Title of the contribution: Carbon cycling and budget in a forested basin of southwestern Hokkaido, northern Japan.

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Short running title: Carbon dynamics at a northern Japanese forest

Abstract: Quantification of annual carbon sequestration is a very important to assess the function and response of forest ecosystem against global climate change. Annual cycling and budget of carbon in a forested basin was investigated to quantify the carbon sequestration of cool-temperate deciduous forest ecosystem in Horonai stream basin, Tomakomai Experimental Forest, northern Japan. Net ecosystem exchange, soil respiration, biomass increment, litter fall, soil solution chemistry and stream export were observed in the basin from 1999 to 2001 as a part of IGBP-TEMA project. We found the 258 gC m^{-2} y^{-1} was annually sequestrated as net ecosystem exchange (NEE) in the forested basin from 1999-2001. Discharge of carbon to the stream was 4 gC m^{-2} y^{-1} (about 2 % of NEE) and consisted mainly of dissolved inorganic carbon. About 43 % of net ecosystem productivity (NEP) was retained in the vegetation, while about 57 % of NEP was sequestrated in soil, suggesting that the allocation of sequestrated carbon in above canopy via photosynthesis to below-ground vegetation was important pathway for the net carbon accumulation in soil. The derived organic carbon from above-ground vegetation to soil was mainly accumulated in the solid phase in soil, resulting in that export of the dissolve organic carbon to the stream was smaller than that of dissolved inorganic carbon. Our results indicated that the above- and below-ground interaction of carbon fluxes was important processes for the rate and retention time of the carbon

sequestration in cool-temperate deciduous forest ecosystem in southwestern part of Hokkaido, northern Japan.

Keywords: Carbon biogeochemistry, Climate change, Eddy flux, Forest ecosystem, Net Ecosystem Productivity

Introduction

Global climate change and increased levels of atmospheric carbon dioxide (CO_2) have motivated the scientific community and the public at large to ponder questions such as "How much carbon can be sequestrated by a forest and where in the forest does that occur?" The quantification of carbon budget and cycling is a useful research tool with which to assess the role of forest vegetation and soil on carbon accumulation in the ecosystem. Given the close relationship that exists between the carbon dynamics of forest ecosystems and productivity within the ecosystem, carbon dynamics has become a fundamental component of the research conducted by ecosystem ecologists since international biological program (IBP) that was conducted late 60s to 70s (Cole & Rapp 1981). However, quantification of the actual carbon sequestration rate in forest ecosystems is complicated by the difficulty associated with measuring the rate of CO_2 exchange in the atmosphere and ecosystem. Eddy-correlation techniques for assessing CO_2 flux over the forest canopy provide quantitative information on net photosynthesis and respiration (for both vegetation and microorganisms), or net ecosystem exchange (NEE) (Baldocchi *et al.* 2001).

NEE, measured using eddy flux at the boundary between the canopy and the atmosphere corresponds with the net flux of CO_2 (= b + c + d – a, in Fig. 1) including photosynthesis and respiration, provides an indication of how much carbon was sequestrated in the ecosystem. However, while NEE provides useful quantitative information on ecosystem functioning associated with carbon sequestration, it cannot be used to derive the extent partitioning of this sequestrated carbon in the terrestrial ecosystem. Given that the difference in turnover time for carbon in the soil and that contained in the vegetation is markedly different (Chapin *et al.* 2002; Malhi *et al.* 1999), it is very important to assess the internal cycling and partitioning of carbon in the vegetation and soil system separately. It is thus essential to compare the carbon budget (= NEE- h, in Fig. 1) and the internal cycling (c to g, in Fig. 1) in the same basin over same period. In a previous study associated with the internal partitioning of carbon in ecosystems, Malhi *et al.* (1999) indicated the carbon distribution and cycling in forest ecosystems was highly dependent upon climate and vegetation type. However, studies that have integrated monitoring of the carbon budget and cycling in the same basin over the same period of time have rarely been conducted to date. In the Asian region particularly, biogeochemical assessments of eddy CO_2 flux and internal cycling and budget have been particularly limited (Yamamoto *et al.* 1999), despite the occurrence unique climatic and other environmental characteristics that distinguish the region from the relatively well-studied forests of the northeastern US and northwestern

Europe. In addition, the studied forest has been recognized as sensitive ecosystem against environmental changes and stresses because the forest was located on the infertile volcanic young soil in transient zone from temperate to sub-boreal region. Quantitative analysis of the carbon dynamics will not only provide fundamental information of the biogeochemical processes of ecosystems, but also contribute towards our current understanding of the impact of carbon sequestration on ecosystem functioning and the effect that this might have on global climate change. The objective of this study was therefore to 1) quantify the carbon budget and cycling, and, 2) understand the quantitative role of the vegetation and soil on carbon sequestration in a forest basin.

