Effects of snow cover-induced microclimate warming on soil physicochemical and biotic properties

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Running title: Snow cover effects on soil properties

Zemin Zhao[1], Pieter De Frenne[2], Josep Peñuelas[3, 4], Koenraad Van Meerbeek[5], Dario A. Fornara[6], Yan Peng[1], Qiqian Wu[7], Xiangyin Ni[1], Fuzhong Wu[1], and Kai Yue[1, 2*]

1. Key Laboratory for Humid Subtropical Eco-Geographical Processes of the Ministry of Education, School of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China
2. Forest & Nature Lab, Ghent University, Geraardsbergsesteenweg 267, 9090 Gontrode, Belgium
3. CREAF, E08193 Cerdanyola del Vallès, Catalonia, Spain
4. CSIC, Global Ecology Unit, CREAF-CSIC-UAB, E08193 Cerdanyola del Vallès, Catalonia, Spain
5. Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, 3001 Leuven, Belgium
6. Sustainable Agri-Food Sciences Division, Agri-Food and Biosciences Institute (AFBI), Belfast, United Kingdom
7. State Key Laboratory of Subtropical Silviculture, Zhejiang A & F University, Lin’an 311300, China

*Corresponding author:** email: kyleyuechina@163.com

Post address: Shangsan Road 8, Cangshan District, Fuzhou 350007, Fujian, China

Abstract

The ongoing warming of the climate system is reducing snow cover depth and duration worldwide. Snow cover can significantly affect the soil microclimate and functioning of many terrestrial ecosystems across latitudinal and elevational gradients. Yet, a quantitative assessment of snow cover effects on soil biogeochemical properties at regional scales is lacking. Here, we systematically synthesized data of 1391 observations from 52 publications of snow manipulation studies to evaluate the effects of snow cover on soil biogeochemical and biotic properties around the globe. We found that the presence of snow (1) significantly increases soil temperature, moisture, and pH; (2) has limited effects on the concentrations and fluxes of soil carbon (C) and nitrogen (N), microbial communities, and the activities of enzymes; (3) affects soil biogeochemical properties depending on ecosystem type, with most of the significant effects in deserts; and (4) other moderator variables such as snow depth, latitude, altitude, macroclimate, and duration of snow cover were also important, with varying direction and magnitude of their effects. Our results provide new insights into the effects that snow can have on soil physicochemical and biotic properties around the globe, and are important for predicting and managing changes in snow-covered ecosystems under future climate change.

Keywords: snow manipulation, carbon, nitrogen, microbes, enzymatic activity, meta-analysis

1. Introduction

Seasonal snow cover is a common feature of (sub)arctic, boreal and many temperate and alpine ecosystems, with up to one-third of the global terrestrial surface covered by seasonal snow around the year (Stocker, 2014). Snow cover can serve as a layer of insulation that protects the soil from cold air temperatures (Brooks et al., 2011), generating a specific warmer soil microclimate when snow is present (Wilson et al., 2020). Snow cover is therefore one of the most important factors controlling belowground ecological processes by influencing, for example, local and regional hydrology, soil nutrient fluxes, the timing and length of the growing season, and the availability of ecological niches (Blankinship and Hart, 2012; Slatyer et al., 2021; Vavrus, 2007). Warming temperatures and an increase in rain-on-snow events (Putkonen and Roe, 2003) under scenarios of climate change can dramatically affect the presence, thickness, and properties of snow cover (Peng et al., 2010; Stocker, 2014), which can significantly affect the ecological functions of soils, such as carbon (C) and nutrient cycling (Du et al., 2013; Durán et al., 2014). Understanding the relationships between snow cover and soil physicochemical and biotic properties is therefore of great importance to better predict potential effects of climate change on snow-covered soils. Available information of snow cover effects on soil properties, however, is mainly based on studies of local snow manipulation, thus potential snow cover effects within and across different types of ecosystems around the globe remain unclear.

Snow has long been recognized as an insulating layer of soil and vegetation, decoupling ground from air temperatures and forming a warmer microclimate that can prevent or reduce the occurrence of sub-zero temperatures (Edwards et al., 2007; Graae et al., 2012). Soil temperatures can remain close to 0 °C under an insulating snow cover, even when air temperature decreases to -20 °C (Sutinen et al., 2008). Higher soil moisture and temperature induced by snow cover are the main drivers of soil biogeochemical processes in snow covered environments (Jusselme et al., 2016), including respiration, nutrient availability, microbial and enzymatic activities. For example, a thick snow cover can maintain soil microbial activities by increasing soil temperature, which can lead to relatively high rates of soil respiration (Blankinship and Hart, 2012; Liu et al., 2016). Studies have also found that the rate of microbial respiration and enzymatic activities are maintained at relatively high levels under snow-covered soils (Gavazov et al., 2017) and that snow reduction significantly reduced microbial activities and affected the associated soil biogeochemical processes (Edwards et al., 2007; Steinweg et al., 2008).

Snow cover is tightly correlated with soil moisture, particularly during snowmelt (Shibata et al., 2013), which is an important driver of soil microbial activities. A higher availability of soil water could benefit microbial activity (Aanderud et al., 2013), but it can also reduce the diffusion of oxygen in the soil and thus reduce microbial respiration (Yohannes et al., 2011). Severe soil freezing due to snow melt can significantly decrease fluxes of dissolved organic carbon (DOC), dissolved organic nitrogen (DON), ammonium (NH_4^+), and nitrate (NO_3^-), possibly because of inhibitory effects of extremely cold soil temperatures on microbial production (Campbell et al., 2014). These results highlight the importance of snow cover on the cycling of soil C and nitrogen (N). Recent studies, however, have also suggested that bacterial and fungal communities in boreal forest soils may be insensitive to changes in snow-cover conditions (Männistö et al., 2018) and that manipulating snow has minor effects on soil CO_2

emission, soil temperature, and soil microbial biomass (Gao et al., 2018). These inconsistent findings on the role of snow cover in controlling winter soil biogeochemical properties need to be better quantified to be understood across different regions worldwide.

