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Effects of freeze–thaw cycles resulting from winter climate change on soil nitrogen cycling in ten temperate forest ecosystems throughout the Japanese archipelago

Rieko Urakawa [a,*], Hideaki Shibata [b], Megumi Kuroiwa [a], Yoshiyuki Inagaki [c], Ryunosuke Tateno [d], Takuo Hishi [e], Karibu Fukuzawa [f], Keizo Hirai [c], Hiroto Toda [g], Nobuhiro Oyanagi [h], Makoto Nakata [i], Asami Nakanishi [d], Keitaro Fukushima [d], Tsutomu Enoki [e], Yuichi Suwa [j]

[a] Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-8657, Japan
[b] Field Science Center for Northern Biosphere, Hokkaido University, N9 W9, Kita-ku, Sapporo, Hokkaido 060-0809, Japan
[c] Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba, Ibaraki 305-8687, Japan
[d] Filed Science Education and Research Center, Kyoto University, Oiwake-cho, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan
[e] Graduate School of Agriculture, Kyushu University, 394 Tsubakuro, Sasagurimachi, Kasuya, Fukuoka 811-2415, Japan
[f] Northern Forestry and Development Office, Field Science Center for Northern Biosphere, Hokkaido University, 250 Tokuda, Nayoro, Hokkaido 096-0071, Japan
[g] Graduate School of Agriculture, Tokyo University of Agriculture and Technology, 3-5-8 Saiwai-cho, Fuchu, Tokyo 183-8509, Japan
[h] Environmental Science Research Niigata, 8-13 Yoshidahigashisakae-cho, Tsubame, Niigata 959-0291, Japan
[i] Faculty of Agriculture, Niigata University, 2-8050, Ikarashi, Nishi-ku, Niigata 950-2181, Japan
[j] Faculty of Science and Engineering, Chuo University, 1-13-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan

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ABSTRACT

In temperate forest ecosystems, accelerated freeze–thaw cycles caused by winter climate change are expected to affect nitrogen (N) cycling in soils. Net N mineralization and nitrification rates were investigated via incubations of sieved soils transplanted from ten temperate forest ecosystems to two northern Japan sites with natural snowfall gradients. This was done to address: 1) how freeze–thaw cycles affect N mineralization and nitrification in temperate forest soils; 2) whether freeze–thaw cycles change the soil N transformation rates in the following growing season; and 3) which soil characteristics affect the response of the N transformation rates to freeze–thaw cycles. The effect of freeze–thaw cycles on inorganic N and dissolved organic carbon productions differed among soils, that is, some soils produced more inorganic N and dissolved organic carbon in the conditions imposed by freeze thaw cycles than in the non-frozen treatment but the others did not. The response to the freeze–thaw cycles was explained by soil microbial activity (gross N mineralization and nitrification rate) and soil fertility (inorganic N pools in the early spring and water soluble ions). Freeze–thaw cycles significantly increased N transformation rates in the following growing season, suggesting that winter climate change might also affect nutrient availability for vegetation and soil microbes in the growing season. The magnitude and frequency of freeze–thaw cycles were considered to be important indicators of N transformation rates during the growing season, suggesting that the higher intensity of freeze–thaw cycles in the original locations of soils changed the microbial communities and functions with high tolerance to freeze–thaw cycles; this resulted in greater N transformation rates in the following growing season. Microbial activity, soil fertility and climate patterns in the original locations of soils are believed to have an effect on the response to winter climate change and to cause large variability of soil response of N transformation rates to freeze–thaw cycles in both the dormant and growing seasons.

* Corresponding author. Tel.: +81 3 5841 5214; fax: +81 3 5841 5464.
E-mail addresses: urakawa@fr.a.u-tokyo.ac.jp, rieko@y7.dion.ne.jp (R. Urakawa).

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1. Introduction

Soil nitrogen (N) transformations are key processes underpinning forest productivity and related ecosystem function and service because N is an essential nutrient for vegetation and soil organisms. Soil microbial activity is responsible for N transformations and is strongly influenced by soil temperature (Stanford et al., 1975; Sierra, 1997). Soil N availability is thus expected to be influenced by soil temperature changes arising from climate change, such as global warming. Therefore, to provide a better understanding of N biogeochemistry and availability in forest ecosystems under a changing environments, it is necessary to clarify the effect of climate change on soil N cycling.

In temperate regions, where precipitation alternates between falling as rain or snow, the intensity of snowfall strongly affects the soil environment in the dormant season (Park et al., 2010). For example, insulation resulting from thick snowpacks prevents soils from freezing, in contrast to shallow snowpacks which induce soil freeze–thaw cycles (Christopher et al., 2008). Therefore, it has been suggested that, in temperate regions, the effect of climate change on the soil environment should be especially apparent in winter where alternation between rain and snow will be more variable (Henry, 2008). In fact, warmer climate over the last half-century has caused significant declines in the extent of snow cover in the Northern Hemisphere (IPCC, 2007), in snowpack accumulation and snow cover duration in the northeastern United States (Campbell et al., 2010), and in a greater than 5% decrease in snowfall amounts on the western side of Japan next to the Sea of Japan (Japan Meteorological Agency, 2012). Studies using winter climate models (Hosaka et al., 2005) and long-term ground observation of snowpack depth (Park et al., 2010) also suggest that northern Japan's snowpack will continue to shrink. Since winter surface air temperatures in Japan are also expected to increase by 1–3 °C by the end of this century compared with the beginning of this century (Japan Meteorological Agency, 2008), additional information revealing how soil N cycling changes with changes in soil freeze–thaw cycles is needed.