Methods

Study site

This study was conducted in the Horonai stream basin in the Tomakomai Experimental Forest (Hokkaido University), located in southwestern Hokkaido, northern Japan (42° 40' N, 141° 36'E). The Horonai stream is a first-order stream with a basin area of 9.4 km^2. The mean annual precipitation is approximately 1,200 mm and the mean annual temperature is 7.1 °C. Vegetation in the basin consists of cool-temperate forest, mainly dominated by secondary deciduous forests that colonized the area after a typhoon in 1954. Approximately 50 tree species are co-existed, including *Quercus mongolica var. crispula*, *Acer mono*, *Acer palmatum* ssp. *matsumurae*, and *Magnolia hyporeuca* (Hiura 2001). The predominant soil type is volcanic regosols (Andic Udipsamments, Soil Survey Staff 1994), with the parent material of the soil consisting of clastic pumice and sand that was deposited by eruptions of Mt. Tarumae in 1667 and 1739 (Sakuma 1987). Other detailed characteristics of the vegetation, soil and streams of the area have been described by Shibata *et al.* (1998, 2001), Takahashi *et al.* (1999) and Hiura (2001).

Net Ecosystem Exchange (NEE)

CO_2 fluxes between atmosphere and canopy (NEE) was measured by applying the eddy correlation method above the canopy layer from a 21-meter high observation tower from 1999 to 2001 (Tanaka *et al*. 2001). The mean height of the vegetation around the tower is approximately 13 m. Atmospheric CO_2 concentration was measured using a NDIR (Non dispersive infrared)-CO_2 sensor (LI-COR 6262, Li-Cor Co. Ltd.) by the closed-path system. An ultrasonic anemometer (DAT-600, Kaijo Co. Ltd.) and CO_2/H_2O fluctuation meter (AH-300, Kaijo Co. Ltd.) were used for the measurement of these fluxes.

Biomass and litterfall

We used long-term inventory data collected for the Tomakomai Research Station of Hokkaido University to calculate the stand volume of various forest stands in the study area. The investigated plot was 1 ha in area, and the stand volume and mortality of the above-ground vegetation were measured at every one year interval. Both above- and below-ground biomass of the stand was estimated by combining the measured stand volume and applying an allometric-growth equation for each species derived from harvesting research previously conducted in the study basin (Takahashi *et al.* 1999). A more detailed description of the vegetation and the methods used to estimate biomass on a landscape scale was described by Hiura (2001, 2005).

Litter traps (1 m^2) were used to collect litter-fall from vegetation with 25 replicates in a representative secondary stand in the study area. These samples were collected on a monthly interval, dried and weighed from 1999 to 2001 (Hiura 2005, this issue).

Soil respiration

Closed-chamber system and NDIR sensor (LI-6200, Licor Co Ltd.) was used to measure soil respiration (Yanagihara *et al.* 2000). Twelve circular chambers (71.6 cm^2) were installed in stands of forest considered representative of the study area. Soil respiration and surface soil temperature (0-10 cm) were measured using the sensor of 10 cm long at monthly intervals during periods of no snowfall from 1999 to 2000. The relationship between soil respiration and soil temperature derived empirically and used to extrapolate annual soil respiration using the continuous soil surface temperature data; one of the long-term meteorological parameters collected at the Tomakomai Experimental Forest.

Carbon export from soil to stream

We installed tension-free lysimeters under the forest floor and in mineral soil (1.5 m deep) to collect the soil gravity water. Four lysimeters were thus installed below the forest floor and two lysimeters in the mineral soil at the bank near the middle part of the stream. Stream water was collected from the upper and lower river reaches at two-week intervals and analyzed for dissolved organic (DOC) and inorganic carbon (DIC) concentrations using a TOC analyzer (TOC 5000A, Shimadzu Co. Ltd.). Particulate organic carbon (POC) (particles > 0.7 μm) was also measured by filtering the stream water collected from the lower stream reaches (Shibata *et al.* 2001). Total carbon content of the particulate material was analyzed using a CN analyzer (PE 2400 II, Perkin elmer Co. Ltd.).