The effects of snow cover on soil biogeochemical properties may be affected by a variety of moderator variables, such as snow depth, soil depth, ecosystem type, and macroclimate. If snow has an insulating effect on soil, this effect should increase with snow depth. Seasonal variation in snow depth may have divergent effects on soil properties because soil organic C and N concentrations are found to be significantly higher under moderate than either deep or shallow snow covers (Freppaz et al., 2012). Previous evidence suggests that changes in snow cover have variable effects on belowground processes in different types of subarctic and boreal ecosystems (Bombonato and Gerdol, 2012), indicating the importance of ecosystem type in modulating the effects of snow cover. The macroclimate would also be a major factor controlling these effects, because it is directly associated with the depth and duration of snow cover. How these moderator variables may affect the effects of snow cover on soil biogeochemical properties at the global scale, however, still remains elusive.

We conducted a systematic meta-analysis of 1391 paired observations from 52 publications to explicitly assess how snow cover might affect the physicochemical and biotic properties of soils worldwide. The main objectives of this study were to determine (1) whether and how snow cover might affect (1) soil microclimate, including temperature, moisture, and frost depth, and (2) soil properties of the concentrations and fluxes of C, N, and P, microbial communities, soil and microbial respiration, and the activities of several enzymes; and (3) how moderator variables (e.g., snow depth, soil depth, ecosystem type, latitude, macroclimate, and experimental duration) might influence the potential effects of snow cover on soil properties. Our hypotheses are that (i) the presence of snow promotes a warmer and humid soil microclimate conditions; (ii) snow cover increases soil microbial biomass and diversity, soil enzymatic activity, and the concentrations and fluxes of C, N, and P; and (iii) the effects of snow cover on soil physicochemical and biotic properties are significantly affected by moderator variables.

2. Methods and materials

2.1 Data collection and compilation

Following the guidelines of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which is an evidence-based minimum set of items for reporting in systematic reviews and meta-analyses (Moher et al., 2009; O'Dea et al., 2021), we systematically searched peer-reviewed articles and theses published before June 2020 for the term “soil AND snow” and its equivalent in Chinese using the *Web of Science* (www.webofknowledge.com), *Google Scholar* (scholar.google.com), and the *China National Knowledge Infrastructure* (www.cnki.net). We used the following criteria to select appropriate studies to be included in our database: (1) studies were conducted in terrestrial ecosystems; (2) experiments were conducted in the field (no modelling studies) and at least one of the soil properties of our list was reported; (3) both plots with snow cover (treatment plots in which all snow was removed for at least 2 weeks) and without snow cover (control plots, and should be maintained during for the experimental duration) were included in the experimental design; (4) the control and treatment plots were established within the same location or ecosystem type and at the time; (5)

the measurement of soil properties should be carried out during the presence of snow, namely the legacy effects (i.e., measured in the following growing season) of snow cover were not considered here; and (6) the means, standard deviations, or standard errors, and sample sizes of the soil properties, were directly reported or could be estimated from the figures, tables or data in the respective publications. This selection provided 1391 observations from 52 articles (33 in English and 19 in Chinese with English abstract) that satisfied the criteria and were included in our database (Fig. 1; Appendix 1).

If a single study reported more than one treatment of snow depths (i.e., two or more set depths of snow) or the same snow depth treatment in different locations or ecosystem types, we treated all comparisons as separate observations using linear mixed-effects models, because they represented different measurements of the effects of snow cover on soil properties. Data were extracted directly from the main texts, tables, or appendices of the articles or were extracted from figures using Engauge Digitizer version 12 (http://markummitchell.github.io/engauge-digitizer/) if graphically presented. We evaluated the influence of moderator variables on the effects of snow cover on soil properties by collecting information on latitude, longitude, elevation, mean annual temperature (MAT), mean annual precipitation (MAP), ecosystem type (including cropland, desert, forest, grassland, tundra, and wetland in our dataset as reported in the primary studies), experimental duration of the snow manipulation (ranging from 0.5 to 18 months), soil depth of measurement (ranging from 0 to 70 cm), and snow depth of the treatment plots (ranging from 1.4 to 191.8 cm), where available. If MAT and MAP were not reported in the primary studies, we obtained these data with the highest resolutions from *WorldClim* (www.worldclim.org) using information of geographical coordinates.

The variables of soil physicochemical and biotic properties we addressed here included temperature, moisture, frost depth, pH, C concentration, DOC concentration, CO_2 flux, CH_4 flux, C:N ratio, total N concentration, available N concentration, DON concentration, NH_4^+ concentration, NO_3^- concentration, N_2O flux, ammonification rate, nitrification rate, total phosphorus (P) concentration, plant-available P (Olsen P) concentration, microbial biomass C (MBC) concentration, microbial biomass N (MBN) concentration, microbial biomass P (MBP) concentration, the MBC:MBN ratio, microbial Shannon index, Simpson index, Pielou index, total microbial phospholipid fatty acid (PLFA) concentration, bacterial PLFA concentration, fungal PLFA concentration, the bacterial:fungal PLFA ratio, microbial respiration (R_m), soil respiration (R_s), and the activities of sucrase, urease, invertase, catalase, and cellulase. As to the measurement of soil properties, C and DOC were measured using TOC analyzer or the dichromate oxidation-ferrous sulfate titration method; N, available N, DON, NH_4^+, and NO_3^- were tested using continuous flow analyzer; P and available P were measured using the colorimetric method; MBC, MBN, and MBP were determined by the chloroform fumigation extraction method; PLFAs were analyzed using a modified version of the Bligh-Dyer method; and microbial Shannon, Simpson, and Pielou indexes were calculated based on PLFAs; and the fluxes of CO_2, CH_4, and N_2O were measured with static chamber method.

