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

Running title: Snow cover effects on soil properties

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Abstract

The continuing warming of the climate system is reducing snow cover depth and duration worldwide. Changes in snow cover can significantly affect the soil microclimate and the functioning of many terrestrial ecosystems across latitudinal and elevational gradients. Yet, a quantitative assessment of the effects of snow cover change on soil physicochemical and biotic properties at large or regional scales is lacking. Here, we synthesized data of 3286 observations from 99 publications of snow manipulation studies to evaluate the effects of snow removal, addition, and compaction on soil physicochemical and biotic properties in winter and in the following growing season across (sub)arctic, boreal, temperate, and alpine regions. We found that (1) snow removal significantly reduced soil temperature by 2.2 and 0.9 °C in winter and in the growing season, respectively, while snow addition increased soil temperature in winter by 2.7 °C but only by 0.4 °C in the following growing season whereas snow compaction had no effect; (2) snow removal had limited effects on soil properties in winter but significantly affected soil moisture, pH, and carbon (C) and nitrogen (N) dynamics in the growing season; (3) snow addition had significant effects on soil properties both in winter (e.g., increases in soil moisture, soil C and N dynamics, phosphorus availability, and microbial biomass C and N) and in the growing season (e.g., increases in mineral N, microbial biomass C and N, and enzyme activities); and (4) the effects of snow manipulation on soil properties were regulated by moderator variables such as ecosystem type, snow depth, latitude, elevation, climate, and experimental duration. Overall, our results highlight the importance of snow cover-induced warmer microclimate in regulating soil physicochemical and biotic properties at regional scales. These findings are important for predicting and

managing changes in snow-covered ecosystems under future climate change scenarios.

Keywords: snow removal, snow addition, snow compaction, soil properties, 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 (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 (Vavrus, 2007; Blankinship and Hart, 2012; Slatyer et al., 2021). 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 the potential effects of snow removal, addition, and compaction within and across different types of ecosystems at regional scales, including the (sub)arctic, boreal, temperate, and alpine regions, remain unclear.

Snow has long been recognized as an insulating and protecting layer for 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 is well below freezing (Sutinen et al., 2008). Higher soil moisture and temperature induced by snow cover are important drivers of soil biogeochemical processes in snow covered environments (Jusselme et al., 2016), including respiration, nutrient availability, and 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 removal 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 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 the lack of accessible water induced by sub-zero 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 properties across different regions need to be further investigated and possibly quantified for a better overall understanding. In addition, even if snow cover has minor effects on soil properties in winter, it may have strong legacy effects in the following growing season (Blankinship and Hart, 2012). It is thus important to disentangle snow cover effects between winter and the subsequent growing season.

The effects of snow cover on soil physicochemical and biotic properties may be affected by a variety of moderator variables, such as snow depth, soil depth, ecosystem type, macroclimate, and compaction. It is well established that snow has an insulating effect on soil, and this effect can 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 such as soil respiration, nutrient dynamics, and microbial communities and activities 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, i.e., the free air temperature, would also be a major factor controlling these effects, because it is directly associated with the amount of snowfall, as well as snow depth and duration of snow cover. How these moderator variables may affect the effects of snow cover on soil biogeochemical properties at the regional scale, however, still remains elusive. Snow compaction can occur, for example, following snow drifts, deformation strains, and human-related activities, and could impact the physical and mechanical properties of snow cover such as snow density (Iwata et al., 2018), thus affecting soil properties. Therefore, assessing the effects of snow compaction will help us to better understand the underlying mechanisms responsible for snow cover effects on soil properties.

Here, we conducted a systematic meta-analysis with 3286 paired observations (i.e., 3286 observations from the control group *vs.* 3286 observations from the corresponding snow manipulation group) from 99 publications to explicitly assess how changes in snow cover, including snow removal, addition, and compaction, might affect the physicochemical and biotic properties of soils in winter and the following growing season across the (sub)arctic, boreal, temperate, and alpine regions. The main objectives of this study were to determine (1) whether and how snow removal, addition, and compaction might affect soil microclimate, including temperature, moisture, and frost depth, and (2) soil concentrations and fluxes of C and N, and P, microbial communities and respiration, and the activities of several enzymes in winter and growing season; 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 manipulation on soil properties. Our hypotheses are that (i) snow removal and compaction promote a colder soil microclimate condition whereas snow addition induces warmer and more humid soil conditions; (ii) snow addition increases soil microbial biomass and diversity, soil enzymatic activity, and the concentrations and fluxes of C, N, and P, while snow removal and compaction have the opposite effects; and (iii) the effects of snow manipulation on soil physicochemical and biotic properties will diminish with experimental duration, and will also be significantly affected by moderator variables such as manipulated snow depth, soil depth, ecosystem type, and macroclimate.