Stream height was measured continuously using a pressure transducer and data logger at the weir station located at the lower stream reaches. Stream discharge was calculated using an empirical relationship between stream height and observed discharge (Shibata *et al.* 2001). Carbon flux in the stream was calculated by multiplying the carbon concentrations for DOC, DIC and POC, with discharge. Given that this basin was located in very flat region, and on course, volcanic, gravel deposit suggesting that the groundwater inflow from the neighboring basin might affect the hydrologic budget, differences of the flux between upper and lower stream reaches were used to quantify net export of DOC and DIC from soil to stream (Shibata *et al.* 2001). We assumed that the influx of POC from the upper stream reaches was negligible because most of the POC would have been derived from the riparian canopy and the riverbank. Throughfall was collected using a circular funnel (30 cm in diameter) at the riverbank and analyzed for DOC and DIC concentrations. More detailed methods for calculating the contributions of the soil and stream on carbon dynamics were reported by Shibata *et al.* (2001).

Budget calculation

All carbon flux measurements were conducted from 1999 to 2001. Mean fluxes for the three years were used in the budget analysis. We used the steady state budget for vegetation and soil as illustrated in Eq. 1 and 2, respectively, to analyze the carbon dynamics of the ecosystem. The letters in parenthesis refer to Fig. 1.

$$NEE - SR = LF + AB + AC \qquad \text{Eq. 1}$$

NEE: Net ecosystem exchange (= b + c + d – a)

SR: Soil respiration (= d + c)

LF: Litterfall and mortality of above vegetation (= e)

AB: Above-ground biomass increment

AC: Allocation from above to below vegetation (= f)

$$AC - BB + LF = SR + DC + SS \qquad \text{Eq. 2}$$

BB: Below-ground biomass increment

DC: Discharge to stream (= h)

SS: Carbon storage in organic and mineral soil

Measured carbon fluxes were NEE, SR, LF, AB, BB and DC, while the estimated carbon fluxes based on these equations were AC and SS. Left side of Eq.1 (=NEE – SR) correspond with gross ecosystem exchange (GEE).

Results

Carbon fluxes in the basin

Figure 2 shows the seasonal fluctuation in monthly NEE over the canopy from 1999 to 2001. Negative values for NEE indicate net CO_2 transport from atmosphere to ecosystem. Atmospheric CO_2 was sequestrated mainly from June to October each year. Maximum estimates of carbon uptake ranged from -80 to -100 gC m^{-2} $month^{-1}$ from June to July (Fig. 2). Annual mean NEE for three years was -258 (±36 SD) gC m^{-2} y^{-1}.

Soil respiration was observed to fluctuate with in response to changes in soil temperature (Fig. 3). The Q_{10} value was 2.7 and the annual flux of soil respiration over three years was 592 (±55 SD) gC m^{-2} y^{-1}. The annual flux of soil respiration was approximately two times larger than the NEE in this studied basin. Given this relationship between respiration and NEE, gross ecosystem exchange (GEE; the net flux of photosynthesis and respiration for the above-ground vegetation) corresponded with 850 gC m^{-2} y^{-1}.

Litterfall occurred mainly in late summer and fall (October and November) of each year. Annual mean litterfall for the three years was 118 gC m^{-2} y^{-1} in the secondary forest stands. The increment of above- and below-ground biomass and tree mortality measured in the secondary forest stand was 92, 16 and 79 gC m^{-2} y^{-1}, respectively. The annual carbon sequestered by the vegetation was 108 gC m^{-2} y^{-1}, and approximately

42 % of the NEE. The sum of the litterfall and mortality for above-ground vegetation was 197 gC m^{-2} y^{-1}, accounting for the organic carbon input from the above-ground vegetation to soil surface.

Stream export of DOC, DIC and POC was considered an output of carbon from the terrestrial ecosystem. Annual mean export of dissolved and particulate carbon from soil to stream for three years was 4.1 ($\pm$1.8 SD) gC m^{-2} y^{-1} (Fig. 4), and DIC, DOC and POC accounted for 68, 13 and 19 % of the total carbon export to the stream. The total export of carbon to the stream corresponded to only 2 % of the NEE flux in this basin. DOC concentration was higher in the surface soil water, and tended to decrease with depth of ground (Fig. 5). DIC was a major carbon forms in stream water collected from both the upper and lower stream.

Carbon budget in the basin

Figure 6 shows the carbon cycling and budget of the basin in the study. Based on the NEE and export to the stream, the annual net carbon sequestration rate in this basin (=NEP; Net Ecosystem Productivity) was 254 gC m^{-2} y^{-1}. The carbon allocation from the above- to below-ground vegetation calculated using Eq. 1 was 549 gC m^{-2} y^{-1}, corresponded to 65 % of GEE. The carbon budget in the soil (Eq. 2) indicated that 146 gC m^{-2} y^{-1} was sequestrated in the soil in this basin. The annual carbon sequestration in vegetation and soil accounted for 43 and 57 % of NEP, respectively. The total input of carbon from the above- and below- ground vegetation to the soil was 730 gC m^{-2} y^{-1}, including the litterfall, mortality of above-ground vegetation, root detritus and root respiration.