2.2 Statistical analysis

We used Hedges' *d* (Koricheva et al., 2013) as the standardized metric of effect size to assess the effects of snow cover on soil properties. We chose Hedges' *d* because negative values (temperature) included in our database were not suitable for the calculation of log-response ratio, and also because Hedges' *d* is not affected by unequal sampling variances in the paired groups due to the inclusion of a correction factor for small sample sizes (Koricheva et al., 2013). Hedges' *d* for each paired observation was calculated as:

$$d = \frac{\overline{Y}_s - \overline{Y}_c}{\sqrt{\frac{(n_s-1)s_s^2+(n_c-1)s_c^2}{n_s+n_c-2}}} J \qquad (1)$$

where Y_s and Y_c are the means of the treatment and control soil properties, respectively, n_s and n_c are the treatment and control sample sizes, respectively, s_s and s_c are the treatment and control standard deviations, respectively, and *J* is a correction factor for small sample sizes, which was calculated as:

$$J = 1 - \frac{3}{4(n_s + n_c - 2) - 1} \qquad (2)$$

The variance (v_d) for Hedges' *d* was calculated as:

$$v_d = \frac{n_s + n_c}{n_s n_c} + \frac{d^2}{2(n_s + n_c)} \qquad (3)$$

The weight associated with each effect size was estimated as the reciprocal of the variances ($1/v_d$).

We ran mixed-effects intercept-only models for calculating the overall weighted effect size (d_{++}) for each response variable of the soil properties. These intercept-only models fitted Hedges' *d* as a response variable and included the identity of primary studies from which raw data were extracted as a random-effects factor. This random-effects factor explicitly accounted for the potential dependence of observations collected from a single study. The linear mixed-effects models were performed using the *lme4* package (Bates et al., 2014). We assessed how the moderator variables may influence the responses of soil properties to snow cover using mixed effects meta-regression models by fitting each moderator variable as a continuous or categorical fixed-effects factor and the identity of primary studies from which raw data were extracted as a random-effects factor. We assessed the effect of each moderator variable on each response variable of the soil properties individually to include as many observations in the model as possible. All statistical analyses were performed in R version 4.1.1 (R Core Team, 2021).

2.3 Publication bias

We assessed the potential publication bias, which can arise when studies published in the literature are a nonrandom subset of the total number of studies, using Egger's regression tests (Egger et al., 1997) along with funnel plots and trim-and-fill tests (Duval and Tweedie, 2000) using the meta-analytic residuals (Nakagawa and Santos, 2012). We used the R_0 estimator implemented with the *trimfill* function in the *metafor* package (Viechtbauer, 2010) to perform the trim-and-fill tests. The Egger's regression tests on the meta-analytic residuals, funnel plots, and trim-and-fill tests (Table S1; Fig. S1) all found no evidence for funnel asymmetry or publication bias, indicating that the studies in our database were a representative sample of the available studies.

3. Results

3.1. Overall effects of snow cover on soil biogeochemical properties

Averaged across all paired observations snow cover significantly affected soil microclimate, increasing soil temperature and moisture, with effect sizes of 0.233 and 0.241, respectively (Fig.

2). Snow cover significantly increased soil pH, with an effect size of 0.292, but decreased the depth of soil frost, with an effect size of -0.720. Snow cover did not affect soil concentrations of C or DOC or fluxes of CO_2 or CH_4 from soils. Soil N concentrations or fluxes were also not affected by snow cover except for N_2O fluxes, which were significantly reduced, with an effect size of -0.402. Total soil N and DON concentrations, however, were only marginally significantly ($p < 0.1$) affected by snow cover. The concentration of soil available P, but not total P, was significantly higher under snow cover. Snow cover was likely not to affect microbial communities, R_s, R_m, or the activities of several kind of enzymes.

3.2. Influence of moderator variables on effect size

Snow depth was significantly correlated with the effects of snow cover on soil temperature (Fig. 3a). Snow cover did not significantly affect ammonification rate or the concentrations of soil C, N, available N, or MBP, but its effect sizes on these soil properties increased significantly with snow depth. The negative effect of snow cover on N_2O flux was negatively affected by snow depth. Soil depth only had significantly negative effects on the effect sizes of snow cover on available N concentration and ammonification rate compared with snow depth (Fig. 3b).

Ecosystem type significantly influenced the effect size of snow cover on soil temperature, with positive effects only in cropland and forest (Fig. 4a). Snow cover positively affected soil moisture and pH only in cropland and desert, respectively, and negatively affected frost only in forest. These effects were significant in wetland for the CO_2 flux and in desert for the C, N, and NH_4^+ concentrations, despite the overall nonsignificant effects of snow cover on soil CO_2 flux and C, N, and NH_4^+ concentrations (Fig. 4a, b). Snow cover had opposite effects on soil available N concentration in desert and forest and on MBN concentration in desert and grassland. The negative effect of snow cover on N_2O flux was only significant in forest (Fig. 4b).

