Soil Biology & Biochemistry 109 (2017) 35–49

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

Altered soil carbon and nitrogen cycles due to the freeze-thaw effect: A meta-analysis

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ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form
22 January 2017
Accepted 26 January 2017
Available online 12 February 2017

Keywords:
Freeze-thaw
Carbon
Nitrogen
Meta-analysis
Biogeochemistry

ABSTRACT

Global climate change may result in changes in snow cover, which may enhance freeze-thaw phenomena in mid and high latitude and high elevation ecosystems, especially in the northern hemisphere, in the future. As a common non-biological stress, the freeze-thaw process can substantially alter soil carbon and nitrogen cycles. However, a comprehensive understanding of nutrient pools and dynamics in response to freeze-thaw cycles is not available. Here, we evaluated the effect sizes of the responses of 18 variables related to soil carbon and nitrogen cycles to the freeze-thaw effect from 46 papers. Seventeen studies that reported field observations and 28 studies that reported results from laboratory experiments were included, as well as one paper that used both methods to explore freeze-thaw processes. We used a random-effects model to examine whether soil origins, effect phases (including initial and long-term effects), methods and soil horizons affect the magnitudes of the responses to freeze-thaw events. The soil sources include forest, shrubland, grassland/meadow, cropland, tundra and wetland. We used meta-regression to explore possible relationships among effect sizes with freezing temperature, soil pH, soil C/N ratios and other factors. Our results suggest that the freeze-thaw process causes microbial N and the microbial C/N ratio to decrease by 12.2% and 8.5%, respectively. Soil solution dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) are enhanced by 27.5% and 37.3%, respectively. The freeze-thaw effect increases the concentrations of NH_4^+, NO_3^- and dissolved inorganic nitrogen (DIN) by 84.1%, 29.6% and 35.4%, respectively. N_2O emissions are also increased by 95.0% in freeze-thaw treatments. Laboratory measurements resulted in contrasting responses in terms of mineralization, nitrification and respiration. Freeze-thaw events promote turnover of fine roots but have no effect on the long-term aboveground biomass of grassland and heath. The results of this meta-analysis help to achieve a better understanding of the overall effects of freeze-thaw events on soil carbon and nitrogen cycles and their modulation across different environments.

1. Introduction

The freeze-thaw process in soils is a common phenomenon in some temperate environments, but it primarily occurs in high-latitude and high-elevation ecosystems (Grogan et al., 2004; Yu et al., 2011). The maximum extent of seasonally frozen ground represents up to 55% of the total land area of the northern hemisphere (Zhang et al., 2003; Kreyling et al., 2008). The freeze-thaw effect is sensitive to climate change and global warming. Previous studies have identified a relationship between surface air temperatures and the winter soil thermal regime, which is affected by snow cover conditions (Stieglitz et al., 2003; Yi et al., 2015). Both field observations (Pederson et al., 2011) and model predictions (Giorgi et al., 1994; Mellander et al., 2007) have suggested that an important indirect effect of winter climate change is the reduction in the depth and duration of snowpack. Additionally, the duration of soil freezing and the intensity of soil frozen commonly exhibit an inverse relationship with the thickness of snow cover (Fitzhugh et al., 2001). Therefore, the frequency and intensity of the soil freeze-thaw process may be enhanced by the increased occurrence of discontinuous snow cover and rain-on-snow events (Putkonen and Roe, 2003; Hentschel et al., 2009).

Increasing attention has been paid to how soil carbon and

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http://dx.doi.org/10.1016/j.soilbio.2017.01.020

nitrogen cycles are altered by the freeze-thaw process under global climate change. Carbon is a material that stores energy in terrestrial biomes, and nitrogen often limits plant productivity in terrestrial biomes. Their cycles are crucial in determining ecosystem functions and services (Liao et al., 2008). The carbon in northern high latitudes is largely stored in permafrost and seasonally thawed soil horizons, which contain approximately twice as much carbon as the global atmosphere (Hugelius et al., 2014). In the past 20 years, great attention has been paid to the influence of climate change on the global carbon and nitrogen cycles, especially during the growing season (Rustad et al., 2001; Luo et al., 2006; Lu et al., 2011). However, an increasing number of studies have revealed that winter processes, especially the freeze-thaw effect induced by changes in snow cover, should not be ignored on the annual scale (Fitzhugh et al., 2001) and may affect the plant growth during subsequent growing season (Urakawa et al., 2014).

Available studies show that the freeze-thaw effect can destroy microorganisms and root cells (Schimel and Clein, 1996; Tierney et al., 2001), releasing their internal organic carbon and nitrogen and thereby increasing the corresponding nutrient concentrations in the soil solution (Risk et al., 2013). Macro-aggregates in soils can be broken down into micro-aggregates by successive freeze-thaw cycles (Oztas and Fayetorbay, 2003), which increase the availability of nutrients to soil microorganisms via exchange across the increased surface area (Risk et al., 2013; Urakawa et al., 2014). In addition, the carbon utilization efficiency of microbial community can increase with decreased temperature (Steinweg et al., 2008). During the freeze-thaw period, nutrients and substrates produced through the abovementioned mechanisms stimulate the metabolisms of microbes and the turnover of carbon and nitrogen in soils, which in turn increases the potential nutrients leaching (Gilliam et al., 2010; Campbell et al., 2014).