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 “(snow* OR freez* OR thaw* OR frost) AND soil” 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 or lab experiments) and at least one of the soil properties of our list was reported; (3) both plots with ambient snow cover (control plots that were maintained during the experimental duration) and snow manipulation (treated plots in which snow was manipulated for at least 2 weeks), including snow removal, snow addition, and snow compaction, were included in the experimental design; (4) the control and treatment plots were established within the same location or ecosystem type and at the same time; (5) the measurements of soil properties were carried out during the winter and/or the following growing season; 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 3286 observations from 99 articles (80 in English and 19 in Chinese with English abstracts) that satisfied the criteria and were included in our database (Fig. 1; Appendix 1).

If a single study reported more than one snow depth treatments (i.e., two or more depths of snow) or the same snow depth treatment in different locations or ecosystem types, we treated all comparisons as separate observations and used linear mixed-effects models to account for the potential dependence in such cases, 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 manipulation on soil properties by collecting information on latitude, longitude, elevation, climate, ecosystem type [including cropland, desert (e.g., the Gurbantunggut desert), forest, grassland, tundra, and wetland in our dataset as reported in the primary studies], experimental duration of the snow manipulation (total number of months till the measurement in winter or in the growing season across the experimental period, ranging from 0.5 to 96 months), soil depth of measurement (ranging from 0 to 60 cm), and difference of snow depth between control and treatment plots (ranging from 1 to 304 cm), where available. Because many of the primary studies did not report climate data of the experimental period or mean annual temperature (MAT) and mean annual precipitation (MAP), we thus obtained MAT and MAP from *WorldClim* (www.worldclim.org) at a 30 arc second resolution for all study sites to avoid potential bias.

The variables of soil physicochemical and biotic properties we addressed here included temperature, moisture, frost depth, pH, C concentration, DOC concentration, CO_2 efflux, CH_4 uptake, C:N ratio, total N concentration, available N concentration (i.e., sum of NH_4^+ and NO_3^-), DON concentration, NH_4^+ concentration, NO_3^- concentration, N_2O efflux, ammonification rate, nitrification rate, total phosphorus (P) concentration, plant-available 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), and the activities of sucrase, urease, invertase, catalase, and cellulase. The values for a specific variable from different studies may either refer to soil or soil solution, resulting in different units, but this did not influence our assessment because we used natural log-response ratio (lnRR) as the effect size, which is not affected by unit (Hedges et al., 1999).

2.2 Statistical analysis

To assess the effects of snow removal, snow addition, and snow compaction on soil properties, we used lnRR as the standardized metric of effect size (Hedges et al., 1999). We chose lnRR because it is a robust effect size metric commonly used in ecological meta-analysis, it is easily interpretable, and its sampling distribution approximates normality (Hedges et al., 1999; Yue et al., 2020). The lnRR for each paired observation was calculated as:

$$\mathrm{lnRR} = \ln\left(\frac{\bar{X}_t}{\bar{X}_c}\right) \qquad (1)$$

where $\bar{X}_t$ and $\bar{X}_c$ are the means of soil properties in treated and control groups, respectively. The variance associated with each lnRR was estimated according to equation (2):

$$v = \frac{s_t^2}{n_t\bar{X}_t^2} + \frac{s_c^2}{n_c\bar{X}_c^2} \qquad (2)$$

where n_t and n_c are the sample size, and s_t and s_c the standard deviation in the treated and control groups, respectively. The weight (w) associated with each lnRR was then calculated as the reciprocal of variance ($w = 1/v$). Because negative numbers cannot be used for the calculation of lnRR, we thus transformed temperature in Celsius degree into absolute temperature in Kelvin degree to calculate the effect size. Where significant effects were found, we compared temperature data in original format (i.e., in Celsius degree) between the control and treated plots using linear mixed-effects models to facilitate the interpretation and understanding.