The effects of snow cover on soil properties varied significantly with geographical location, climate, and snow-cover duration (Table 1). Specifically, the effects of snow cover on soil temperature, ammonification rate, available N and MBN concentrations, and urease activity were all positively correlated with latitude, but snow cover effects on temperature and MBN concentration were negatively correlated with altitude. The responses of soil C, N, and MBN concentrations to snow cover were positively correlated with MAT, and the responses of the CH_4 and N_2O fluxes, ammonification rate, the MBC:MBN ratio, and urease activity to snow cover were negatively correlated with MAT. The effects of snow cover on soil properties were consistently negatively correlated with MAP, and its effects on the concentrations of soil moisture, available N, NO_3^-, and MBN increased significantly with snow-cover duration.

4. Discussion

4.1. Snow cover promotes warmer and more humid soil microclimate conditions

Snow cover significantly increased soil temperature and moisture across the studied regions, a finding which is consistent with our first hypothesis. Snow cover has a thermal insulating effect on soils, it generally restricts soil sub-zero temperatures and reduces the frequency of freeze-thaw cycles thus maintaining a relatively higher temperature compared with the free air temperature (Groffman et al., 2001a; Li et al., 2017). It is commonly acknowledged that a snow cover of 30-40 cm is sufficient for decoupling soil thermal changes from air temperature

(Steinweg et al., 2008). The average depth of snow cover in our study was 39.0 cm, which should be ideal to observe significant effects on tested soil variables. The significant positive effects of snow cover on soil pH may be attributed to the altered availability of NO_3^- or NH_4^+. For example, snow-removal studies have found that soil NO_3^- concentration increased significantly with the absence of snow, probably by stimulating nitrification rates or inhibiting root uptake (Groffman et al., 2001b). Previous studies have also found that soil NH_4^+ concentration was higher in treatments of snow removal (Fitzhugh et al., 2001; Hardy et al., 2001), but also depended on snow depth and stage of snow cover, e.g., early snow cover, deep snow cover, and snow-cover melting (Tan et al., 2014). Increases in soil pH with higher snow cover could thus be caused by lower soil NO_3^- and NH_4^+ concentrations. We found, however, no overall significant effect of snow cover on NO_3^- and NH_4 concentrations (Fig. 2), which may be attributed to their opposite responses to snow cover in different types of ecosystems (Fig. 4b).

4.2. Minor effects of snow cover on soil physicochemical and biotic properties

Overall, the impact of snow cover on studied soil properties across all observations was small, contrary to our second hypothesis (Fig. 2). Our results show only significant negative effects of snow cover on N_2O flux and significant positive effects on concentration of available P. Studies of local snow manipulation have reported that variables related to heterotrophic microbiological activities, including soil net N mineralization, the concentrations of DOC, DON, and microbial MBN, are sensitive to the timing and duration of soil thaw, which is controlled by the accumulation of snow cover (Edwards et al., 2007). Our results indicate that snow cover marginally significantly ($p < 0.1$) decreased soil DON concentration, but had no effect on DOC concentration (Fig. 2). Soil dissolved organic matter (DOM) can increase after snow removal, which has been attributed to the daily variation of soil temperature and frequent freeze-thaw cycles (Tan et al., 2014). Daily variation in soil temperature can accelerate the release of DOM from plant litter and soil aggregates (Freppaz et al., 2012), and freeze-thaw cycles can negatively affect soil microbes and fine roots and thus promote the accumulation of DOM via microbial cells lysis (Comerford et al., 2013). These processes may therefore be prevented by snow cover, and existing soil DOM may be lost by leaching under snow cover (Hardy et al., 2001).

Soil temperature is a major factor controlling soil microbial enzymatic activities, which drive soil CO_2 and CH_4 fluxes (Puissant et al., 2015; Schindlbacher et al., 2007). Somewhat surprisingly, our results indicate that snow cover did not affect soil CO_2 fluxes, microbial biomass concentration, microbial diversity, or soil enzymatic activities, despite the significant positive effects of snow cover on soil temperature. Previous studies have found that reduced snow cover can reduce microbial activities by increasing the intensity of soil frost and freeze-thaw cycles that destroy microbial cells (Larsen et al., 2002), affect microbial metabolism (Schimel and Mikan, 2005), bacterial and fungal abundance and community structures (Ricketts et al., 2016; Semenova et al., 2016). However, limited impacts of frost and freeze-thaw events on soil microbial communities in boreal forests have also been reported (Haei et al., 2011), and microbial communities experiencing periodic freezing may be physiologically well adapted and resistant to freeze-thaw cycles (Stres et al., 2010). These nonsignificant effects of snow removal on microbial activities were similar to our findings, which may be attributed mainly to the high resilience of soil microbial communities to snow-cover manipulation (Männistö et al., 2018).

Snow cover had no effect on soil microbial communities, but significantly reduced soil N_2O emission and increased the concentration of soil available P (Fig. 2). As discussed above, increased freeze-thaw cycles with reduced snow cover can enhance the mortality rate of microbes and fine roots, leading to the release of labile organic N into the soil. Denitrification is a dominant source of N_2O in these soils (Groffman et al., 2001b). Also, the physical disruption of soil aggregates due to more freeze-thaw cycles may promote the release of previously protected organic matter to microbial attack, thereby increasing substrate availability (van Bochove et al., 2000). These processes would therefore be weakened or prevented by the warmer soil temperatures induced by snow cover, leading to a decrease in N_2O emission. The positive effects of snow cover on the concentration of soil available P may be attributed to higher release of P from plant litter in warmer and wetter environments. Findings from a previous study show how snow-cover reduction slowed the release of P from litter (Wu et al., 2015). In addition, the higher available P concentration may also attributed to a lower oxygen availability under snow cover, because anoxic events may potentially increase P bioavailability by decreasing the strength of P sorption (Lin et al., 2020).