Numerous laboratory studies have been conducted to clarify the effect of freeze–thaw cycles on soil nutrient cycling. Considerable numbers of soil microbes survive after multiple freeze–thaw cycles (Morley et al., 1983) and their activity is maintained even in sub-freezing temperatures down to −4 °C (Öquist et al., 2007). Thawing after soil freezing stimulates microbial activity resulting in temporal increases in emission of N_2O (Christensen and Christensen, 1991), CO_2 (Neilsen et al., 2001; Herrmann and Witter, 2002), and N mineralization (Schimel and Clein, 1996). These flushes are caused by decomposition of dead organisms by surviving microbes (Skogland et al., 1988; Neilsen et al., 2001). This mechanism is similar to the response of soil N transformation processes (mineralization and nitrification/nitrate production) to drying-rewetting treatments (Skogland et al., 1988; DeLuca et al., 1992). Recent studies with realistic *in situ* incubation temperatures did not always correspond well to studies with extreme freeze–thaw cycles as described above. Moderate freeze–thaw cycles had minimal influences on microbial biomass pools (Lipson et al., 2000; Grogan et al., 2004). Also, inorganic N leached from the O-layer column incubated with moderate freeze–thaw cycles was significantly less than that from the non-frozen column; this effect might be masked by other soil responses to frost such as denitrification induced by the increased release of dissolved organic carbon (DOC) (Hentschel et al., 2008; Groffman et al., 2011; Reinmann et al., 2012). This suggests that the response of N transformations to freeze–thaw cycles is more complicated and additional studies with realistic freeze–thaw regimes are needed.

In contrast to the many laboratory studies, there has been little research conducted *in situ* evaluating the effect of freeze–thaw cycles on soil N cycling (Groffman et al., 2001a; Christopher et al., 2008; Joseph and Henry, 2008). As expected from laboratory incubation studies, field research on freeze–thaw cycles has shown increases in the soil inorganic N pool (Groffman et al., 2001b; Christopher et al., 2008) and in nutrient leaching (Fitzhugh et al., 2001; Joseph and Henry, 2008). However the responses of soil N processes to freeze–thaw cycles differed among these studies. In the snow removal experiment at Hubbard Brook Experimental Forest, New Hampshire, northeastern USA, Groffman et al. (2001b) observed that freeze–thaw cycles led to no increase in N mineralization, nitrification or microbial biomass and concluded that increased nitrate-N (NO_3–N) leaching was ascribable to tree root mortality. In contrast, Christopher et al. (2008) showed an increase in soil mineralization rates yet a decrease in nitrification rates following increased freeze–thaw cycles in a soil transplant experiment conducted in northern Japan. Such an inconsistency among different locations in the response of nutrient cycling to freeze–thaw cycles suggests that further investigation is required that examines the relationship between soil responses to freeze–thaw cycles and soil characteristics.

Freeze–thaw cycles in winter may also affect N cycling in the following growing season. Long-term ecosystem monitoring studies have shown unusually cold winters or low snowfall induced soil frost and increased NO_3–N concentrations in stream water in the following growing season (Likens and Bormann, 1995; Mitchell et al., 1996). However, there have only been a few field measurements investigating the effect of freeze–thaw cycles on N cycling in the growing season (Groffman et al., 2001b; Joseph and Henry, 2008; Hentschel et al., 2009), and the relationship between the effect and soil characteristics (e.g. soil chemical and physical properties and indices of organic matter accumulation such as O-layer amount, bulk density, pH (H_2O), Total-C, N, C/N, water soluble anions and cations) is unclear. Therefore, there is a need to understand whether there are general patterns and processes inducing changes in soil N cycling arising from freeze–thaw cycles among different soil characteristics, and to identify the explanatory factors and mechanisms behind the creation of site-to-site differences in their responses.

The Japanese archipelago extends for 3000 km from 45° 33′ N to 20° 25′ N and the climatic zones range from cool-temperate to subtropical. Also, the archipelago is divided into western and eastern sides by a central mountain chain. The western border is the Sea of Japan and has comparable snowfall, and the eastern side borders the Pacific Ocean and has much less snowfall in winter. On the Sea of Japan side, soils do not freeze because of the insulation of the dense snowpack and a stable soil temperature is maintained (Whitaker and Sugiyama, 2005; Christopher et al., 2008). However, on the Pacific side, uncovered soil is subject to repeated freeze–thaw cycles with consequent fluctuations in soil temperature (Christopher et al., 2008; Iwata et al., 2008). These geographical and climatic conditions likely provide soils which show high variability in N transformations. Previous *in situ* incubation studies found that 10–40% of the annual amount of soil inorganic N was produced in the winter in soils from the Japanese archipelago (Hirai et al., 2007a; Shibata et al., 2011), suggesting that soil N cycling in winter in Japanese forests greatly affects annual N cycles. We conducted field research in Japan and developed the following research questions:

1. How do winter freeze–thaw cycles affect N mineralization and nitrification in the temperate forest soils of Japan?
2. Do N transformation rates change in the growing season following the freeze–thaw cycles?