Discussion

In forest basin of this study, net carbon sequestrated in the ecosystem is partitioned between the vegetation and soil almost equally on an annual basis. The total litterfall and above-ground tree mortality (197 gC m^{-2} y^{-1}) accounted for 27 % of the total carbon input from the vegetation to soil (730 gC m^{-2} y^{-1}). Consequently, the transport carbon through the roots into the soil was an important pathway for carbon input to the soil. Since CO_2 input via root respiration to soil would ordinarily be balanced by emission from the soil surface to the atmosphere in a annual steady-state (no net change in the storage of CO_2 in soil on annual basis), the organic carbon input via root detritus and exudates could be an important form of carbon for the net release of carbon from below-vegetation to soil. The net increment of root biomass (16 gC m^{-2} y^{-1}; estimated using the allometric-growth equation obtained from harvesting measurements) suggested that the increment in very fine root biomass might have been underestimated in this budget. Detailed measurement and estimation methods will be required to clarify the extent of fine and very fine root production with respect to the carbon sequestration (Shutou and Nakane 2004; Satomura et al. 2003). Reich & Bolstad (2001) reported that the net primary production of below-ground vegetation accounted for 14-80 % of the total net primary production in various temperate forest ecosystems.

Raich & Schlesinger (1992) estimated annual soil respiration rates for the various global biome. The soil respiration rate in our study area fell within the range (647±51 gC m^{-2} y^{-1}) they gave for temperate deciduous forests. In the soil system, dissolved organic carbon decreased with depth of the ground, suggesting that the adsorption and/or decomposition of the DOC were the dominant mechanisms of DOC retention in ground (Shibata *et al.* 2001). In general, volcanic pumice is considered to have a relatively high ability to adsorb solutes to the solid phase of soil. We estimated the total carbon pool in the organic and mineral soil using previously reported data (Sakuma 1987; Eguchi *et al.* 1997). The total carbon pool in soil from the O horizon to mineral soil of 100 cm depth was approximately 5500 gC m^{-2}, corresponding to values approximately 38 times larger than annual net carbon sequestration in soil. Assuming most of the organic carbon accumulates within the 0-100 cm soil, then the mean residence time of sequestrated carbon in soil is estimated at approximately forty years in this basin. DOC concentration in soil water from the mineral soil (1.5 m deep) was still significantly higher than that of stream water (Fig. 5), suggesting that the depletion of DOC in soil water occurred deeper in mineral soil. Consequently, the mean residence time of the carbon in soil that estimated above could be still underestimation in this study. The analysis of the quantitative dynamics in the deeper mineral soil would be a key process to understand the buffering function of the soil system on the temporal fluctuations of the carbon input from atmosphere-vegetation system.

Annual mean NEE (-258 gC m^{-2} y^{-1}) in this basin is comparable with that reported for a growing of season similar length (about 150 days) in the worldwide CO_2 flux network (FLUXNET, Baldocci *et al.* 2001). However, for the eddy measurements, it should be noted that several uncertainties regarding the applicability of the techniques still remain including, (i) difficulties in measuring eddies during periods of high atmospheric stability and the irregularity of the canopy surface, and, (ii) the drainage flow of CO_2 across the stream valley (Baldocci *et al.* 2001) These uncertainties might affect the estimation of the unmeasured flux; particularly the allocation of carbon from the vegetation to the soil. In addition, we used the compartment model for the carbon budget, which assumes a steady state on an annual basis. It should be noted that actual carbon transport sometimes fluctuates and is transient. For example, the aforementioned buffering function of the soil system against temporal fluctuations in carbon input would be attributed to the transient system.

