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Review paper

Response of terrestrial nitrogen dynamics to snow cover change: A meta-analysis of experimental manipulation

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ABSTRACT

Snowpack in winter is very sensitive to climate change, and may in turn induce complex effects on nutrient cycling in terrestrial ecosystems. This study synthesized data from 41 publications based on snow depth manipulation experiments and conducted a meta-analysis to assess the general responses of 12 variables related to terrestrial nitrogen (N) pools and dynamics to altered snowpack depth. Our results indicated that increasing snow depth significantly increased foliar N (+4.5%) and microbial N (MBN, +35.9%), but significantly decreased soil N_2O efflux (−34.1%). However, altered snow depth did not significantly affect soil dissolved organic N (DON), total inorganic N, nitrate and N leaching. The decreased net nitrification (−24.8%) by deeper snowpack suggested that less soil N transformed to nitrate, which might contribute to reduce soil N losses. Since increasing snowpack depth promoted MBN, the unchanged net N mineralization and soil ammonium content were probably due to limitation of the soil N availability and other soil abiotic factors rather than soil microbes. In addition, long-term and snowfence or shelter methods generated the most significant effects on N dynamics for snow addition or removal experiments, respectively. Our results provide a comprehensive understanding of how N cycling responses to altered snow cover under climate change scenarios.

1. Introduction

Climate change has influenced Northern hemisphere snow cover through directly altering annual snowfall patterns and indirectly modifying the timing of snowmelt and freeze-up (Brown, 2000; Liu et al., 2012). Thus, winter snow cover is one of the greatest climate changing features under current global change scenarios (IPCC, 2007). Snow cover may strongly impacts soil temperature (Brown and DeGaetano, 2011), moisture (Litaor et al., 2008), frequency of freeze-thaw (Brown and DeGaetano, 2011; Campbell et al., 2010), and duration of the growing season (Jonas et al., 2008), which in turn can influence essential ecosystem processes (C, N cycling) (Bombonato and Gerdol, 2012; Sommerfeld et al., 1993). Although many studies have tried to explore the responses of terrestrial ecosystems to warming (Bai et al., 2013) or precipitation change (Wu et al., 2011), the effect of changing snow cover may be more complicated and has rarely been meta-analyzed. For example, increasing air temperature increased length of growing season and the soil temperature (Starr et al., 2000), but decreased soil temperature during winter in snow covered regions (Groffman et al., 2001). In addition, snow cover can decouple soil from air and generate a specific microclimate (Schindlbacher et al., 2014; Sommerfeld et al., 1993), where the interaction between temperature and moisture may offset each other. Therefore, more accurate projections of future terrestrial C and N dynamics require a better understanding of the effects of snowpack change.

The insulating snow cover may dampen soil temperature fluctuations, resulting in higher activities of microbial metabolism and enzymes, thereby increasing organic matter decomposition and N mineralization rates. The higher N mineralization may increase nutrient availability, which in turn increase microbial N immobilization and plant N uptake (Hobbie and Chapin, 1996). Previous studies demonstrated that N mineralization rates depended on the duration and depth of snowpack in cold regions (Brooks and Williams, 1999; Olsson et al., 2003). Brooks et al. (1995) also

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revealed that longer and deeper snow accumulation areas had greater N mineralization rates and higher soil N levels, which was caused by warmer soil temperature. However, the N mineralization rate was higher during winter than the growing season in tundra (Brooks et al., 1998; Giblin et al., 1991; Hobbie and Chapin, 1996; Williams et al., 1996), which was completely different from the result conducted in temperate forests (Boone, 1992; Hill and Shackleton, 1989). We hypothesized that these inconsistencies were due to different effects of snowpack on N cycling in different ecosystems as a result of the interaction of snowpack with other abiotic factors (e.g. soil N availability and quality of substrate).

The substrate quality for microbes from root and microbial mortality may also change with changing snow cover. Root and microbial mortality are main N sources and play critical role in N cycling processes under snow cover, especially in tundra ecosystems where nitrogen is strongly limiting (Chapin et al., 1988; Tierney et al., 2001). Denitrification was found to be limited when soil temperature was below 0 °C (Malhi and Nyborg, 1990; Smid and Beauchamp, 1976) and mainly occurred in melting periods with saturation water (Aulakh et al., 1991; Malhi et al., 1990). Nyborg et al. (1997) proposed that a large amount of soil nitrate was denitrified during snow melting period, but with smaller amount emitted as N_2O. Altered snow cover may affect N_2O emission and N leaching by changing NO_3^- production, soil water, frost depth, and the frequency of soil freeze-thaw cycles during snow melting period (Malhi et al., 1990; Turner and Henry, 2010). Previous studies indicated that soil freezing may damage plant roots (Cleavitt et al., 2008; Tierney et al., 2001), resulting in reduction of inorganic N uptake (Socci, 2012), which in turn lead to greater N leaching losses. N_2O emission was supposed to be greatest during snow melting periods with water saturated soil and higher NO_3^- concentration (Malhi et al., 1990).