4.3. Environmental variables regulated the effects of snow cover

Snow depth, soil depth of measurement, ecosystem type, latitude, and macroclimate had significant impacts on the effects of snow cover. The influence of snow cover on soil biogeochemical properties was mainly attributed to its insulating effects, so understanding that its effects would increase with snow depth is easy, and is also supported by our findings (Fig.

3a). The insulating effects of snow cover, generally decrease with soil depth, and we found evidence that responses of available N concentration and ammonification rate to snow cover significantly decreased with soil depth. Ecosystem type was also an important moderator variable regulating the effects of snow cover on soil properties, with the strongest effects observed in deserts (Fig. 4). A previous study, showed that the effects of snow cover on vegetation across China were largest in deserts (Peng et al., 2010), which could mainly be attributed to the persistent effects of snow cover on soil moisture given the low availability of water in deserts. Latitude was found to be a more significant factor compared to MAT in explaining legacy effects of snow cover on CO_2 emission during the growing season (Blankinship and Hart, 2012). We found that latitude, altitude, MAT, and MAP were all important factors controlling the effects of snow cover in winter (Table 1), but their moderating influence varied among soil properties. Interestingly, we found that MAP negatively affected the effect size of snow cover for several soil properties, which may be attributed to that MAP decreased the effects from certain snow cover. In addition, experimental duration with snow cover was also an important variable moderating snow cover effects, but its influences varied among different soil properties.

5. Conclusions

The results of our systematic meta-analysis show that snow cover significantly increased soil temperature and soil moisture, generating a unique warmer and more humid soil microclimate. Snow cover, however, had limited effects on the concentrations and fluxes of soil C and N, microbial communities, and the activities of enzymes. The effects of snow cover on soil physicochemical and biotic properties depended significantly on ecosystem type, with the strongest effects found in deserts. Other moderator variables such as snow depth, latitude, altitude, MAT, MAP, and snow-cover duration were also important, but the direction and magnitude of their effects varied among soil properties. Our results provide a tantalizing glimpse into the role of soil cover in regulating soil biogeochemical properties in winter. These findings contribute to improve our understanding and ability to predict potential effects of snow cover on soil biogeochemical processes such as C and N cycling under future global change scenarios. We also propose that more multiyear and multifactor studies are needed to determine if the effects of altered snow cover may increase or decrease over time (e.g., >5 year). Finally, more research is needed to address how snow-cover induced effects on soils could be altered by variations in other global change factors such as rain-on-snow events, elevated CO_2 concentration, atmospheric N deposition, and land-use changes.

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Author contributions

K.Y. conceived the study. Z.Z. collected the raw data. Z.Z. and K.Y. performed data analyses and wrote the first draft of the manuscript. All authors contributed to revisions of the manuscript.

Competing interests

The authors declare no competing interests.

Data availability

Raw data and R code used in the study will be deposited in figshare (https://figshare.com) if this manuscript is accepted.

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Table 1 Mixed-effects meta-regression modeling assessing the effects of moderator variables (latitude, elevation, MAT, MAP and duration) on the effect sizes (Hedges' *d*) of soil properties in response to snow cover. Estimate (slop), *p* value, and number of observations (n) are shown. Values in bold indicate significant effects. Several variables were not assessed here because of limited number of observations.

Soil property	n	Latitude		Elevation		MAT		MAP		Duration	
		Estimate	*p*	Estimate	*p*	Estimate	*p*	Estimate	*p*	Estimate	*p*
Temperature	227	0.016	**0.047**	-0.001	**0.043**	0.018	0.452	0.001	0.818	-0.034	0.284
Moisture	82	0.003	0.681	-0.001	0.269	-0.017	0.425	-0.001	**0.017**	0.055	**0.017**
Frost	37	-0.001	0.966	-0.001	0.713	0.140	0.218	-0.005	**0.009**	0.038	0.633
pH	20	-0.010	0.505	-0.001	0.192	0.067	0.096	-0.001	0.059	0.027	0.095
C concentration	25	-0.056	0.338	0.001	0.112	0.171	**0.033**	-0.002	**0.015**	0.034	0.061
DOC concentration	36	0.004	0.801	0.001	0.945	-0.066	0.599	0.001	0.793	-0.027	0.458
CO_2 flux	20	0.022	0.517	-0.001	0.592	-0.197	0.529	-0.001	0.348	-0.037	0.795
CH_4 flux	22	0.028	0.153	-0.001	0.200	-0.309	**0.038**	-0.001	0.229	-0.129	0.228
C:N ratio	14	0.124	0.774	-0.003	0.774	-0.216	0.773	0.001	0.772	-0.014	0.740
N concentration	22	-0.051	0.078	-0.001	0.257	0.172	**0.016**	-0.001	**0.045**	0.053	0.028
Available N concentration	17	0.133	**0.002**	-0.001	0.117	-0.073	0.216	-0.002	**0.003**	0.087	**0.002**
DON concentration	30	0.012	0.739	-0.001	0.888	-0.613	0.314	-0.001	0.558	-0.034	0.549
NH_4^+ concentration	90	0.010	0.161	-0.001	0.142	0.001	0.969	-0.001	**0.032**	0.053	**0.002**
NO_3^- concentration	88	-0.001	0.906	0.001	0.815	0.014	0.604	-0.001	0.087	0.022	0.176
N_2O flux	28	0.020	0.225	-0.001	0.398	-0.332	**0.030**	-0.001	0.818	-0.178	0.056
Ammonification rate	7	0.819	**0.003**	0.030	**0.003**	-0.709	**0.003**	-0.107	**0.002**	-1.418	**0.003**
Nitrification rate	9	-0.019	0.634	0.001	0.532	-0.199	0.538	-0.001	0.518	-0.385	0.392
MBC concentration	129	0.015	0.190	-0.001	0.208	0.003	0.908	-0.002	0.262	0.005	0.682
MBN concentration	104	0.029	**0.019**	-0.001	**0.005**	0.175	**0.001**	-0.008	**0.005**	0.043	**0.002**
MBC:MBN ratio	72	-0.013	0.261	0.001	0.187	-0.071	**0.047**	0.001	0.117	-0.020	0.059
PLFA concentration	8	0.110	0.441	0.001	0.498	-0.254	0.438	-0.001	0.808	-0.095	0.467
Bacterial PLFA	11	0.053	0.534	-0.001	0.917	-0.101	0.599	-0.001	0.139	-0.094	0.453
Fungal PLFA	11	-0.051	0.548	-0.001	0.321	0.125	0.507	-0.001	0.298	-0.108	0.345
R_s	55	-0.061	0.172	0.001	0.159	-0.082	0.219	-0.002	0.212	-0.142	**0.041**
Urease activity	40	0.198	**0.001**	-0.001	**0.003**	-2.750	**0.009**	-0.012	**0.002**	-0.014	0.752
Invertase activity	37	0.029	0.302	-0.001	0.305	-0.921	0.166	-0.002	0.251	-0.052	0.394