Hiura (2005, this issue) indicated that the secondary forest that is the dominant vegetation type in this basin showed more higher net biomass increment than the mature forest also found in this basin, albeit to a lesser extent. The higher sequestration rate of the vegetation and soil in this basin may mean that the forest in the study area was relatively young and at an early stage of succession. Since most of the forest stands in this basin became established after a large disturbance caused by a by typhoon in 1954, the growth rate of the vegetation seems to be still increasing. The soil is also a very young regosol that developed after the recent eruption of a volcano within the last several centuries. These age characteristics of vegetation and soil would affect the NEP in the basin. Furthermore, since the study area is located near urban and industrial areas (Shibata *et al.* 1998), the forest ecosystem currently receives slightly elevated amounts of atmospheric nitrogen (4-5 kgN ha^{-1} y^{-1} of wet deposition, Shibata *et al.* 1998). The effect of nitrogen deposition as a nutrient input on carbon sequestration would need to be examined more closely to determine if the input of nitrogen nutrients from the atmosphere would enhance the uptake of carbon in the forest (Lloyd 1999; Nadelhoffer *et al*. 1999)

Our results suggest that the fundamental characteristics of the parent materials of soil and the chronological attributes of the vegetation and soil - including natural disturbances in the past - was an important factor affecting the current NEP and the partitioning of sequestrated carbon in the ecosystem. An integrated regional cross-site analysis of carbon biogeochemistry, including eddy measurements and budgets under the various environmental conditions would improve our understanding of the role of forest ecosystem functioning on global climate change.

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Legends of figures

Figure 1. Outline of the carbon budget and cycling in vegetation-soil-stream ecosystem.

Figure 2. Seasonal fluctuation in monthly net ecosystem exchange (NEE) over the forest canopy from 1999 to 2001. Negative values represent net inflow of carbon from atmosphere to canopy.

Figure 3. Relationship between soil respiration and soil surface temperature (0-10 cm). Data were obtained at different months during non-snowy period. Bars represent standard deviations.

Figure 4. Annual carbon export from the terrestrial ecosystem to a stream in the Horonai stream basin. DOC, DIC and POC are dissolved organic carbon, dissolved inorganic carbon and particulate organic carbon, respectively. Data are mean values obtained after three years. Each bar represents standard deviation.

Figure 5. Mean concentration of DOC and DIC in throughfall (TF), surface soil water (SSW), deep soil water (DSW), upper stream (US) and lower stream (LS). Bars represent standard deviations.

Figure 6. Annual carbon budget and cycling (gC m^{-2} y^{-1}) in the Horonai stream basin. Delta values (⊿＝) indicate net accumulation of carbon in above- and below-ground vegetation and soil, respectively. Allocation of carbon from above- to below-ground

vegetation and carbon accumulation of soil are estimated values based on the budget (See details in the text and Eq. 1 & 2).