All plant species can take up N through root systems when snow is present, while the uptake ability varied among species (Bilbrough et al., 2000; Inselsbacher et al., 2007). In addition, Bowman (1992) found that N reservoir in snowpack was very important to plant growth in the early growing season. Therefore, the plant N content in cold regions may greatly depend on the snow cover depth and ecosystem types.

In the past two decades, snow cover manipulation experiments which simulated increasing winter precipitation in the form of snow (snow addition), or less winter precipitation in the form of snow and increasing occurrence of midwinter thawing events (snow removal), were conducted around the world to investigate the responses of terrestrial N pools and dynamics. While numerous studies have been conducted, a data synthesis is still unavailable. The present study compiled 570 observations from 41 individual studies and provided a comprehensive analysis to identify the general pattern of the effects of snow manipulation experiments on terrestrial N pools (soil dissolved organic N, soil inorganic N, soil NH_4^+, soil NO_3^-, microbial biomass N, and foliar N) and dynamics (net mineralization, net nitrification, denitrification, net ammonification, N leaching, and N_2O emission); and to analyze the differences among different settings of snow manipulation experiments (e.g. method and ecosystem types, sampling seasons and durations).

2. Materials and methods

2.1. Data collection

We collected data from journal articles which terrestrial nitrogen pools and dynamics were reported in response to altered snow cover (snow addition or removal). In this study, we searched the references by using the search terms “snow” and “nitrogen” or “freeze-thaw” and “nitrogen” in the Web of Science resource. A total 570 observations of 12 variables (Supporting Information, Appendix S1) were taken from 41 papers (Appendix S2). The following criteria were adopted to choose appropriate studies: only field snow cover manipulation studies were selected but laboratory incubation studies were not included; the control and treatment plots experienced the same climatic and soil conditions; only control and snow manipulation treatment data were used and the interacting effects were excluded in the multifactorial studies (e.g. warming treatment).

For each publication, we noted the snow cover manipulation type (addition or removal), experiment location, snow cover manipulation method, ecosystem type, sampled seasonality, treatment duration, and the response variables. We also collected soil temperature and moisture values of control and treatment plots if reported. Data in the original paper's figures were extracted by Engauge software (4.1). If the standard deviation was not reported, we calculated it from standard error and sampling size. A few studies did not report either standard deviation or standard error, we approximated the missing standard deviation by multiplying the reported mean by the average coefficient of variance (CV) (Bai et al., 2013). In order to integrate the results of snow addition and removal experiments, we defined thinner snow cover plots as control, deeper snow cover plots as treatment. Thus, all the effect sizes of under both snow removal and addition represent the effects of increasing snowpack depth on each variable.

Each study was grouped into one of these four ecosystems: tundra, grassland, forest and cropland (Appendix S1). There were five categories of snow manipulation method (snowfence, natural snowed, natural removal, shelter and manual removal). The sampling seasons included spring, summer, autumn and winter. The treatment durations ranged from two months to 43 years, which were divided into short (≤one year), medium (>one and ≤three years), and long terms (>three years). When the variables were reported for multiple plant species and soil depths, they were treated as separate entries; while the variables were reported for multiple sampling dates, only the monthly means were collected.

2.2. Meta-analysis

For each individual observation of snow manipulation experiments, the effect size (R) was calculated by the natural log-transformed response ratio (RR): $R = \ln RR = \ln(\overline{X}_t/\overline{X}_c)$, where $\overline{X}_t$ is the treatment mean, $\overline{X}_c$ is the control mean (Hedges et al., 1999). We calculated the average effect sizes and generated confidence intervals (CIs, bootstrapping with 9999 iterations) using a fixed effects model in MetaWin software (2.1) (Rosenberg et al., 2000). The effect size of a response variable was considered significant if the 95% CI did not cover zero. The detailed of methods were described by Li et al. (2015).

3. Results

Based on the entire dataset of snow removal and addition, increasing snowpack depth significantly increased microbial biomass N (MBN, +35.9%) and foliar N (+4.5%), but did not significantly affect soil dissolved organic N (DON), soil inorganic N (INON), soil NO_3^- and soil NH_4^+ (Fig. 1a). For N dynamics, increasing snowpack depth significantly decreased N_2O emission (−34.1%), and net nitrification (−24.8%), but did not significantly change net N mineralization (Fig. 1a). The observed numbers of N leaching, denitrification and net ammonification were less than 20 (Fig. 1a). Based on the current limited number of observations, results suggested that increasing snow cover significantly increased denitrification (+32.0%), but did not significantly change N leaching and