To simulate freeze-thaw cycles, field experiments such as snow removal treatments, and laboratory simulations are two currently common methods for performing freezing or freeze-thaw treatments. In recent years, numerous studies have reported the effects of the freeze-thaw process on soil carbon and nitrogen cycles (Matzner and Borken, 2008; Wipf et al., 2015; Yi et al., 2015). Because of differences in soil types, water content, the timing of sampling and the diversity of methods used, there are still debates on how the freeze-thaw process influence nutrient cycles in soils (Kreyling et al., 2010; Smith et al., 2010; Su et al., 2010). The highly diverse results from individual experiments make it impossible to appraise the overall effect of the freeze-thaw process and its modulation by environmental factors, including the potential future effects of climate change. For example, large variations have been observed in the effects of freeze-thaw processes on nitrogen mineralization, which ranges from −13.6% to 28.1% (Appendix S1). Although some studies have reported that soil inorganic nitrogen release was stimulated by the freeze-thaw process (Nielsen et al., 2001; Schimel et al., 2004), one study reported that N mineralization was unaffected in two sites, one with birch and another with maple (Groffman et al., 2001). In addition, although some studies found a pulse of CO_2 after thawing (Herrmann and Witter, 2002; Grogan et al., 2004; Feng et al., 2007), there is still a lack of evidence for increasing C losses caused by the freeze-thaw treatment (Matzner and Borken, 2008). Although some review studies have reported detailed mechanisms for carbon and nitrogen under the freeze-thaw process, we do not know the quantitative changes of variables under different environmental factors (such as pH, soil C/N ratio) (Henry, 2007; Matzner and Borken, 2008). Few meta-analyses exist in this research field, which mainly focuses on soil gaseous emissions in the growing season (Blankinship and Hart, 2012). In addition, although laboratory simulations lack realism compared with field observations, they can accurately control the pattern of freeze-thaw process which gives us uniquely detailed insight into the effects of the freeze-thaw process on carbon and nitrogen turnover. Therefore, it is better to obtain data from a variety of ecosystem types and compare their effect results according to different experimental methods. This type of analysis can contribute a better understanding of the alteration of soil carbon and nitrogen cycles by freeze-thaw events.

Here, we compiled data on 2050 comparisons of 18 variables from 46 individual studies to conduct a meta-analysis. The results from individual studies can be synthesized to discuss the effect sizes and general patterns of soil carbon and nitrogen cycles under certain defined freeze-thaw conditions. We also want to determine how freeze-thaw cycles, freezing temperatures and other environmental factors (such as soil pH and C/N ratios) increase or decrease the effect size results (Vestgarden and Austnes, 2009; Groffman et al., 2011).

2. Materials and methods

2.1. Data collection

We searched peer-reviewed journal articles published before March 2016 using the Web of Science and retrieved the references cited in the papers. To avoid bias in publication selection, 46 out of the 474 papers included in this meta-database (Appendix S1, Appendix S2) fulfilled the following five criteria. (1) The experimental methods were not limited to field treatments, such as snow removal; laboratory simulations were also included in our meta-analysis. (2) The laboratory simulations must have control groups or initial values, and field treatments should have reference values by which we can evaluate whether freeze-thaw cycles have significant effects on soil carbon and nitrogen variables. (3) The means, standard deviations (SD) and sample sizes (n) of the variables were reported or could be calculated. As a few studies did not report standard deviations, we calculated the average coefficient of variation (CV) within each data set and assessed the variances using the sample sizes and CVs in order to reduce the impact on the final results as much as possible (Bai et al., 2013); (4) Soil type, freezing temperature, effect phase, freeze-thaw cycles and soil horizons were treated as independent comparisons. While we focused on specific categories (e.g., treatment method), modulation of the effect sizes by environmental factors (e.g., multiple sampling sites or different soil horizons) was also included. (5) For studies containing multiple treatments, we chose results influenced only by the freeze-thaw process; comprehensive effects were excluded. The response variable under consideration had to be reported at least in two different papers with more than 8 paired comparisons, so that more robust and reasonable conclusions can be obtained as this condition is satisfied.

In total, 18 variables were collected in the meta-database (Appendix S3). Nutrient pool-related variables included microbial biomass; microbial C; microbial N, NH_4^+ and NO_3^-; dissolved inorganic nitrogen (DIN); dissolved organic nitrogen (DON); and dissolved organic carbon (DOC). Flux variables included net mineralization rates, net ammonification rates, net nitrification rates, respiration rates, and N_2O emissions. Other descriptive variables associated with soil C and N cycles were also included, such as microbial C/N ratios, aboveground biomass, fine root lengths, fine root production and fine root mortality. We distinguish between laboratory and in-situ measurements of respiration, mineralization and nitrification processes because they do not represent similar integrated responses. For example, if respiration were measured in the laboratory, the result would represent potential microbial respiration. However, if soil respiration were measured in situ, then the data represent the integrated response of both autotrophic and