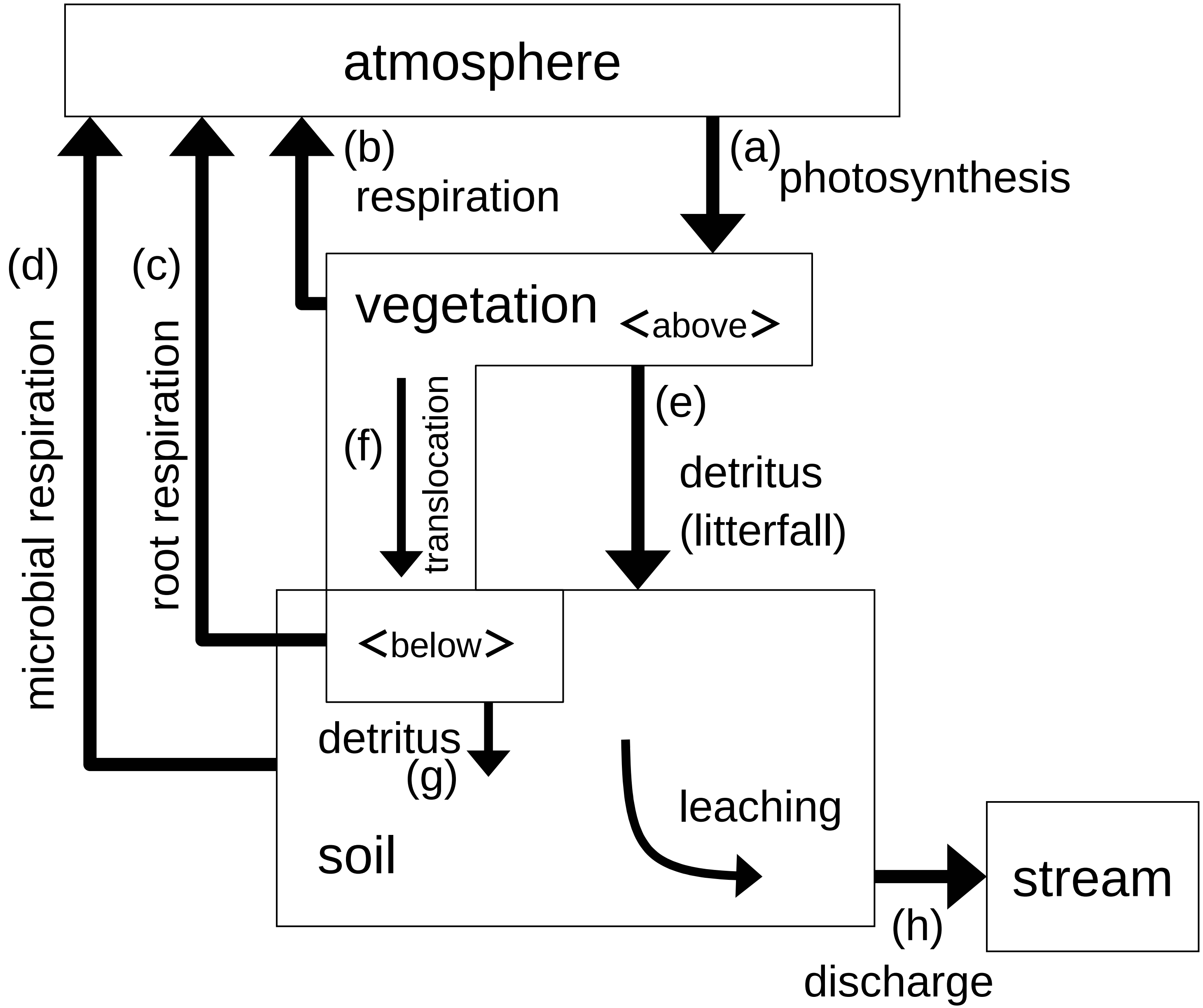

Fig. 1

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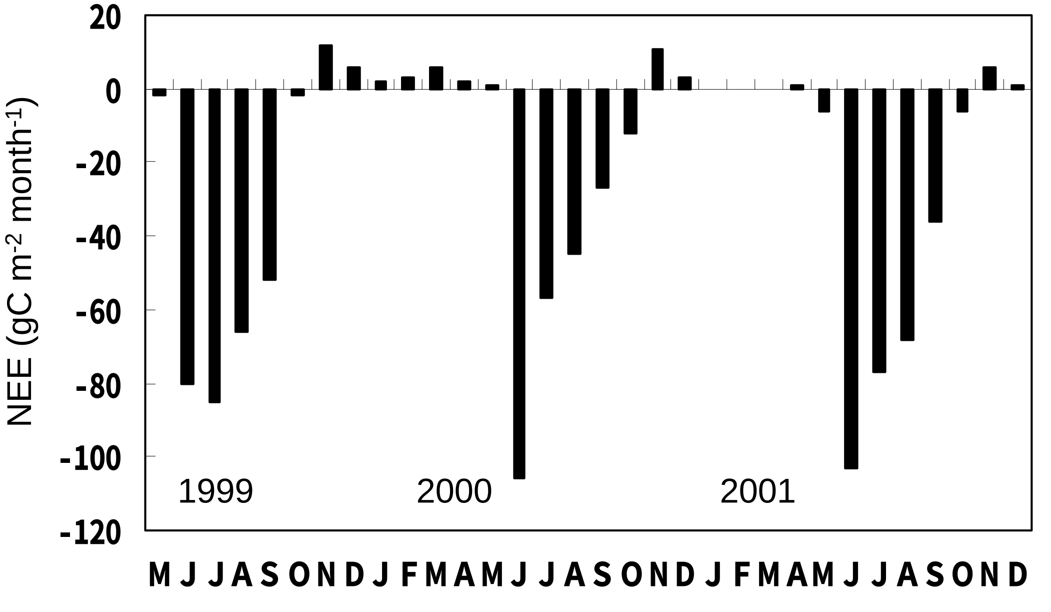

