], i.e. $R_R = 0.5S_R$. Uchida et al. [unpublished] reported that the root contribution was 53% of the total soil metabolism in the same black spruce stand as in this study, based on the separate measurement data of root respiration from soil respiration rates. L_R can also be assumed to be $0.1B_r$ per year based on the data of amount of living and dead fine roots in the mineral soil and loss rate of dead roots, which were obtained by root bag method in this study. $\nu_R + \kappa_R$ (equal to ε_R of fine dead roots) was observed, and thus $\nu_R M_r$ can be derived under the assumptions that M_r is nearly constant in the mature forest stage and $\delta_R = \nu_R / \kappa_R = 1.8$ irrespective of forest type, as in the case of A_0 layer of broad leaves [11, 12]. Therefore,

$$M_r = \sigma B_r / (\kappa_R + \nu_R) \qquad (4)$$

and so

$$\nu_R M_r = \nu_R \sigma B_r / (\kappa_R + \nu_R) = \sigma B_r / (1/\delta_R + 1) \qquad (5)$$

According to the procedures mentioned above, the annual cycling of soil carbon in the black spruce stand was obtained and analyzed, and values were compared between those in Plots A and B, or with those in the natural forests in the different climate zones.

5.3 Comparison of soil carbon cycling between the two plots

The relative decomposition rate of A_0 layer (ν_A) and humus (μ) in mineral soil was calculated at 0.0616 and 0.0039 y^{-1} for Plot A, and 0.0275 and 0.0017 y^{-1} for Plot B, respectively. The transfer factor of humus from A_0 layer to mineral soil (κ_A) was 0.0095 y^{-1} for Plot A and 0.0028 y^{-1} for Plot B. These values suggested that the cycling of soil carbon in Plot A was 2-3 times as fast as in Plot B. The slower cycling in Plot B might be caused by the lower soil temperature and per-humid soil condition due to higher groundwater level in Plot B.

The both forest stands function as the sink of CO_2 in atmosphere. Because input of carbon to soil was 1.97 tC ha^{-1} y^{-1} (litterfall + root turnover) for Plot A and 1.44 for Plot B, but the output was 1.78 tC ha^{-1} y^{-1} (mineralization of organic carbon in soil) for Plot A and 1.36 for Plot B, and so the difference between input and output, that is, +0.19 and +0.08 tC ha^{-1} y^{-1} were sunk in the soil at Plots A and B, respectively. The value (0.2 ~ 0.1 tC ha^{-1} y^{-1}), which was observed to be sunk in the soil of old black spruce stands in this study, coincided with that estimated by the model of soil carbon cycling under the assumption that CO_2 fertilization increased the net primary production of the forest ecosystems about 10% per 30 years (0.33% per year) or 0.2 % per ppm CO_2 [13].

The fact suggests that the amount of CO_2 corresponded roughly to the missing sink (1.6 Gt C y^{-1}), which was indicated by IPCC [1990][1], may be sunk into soils of forests including the boreal forest.

5.4 Comparison of soil carbon cycling between other climate forests

The amount of A_0 layer in the boreal (black spruce) forest in Canada was about three times as much as that in the cool-temperate (beech) forest in Japan [14], but that of humus in mineral soil in the former was only one - third of that in the later. However, the both relative decomposition rate of A_0 layer and humus in mineral soil in the boreal forest was about half or one - third of those in the cool-temperate forest. The slower cycling of soil carbon in the boreal forest was owing to the lower soil temperature (annual average: 1.9 °C at soil surface) than those in the cool-temperate (7.0 °C) and warm-temperate (13.1 °C)[15]. The cycling in the boreal forest was conducted concentratedly in or on the surface of mineral soil. Therefore, the decomposition of soil organic matter in the boreal forest will be facilitated strongly more than in the forests developed in other climate zones when the climate become warmer. The fact suggests that the boreal forests change easily to function as the source of CO_2 in atmosphere under the global warming.

REFERENCES

1) IPCC, Climate change: the IPCC Scientific Assesment , edited by J.T. Houghton, G.J. Jenkins and J.J. Ephraums, 365pp., Cambridge University Press, Cambridge, U.K., 1990.

2) IPCC, Climate change 1994: Radiative forcing of climate change and evaluation of the IPCC IS92 emission scenario , edited by J.T. Houghton, L.G. Meria Filho, J. Bruce, H. Lee, B.A. Callander, E. Haites, N.H. Arris and K. Maskell, 339pp., Cambridge University Press, New Yprk and Melbourne, 1995.

3) Tans, P.P., I.Y., Fung, and T., Takahashi, Observational constrains on the

global atmospheric CO2 budget, Science , 247, 1431-1438, 1990.
4) Whittaker, R.H. and G.E. Likens, The biosphere and man, In Primary Productivity of the Biosphere , edited by H. Leith, and R.H., Whittaker, Spring, New York, 1973.
5) Research Group of Forest Productivity of Four Universities, Studies on the productivity of the forest I. Essential needle-leaved forests of Hokkaido, Kakusaku Pulp Industry Co. Ltd., Tokyo.
6) Kitrita, H., Re-examination of absorption method of measuring soil respiration under field condition IV. An improved absorption method using a disc of plastic sponge as absorbent holder. Jpn. J. Ecol., 21, 119-127, 1971. (in Japanese with English summary)
7) Nakane, K., and M. Yamamoto, Simulation model of the cycling of soil organic carbon in forest ecosystems disturbed by human activities I. Cutting undergrowth or raking litters, Jpn. J. Ecol., 33 , 169-181, 1983.
8) Behera, S.K., S.K. Joshi, and D.P. Pati, Root contribution to total soil metabolism in a tropical forest soil from Orissa, India. Forest Ecology and Management , 36, 125-134, 1990.
9) Hendrickson, O. and J.B. Robinson, Effects of roots and litter on mineralization processes in forest soil, Plant and Soil, 80,, 391-405, 1984.
10) Nakane, K., M. Yamamoto, and H. Tsubota, Estimation of root respiration rate in a mature forest ecosystem, Jpn. J. Ecol., 33, 397-408, 1983.
11) Kononova, V.V., Transformation of organic matter and their relation to soil fertility. Soviet Soil Science , 1968 , 1045-1055, 1968. (English translation)
12) Nakane, K., Comparative studies of cycling of soil organic carbon in three primeval moist forests, Jpn. J. Ecol., 30, 155-172, 1980. (Japanese with English summary)
13) Nakane, K., and Lee N.J., Simulation of soil carbon cycling and carbon balance following clear-cutting in a mid-temperate forest and contribution to the sink of atmospheric CO_2, Vegetatio, 121, 147-156, 1995.
14) Nakane, K., Dynamics of soil organic carbon and its seasonal variation in a cool-temperate beech/fir forest on Mt. Odaigahara. Jpn. J. Ecol., 28 , 335-346, 1978. (in Japanese with English summary)
15) Nakane, K., Dynamics of soil organic matter in different parts on a slope under an evergreen oak forest, Jpn. J. Ecol., 25, 206-216, 1975. (in Japanese with English summary)