C, carbon; DOC, dissolved organic carbon; N, nitrogen; DON, dissolved organic nitrogen; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; PLFA, phospholipid fatty acid; R_s, soil respiration.

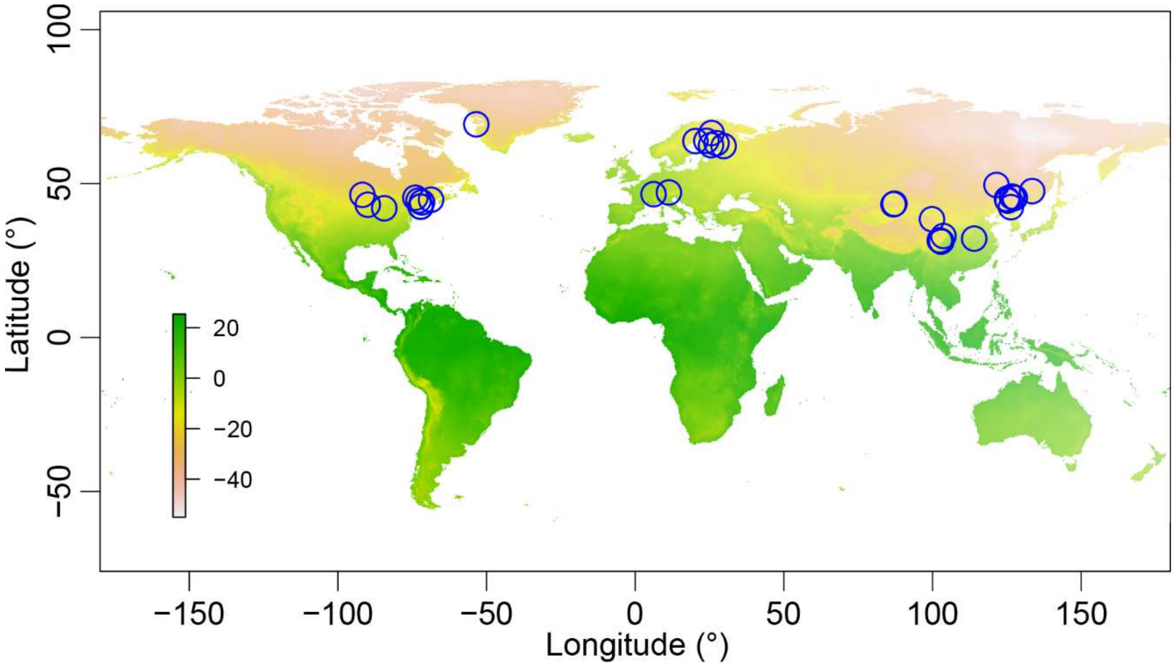

Figure 1 Global distribution of paired observations (blue circles) of the responses of soil properties to snow cover collected from the 52 publications. The color scale indicates the long-term (1970-2000) minimum temperature (°C) of the coldest month derived from *WorldClim* (https://www.worldclim.org).