Figure 2

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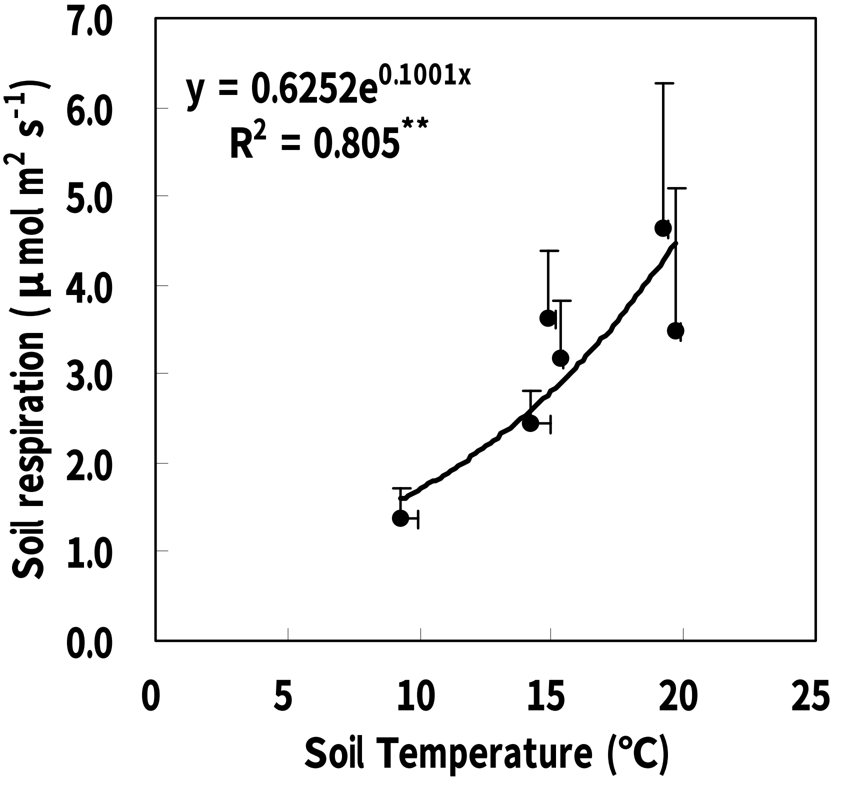

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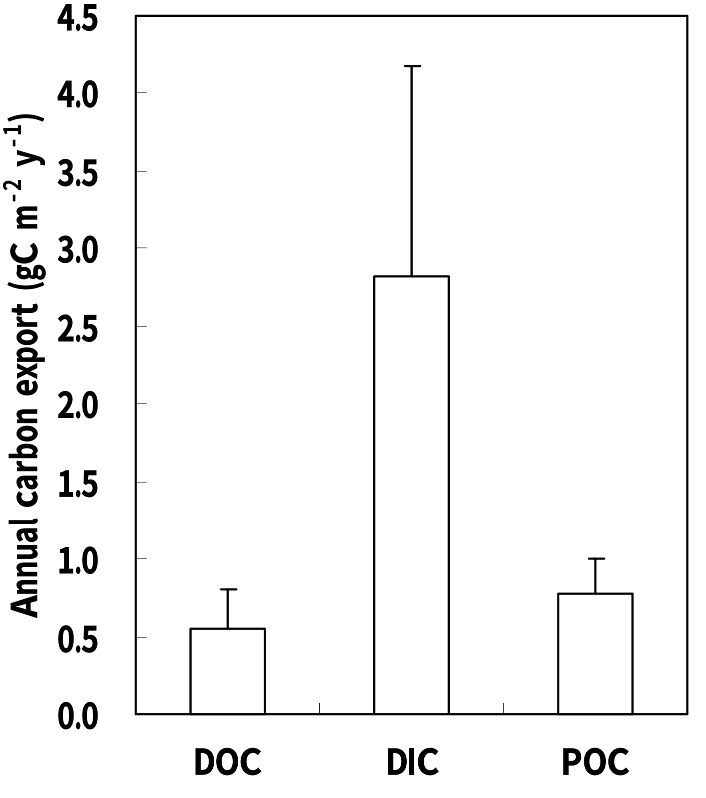

