



Seasonal and snowmelt-driven changes in the water-extractable organic carbon dynamics in a cool-temperate Japanese forest soil, estimated using the bomb-¹⁴C tracer



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ABSTRACT

Water-extractable organic carbon (WEOC) in soil consists of a mobile and bioavailable portion of the dissolved organic carbon (DOC) pool. WEOC plays an important role in dynamics of soil organic carbon (SOC) and transport of radionuclides in forest soils. Although considerable research has been conducted on the importance of recent litter versus older soil organic matter as WEOC sources in forest soil, a more thorough evaluation of the temporal pattern of WEOC is necessary. We investigated the seasonal variation in WEOC in a Japanese cool-temperate beech forest soil by using the carbon isotopic composition (¹⁴C and ¹³C) of WEOC as a tracer for the carbon sources. Our observations demonstrated that fresh leaf litter DOC significantly contributed to WEOC in May (35–52%) when the spring snowmelt occurred because of the high water flux and low temperature. In the rainy season, increases in the concentration of WEOC and the proportion of hydrophobic compounds were caused by high microbial activity under wetter conditions. From summer to autumn, the WEOC in the mineral soil horizons was also dominated by microbial release from SOC (>90%). These results indicate that the origin and dynamics of WEOC are strongly controlled by seasonal events such as the spring snowmelt and the rainy season's intense rainfall.

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1. Introduction

In forest soils, dissolved organic carbon (DOC) is the main form in which organic carbon is transported downward into the subsoil to be mineralized, stabilized, or further leached into groundwater (Kalbitz et al., 2000; Qualls et al., 2000). The leaching of DOC accounts for significant carbon fluxes in terrestrial ecosystems (Siemens, 2003). It is also well known that DOC plays an important role as a transporter of radionuclides in soils. For example, downward flux of ¹³⁷Cs accompanied by DOC flux has been observed in a forest soil (Teegen and Dörr, 1996). In addition, DOC itself comprises

a radioactive isotope of carbon (¹⁴C), which is one of the most radiologically important radionuclides released from the nuclear industry (e.g., Koarashi et al. 2011) because of its relatively long half-life of 5730 y and the role of carbon in the metabolism of all life forms. Although several studies have obtained information on the evolution, stability, and dynamics of DOC in soils, further research is needed for better understanding of the role of DOC in the translocation and mineralization of soil organic carbon (SOC) and in the migration of radionuclides through the soil profile.

Water-extractable organic carbon in soil (WEOC) is commonly used to study the processes involved in DOC formation, and provides information for identifying the relevant DOC fraction type such as hydrophobicity. Hagedorn et al. (2002) reported that WEOC contains more recent C than DOC collected by lysimetry. The water-soluble “new” organic components with short turnover rates are most likely not captured by standard sampling techniques for DOC (Küsel and Drake, 1999), or they vanish in the bulk DOC, where refractory compounds dominate (Qualls and Haines, 1992). Thus,

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the water extraction method is considered to be more useful to detect the recent dynamics of C in the soil.

WEOC is complex and heterogeneous because it originates from plant litter, root exudates, microbial biomass, and soil humus (Hassouna et al. 2007). The production and consumption of WEOC are thought to be controlled by the amount of carbon and other environmental factors (Kalbitz et al. 2000). The amount of fresh leaf litter mass, thickness of the organic layer, and concentration of SOC also affect the concentration of WEOC as carbon sources (Michalzik et al., 2001; Fujii et al., 2009). In addition, temperature, precipitation, and water content are the physicochemical soil factors that indirectly affect the concentration of WEOC. Although considerable research has been conducted on the importance of recent litter versus older soil organic matter as WEOC sources in forest soil, a more thorough evaluation of the temporal patterns of WEOC is necessary.

Atmospheric nuclear weapons testing in the 1950s and early 1960s injected a large quantity of ‘bomb-¹⁴C’ into the atmosphere with a peak value in 1963 that almost doubled the natural concentration. Since the nuclear test ban treaty in 1963, the concentration of ¹⁴C in atmospheric CO₂ has gradually declined as the bomb-¹⁴C has moved into the ocean and terrestrial C reservoirs, and as the atmospheric CO₂ concentration has become diluted by the burning of ¹⁴C-free fossil fuels. This global bomb-¹⁴C spike has proven to be useful as a tracer for studying soil C dynamics on a time scale of years to decades (e.g., Trumbore, 2000; Koarashi et al. 2009).

Previous ¹⁴C isotope studies on WEOC dynamics have directly traced the sources of WEOC and DOC. Karlton et al. (2005) and Fröberg et al. (2009) showed that the DOC captured in mineral soils is derived only to a minor extent from fresh (¹⁴C-enriched) surface litter. In a companion study, we conducted an isotopic analysis (¹⁴C and ¹³C) of WEOC and its hydrophobic and hydrophilic fractions (Nakanishi et al. 2012), and provided direct support for the hypothesis that the WEOC in the mineral soil is dominated by the microbial release of water-soluble compounds from SOC, which has longer residence times of decades to centuries.