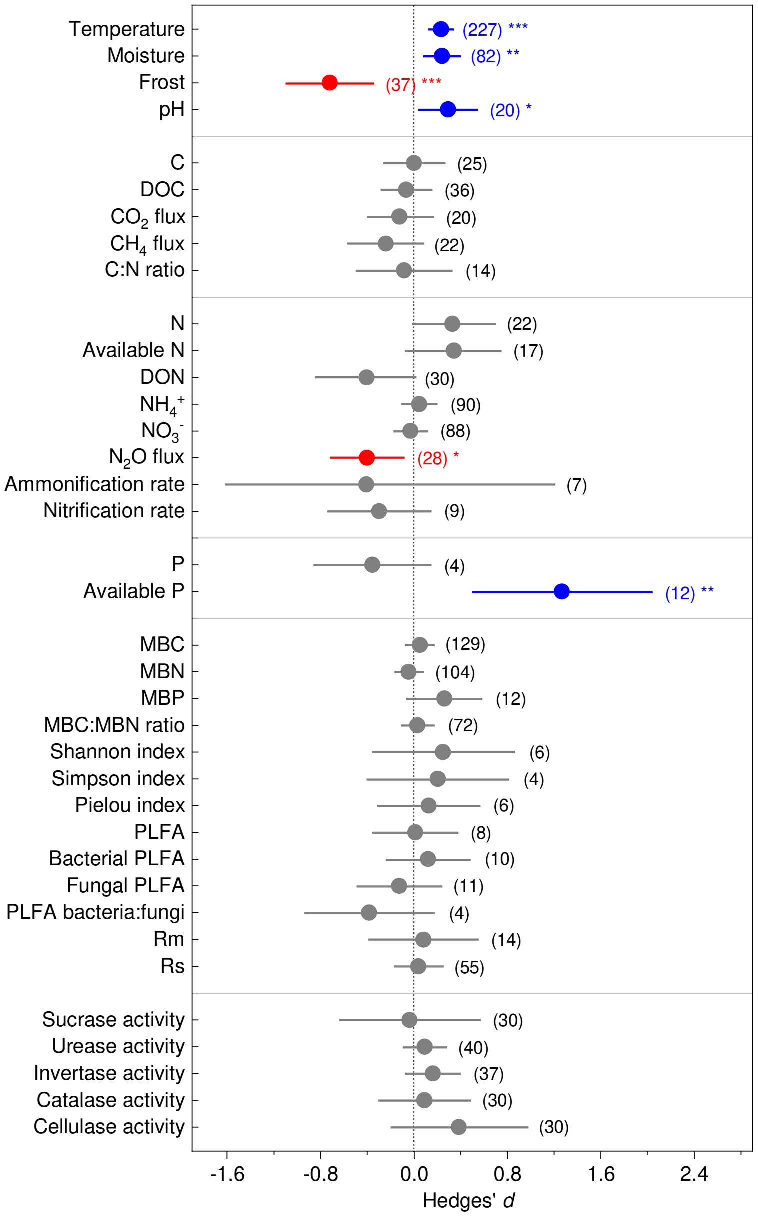

Figure 2 Effect sizes (Hedges' *d*) of soil properties in responses to snow cover manipulation. Values indicate means with 95% confidence intervals, and the number of observations for each parameter of soil properties are shown in parentheses. Blue and red indicate significant positive and negative effects, respectively. Negative (positive) effects indicate that the presence of snow negatively (positively) affected the soil property. C, carbon concentration; DOC, dissolved organic carbon concentration; N, nitrogen concentration; DON, dissolved organic nitrogen concentration; P, phosphorus concentration; MBC, microbial biomass carbon concentration; MBN, microbial biomass nitrogen concentration; PLFA, phospholipid fatty acid concentration; R_m, microbial respiration; R_s, soil respiration; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