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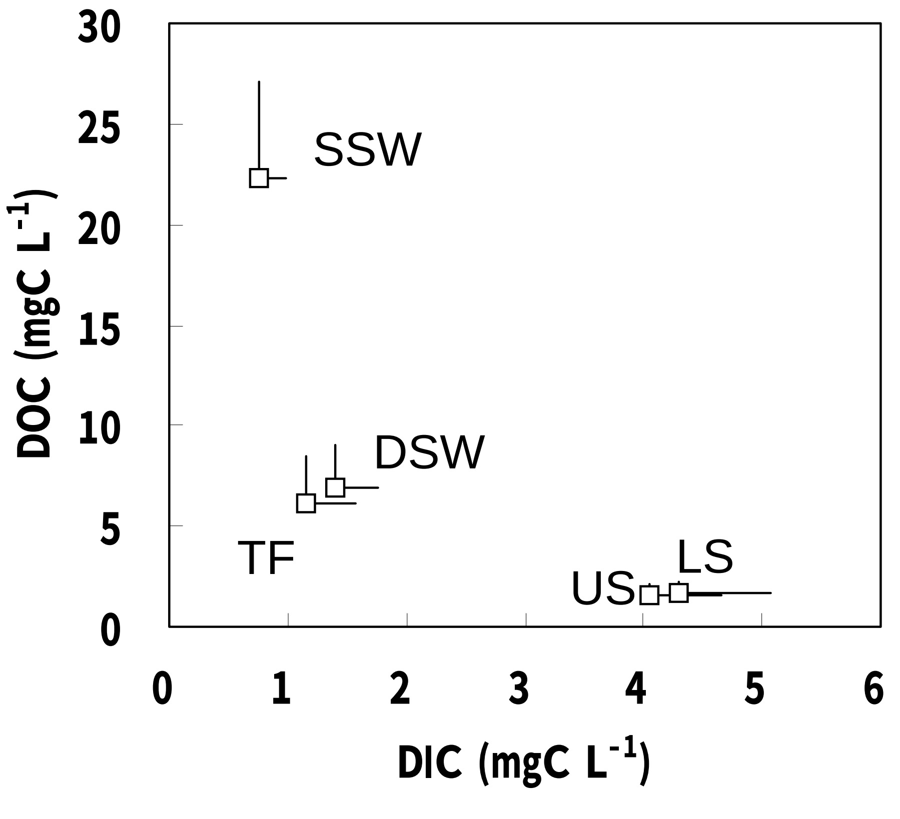

Figure 5

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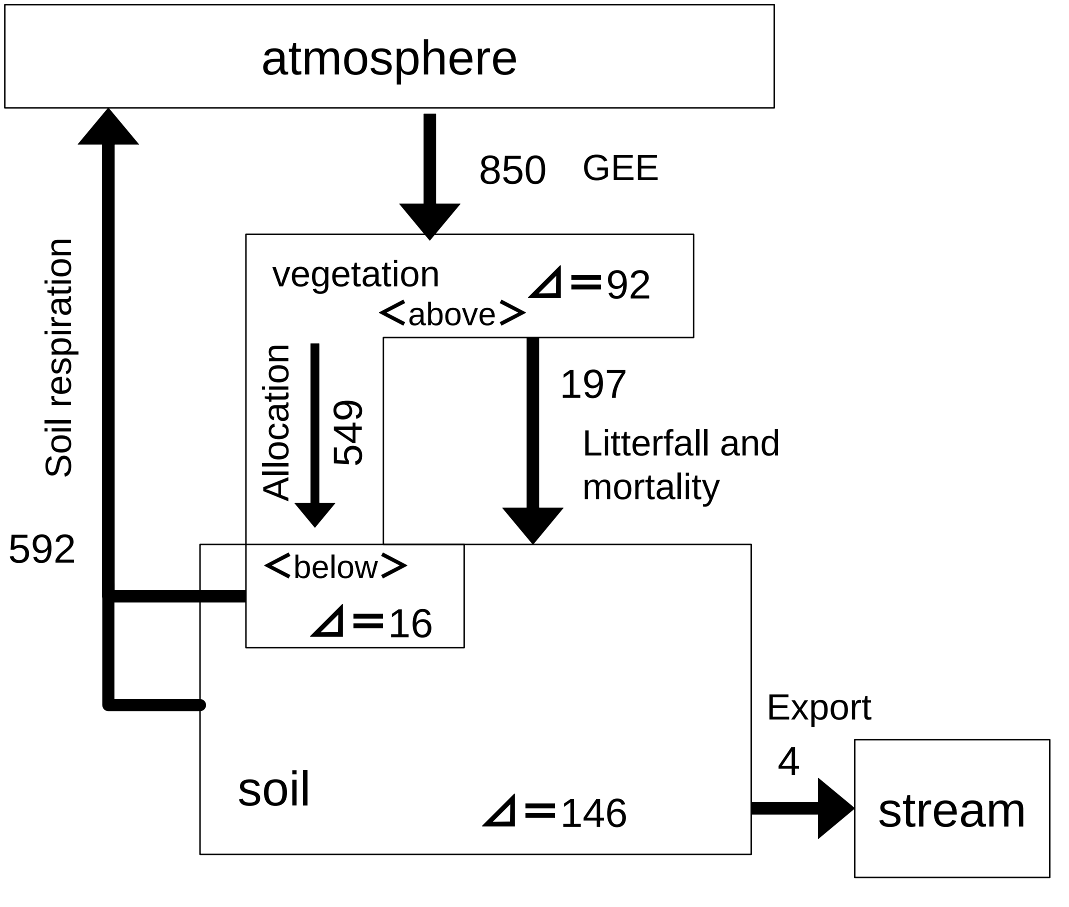

Figure 6

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