In snowfall areas, however, snowpack and snowmelt are very likely to affect the WEOC dynamics. In particular, spring snowmelt can be an important process to increase DOC fluxes. During the snowmelt period, DOC that accumulated in the snowpack over the winter season are flushed (Rascher et al., 1987) and, the increased DOC flux coupled with temperature rise may stimulate microbial biomass production (Brooks et al., 1998), SOC mineralization, and losses of CO₂ in soils (Monson et al., 2006; Pacific et al., 2008). In Japan, a hot and very humid rainy season in which most of the average annual rainfall occurs comes after the snowmelt period, followed by summer season. Therefore, the seasonality is expected to alter the concentration and composition of WEOC in soils.

Therefore, the objective of this study was to reveal the seasonal variations in WEOC, particularly in the spring snowmelt period and rainy season (early summer), which is characteristic of a cool-temperate Japanese forest, using the carbon isotopic composition (¹⁴C and ¹³C). The isotopic composition of WEOC was determined to track its origin from rapidly and slowly cycling sources, and to evaluate the seasonal variation in its dynamics.

2. Materials and methods

2.1. Site description

Sampling was conducted at the Appi forest meteorological research site within a cool-temperate deciduous broad-leaved forest in Iwate Prefecture, Japan (40°00'N, 140°56'E; 825 m a.s.l.). The forest is dominated by a 70- to 80-y-old Japanese beech (*Fagus crenata*), and virtually no understory is apparent. The mean annual

temperature and precipitation are 6.9 °C and 1207 mm, respectively (Ishizuka et al. 2006). Snow cover normally occurs from November (after the concentrated litterfall in mid-October) to May at a maximum depth of 2 m. The site is located on a lava plateau (consisting of andesite lava) at the foot of the Hachimantai volcanic chain. Allophanic volcanic ash soils are common in the study area (Takahashi and Shoji, 2002). The soil type at the site has been classified as moderately moist brown forest soil in the classification of forest soils of Japan (Forest Soil Division, 1976) and Andosols (ISSS Working Group RB, 1998; Ishizuka et al. 2006). The top 60 cm of the mineral soil consists of A1 (0–6 cm), A2 (6–12 cm), AB (12–30 cm), and B (30–60 cm) horizons. The physicochemical properties for the top 15 cm of mineral soils are described in Koarashi et al. (2009). Tephra fragments from the Towada-a ash fall deposit, ca. 1000 y B.P., were observed in the mineral soil at 15–20 cm during a soil profile investigation in October 2005, suggesting that the surface soil is of volcanic ash origin and has been developing for more than 1000 y (Koarashi et al. 2009). The rooting depth of the vegetation was approximately 25 cm, with significant abundance in the top 5 cm.

2.2. Sampling and preparation of water-extractable organic carbon

Soil samples were collected in May, June, August, and October 2009, and May 2010. May and June are, respectively, the spring snowmelt period and the rainy season. Because this area is covered with heavy snow (up to 2 m deep) during the winter, we could not collect soil samples from November until May. Soil sampling was conducted more than 2 d after precipitation. In a 10 × 10 m square, three subsamples of soil cores (10 cm in diameter and 20 cm in depth) were collected after removing the litter layer. The air and soil temperatures at a depth of 5 cm were measured using thermo recorders (HL3631, TL3633, CB3911; As One Co., Ltd., Tokyo, Japan). The volumetric soil water content at a depth of 0–5 cm was also measured using a soil moisture meter (TDR-251A; Nakamura Rika Co., Ltd., Tokyo, Japan). The meteorological data are given in Table 1. The fresh soil cores were placed in a cooler for transport back to the laboratory and then divided into the fermentation–humus (FH) horizon (2–3 cm thick) and 0–5 cm, 5–10 cm, and 10–15 cm depths of the mineral soil; the samples of the same layers for the three cores were then mixed. All recognizable plant leaf fragments and remaining roots were manually removed from the samples before sieving at <2 mm.

Water extraction was performed by a procedure by Nakanishi et al. (2012). A 300–1000 g subsample of each soil sample was shaken overnight at 5 °C with ultrapure water at a soil-to-solution ratio of 1:5 on the basis of the oven-dry mass. After centrifugation for 30 min at 3500 rpm, the supernatant was filtered through a prewashed 0.45-μm-pore cellulose acetate membrane filter (Advantec, Tokyo, Japan). These water extracts were then stored in a refrigerator at 5 °C before chemical analyses. The remaining soil samples were dried at 50 °C for analyses of the organic carbon content and isotopic compositions.

Table 1

Seasonal changes in air temperature, soil temperature, and soil water content at the study site.

	Air temperature (°C)	Soil temperature at 5 cm (°C)	Water content at 0–5 cm (%)
May 2009	17.4	9.0	49.3
June 2009	21.1	12.7	42.1
August 2009	17.1	15.5	32.1
October 2009	12.8	9.6	39.0
May 2010	14.7	8.7	43.3

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