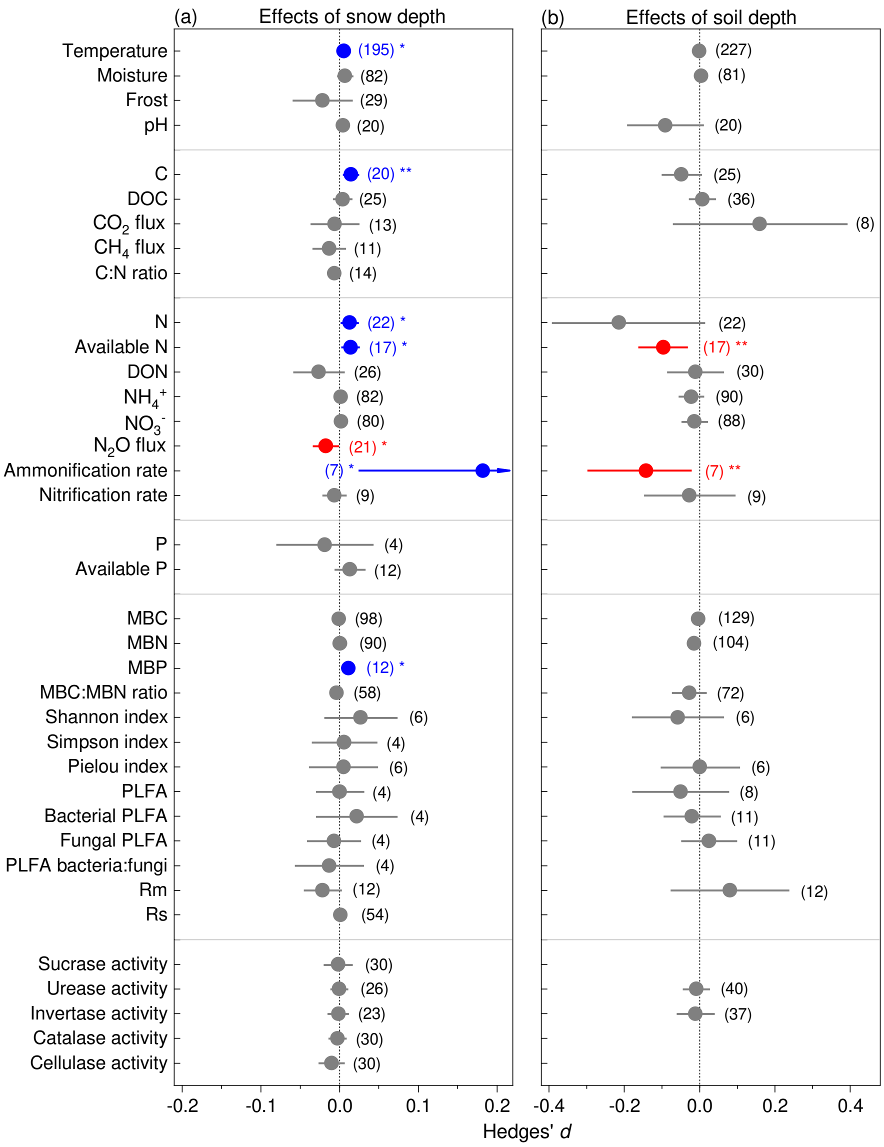

Figure 3 Effects of snow depth (a) and soil depth (b) on the effect sizes (Hedges' *d*) of soil properties in response to snow cover. Values indicate means with 95% confidence intervals, and the number of observations for each parameter of the soil properties are shown in parentheses. Blue and red indicate significant positive and negative effects, respectively. Negative (positive) effects indicate that the presence of snow negatively (positively) affected the soil property. C, carbon concentration; DOC, dissolved organic carbon concentration; N, nitrogen concentration; DON, dissolved organic nitrogen concentration; P, phosphorus concentration; MBC, microbial biomass carbon concentration; MBN, microbial biomass nitrogen concentration; PLFA, phospholipid fatty acid concentration; Rm, microbial respiration; Rs, soil respiration; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

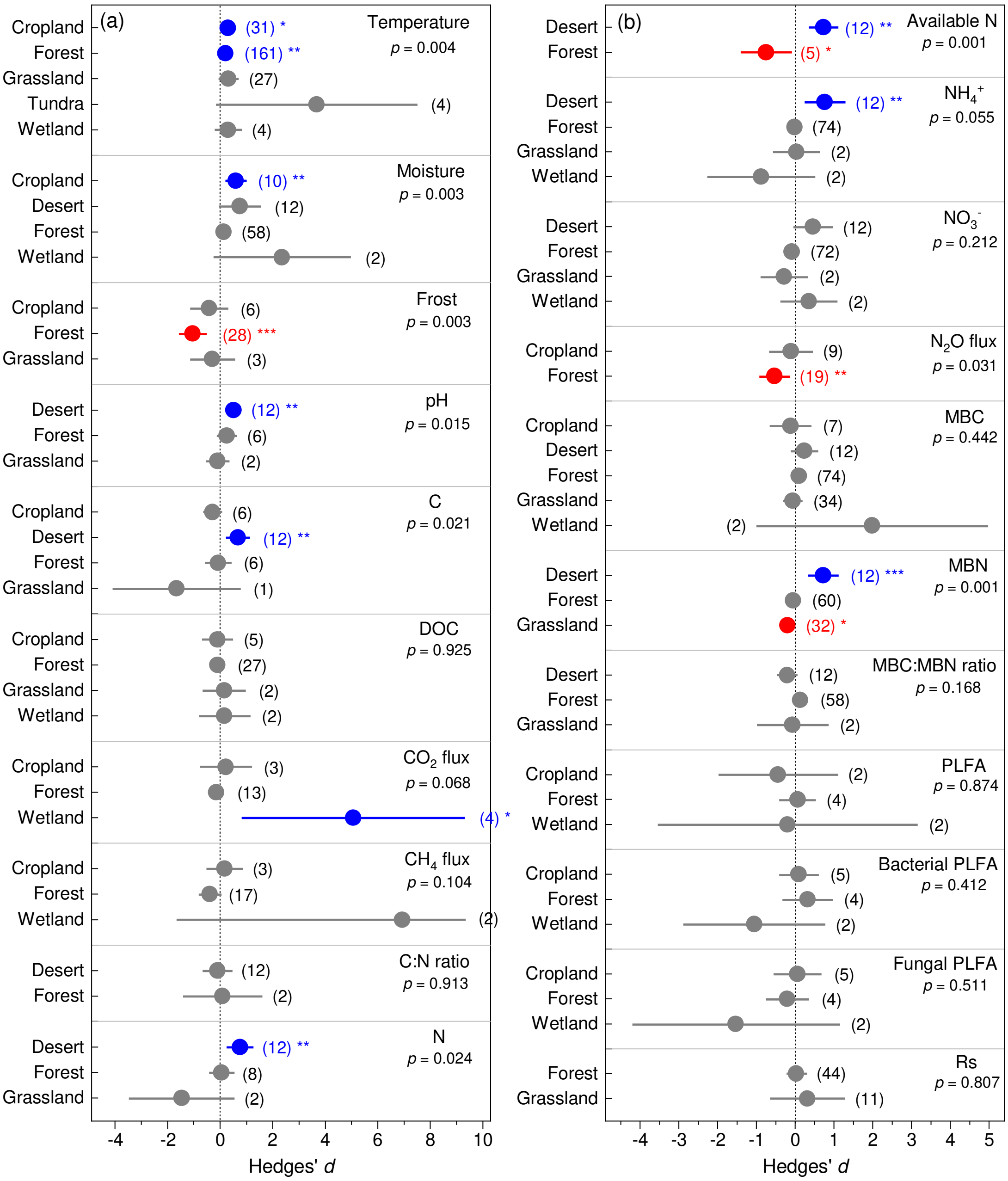

Figure 4 Effects of ecosystem type on the effect sizes (Hedges' *d*) of the soil properties in responses to snow cover. Values indicate means with 95% confidence intervals, and the number of observations for each index of soil properties are shown in parentheses. Blue and red indicate significant positive and negative effects, respectively. C, carbon concentration; DOC, dissolved organic carbon concentration; N, nitrogen concentration; DON, dissolved organic nitrogen concentration; P, phosphorus concentration; MBC, microbial biomass carbon concentration; MBN, microbial biomass nitrogen concentration; PLFA, phospholipid fatty acid concentration; Rm, microbial respiration; Rs, soil respiration; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.