We ran mixed-effects intercept-only models to calculate the overall weighted effect size (lnRR_{++}) for each response variable of the soil properties. These intercept-only models fitted lnRR 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 manipulation using mixed effects meta-regression models by fitting each moderator variable as a continuous (snow depth, soil depth, latitude, elevation, MAT, MAP, and experimental duration) or categorical (ecosystem type) 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). In addition, to assist the interpretation of results, $\ln RR_{++}$ and the corresponding 95% confidence interval were back-transformed as $\left(e^{\ln RR_{++}} - 1\right) \times 100\%$.

2.3 Publication bias

Publication bias threatens the validity of results generated from meta-analyses because it results in some findings being overrepresented in meta-analytic datasets as they are published more frequently or sooner (Nakagawa et al., 2022), or in other words, studies published in the literature are a nonrandom subset of the total number of studies. To assess the potential publication bias in our meta-analysis, we used 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 manipulation on soil properties

Averaged across all the observations, snow removal significantly reduced soil temperature by 2.2 and 0.9 °C in winter and growing season, respectively, while snow addition significantly increased and decreased soil temperature by 2.7 °C and 0.4 °C in winter and growing season, respectively (Fig. 2, Fig. S2). Snow compaction had no effect on soil temperature in winter (Fig. S3). Snow removal significantly increased the depth of soil frost (129.2%), ammonification rate (87.0%), and nitrification rate (52.0%) in winter, but significantly decreased the activity of urease by an average of 20.0% in winter (Fig. 2a). Snow addition generally showed positive effects on soil properties during winter, increasing soil moisture (14.4%), C content (14.3%), CO_2 efflux (26.0%), C:N ratio (14.1%), and the concentrations of NH_4^+ (17.4%), NO_3^- (21.1%), P (44.5%), MBC (23.9%), and MBN (15.3%) (Fig. 2b), while snow compaction significantly increased soil frost by 163.5% (Fig. S3).

Snow removal in winter significantly reduced soil moisture by an average of 28.3% in the following growing season, but increased soil pH, C, and DOC by 30.7, 28.1, and 25.8%, respectively (Fig. 2c). Snow removal also stimulated the concentrations of growing season N (42.6%), DON (26.8%), NH_4^+ (31.3%), and N_2O efflux (90.7%), but had no effect on P, microbes, or the activities of several enzymes. In contrast, winter snow addition had no effect on growing season soil moisture, pH, or C, but significantly increased the concentrations of NH_4^+ (25.5%), NO_3^- (25.7%), MBC (22.4%), MBN (34.6%), sucrase activity (17.2%), and urease activity (29.0%) (Fig. 2d).

3.2. Influence of moderator variables

The removed snow depth negatively correlated with the lnRR of soil temperature, moisture, C, and NO_3^-, but positively affected the lnRR of frost, N_2O efflux, nitrification rate, and catalase activity in winter (Fig. 3a). The depth of added snow only significantly affected the lnRR of winter soil temperature, moisture and urease activity (Fig. 3b). Soil depth positively affected the lnRR of temperature, NH_4^+, MBP, PLFA, and PLFA ratio of bacteria to fungi to snow removal in winter, but negatively affected the lnRR of temperature, P, and MBC:MBN ratio (Fig. 4). Soil depth had limited effects on the responses of soil properties to snow addition in winter or to snow removal and addition in growing season. Ecosystem type significantly affected the lnRR of snow removal on soil temperature, moisture, frost, CH_4 uptake, available N, N_2O efflux, available P, and invertase activity during winter (Fig. 5a), but only affected the lnRR of snow addition on winter soil NO_3^- concentration (Fig. 5b) and the lnRR of snow removal on growing season soil pH (Fig. 5c). The negative effects of snow removal on soil properties in winter were likely to be most significant in desert, such as moisture, available N, NO_3^-, available P, and MBN, while its negative effect on CO_2 efflux and CH_4 uptake were only significant in wetland. In contrast, snow removal effects on winter soil available N and N_2O efflux were positive in forest.

The effects of snow manipulation on soil properties varied significantly with geographical location, climate, and experimental duration (Table 1 and Table S2). Specifically, the effects of snow removal on soil temperature depended on latitude, while snow addition effects on soil temperature were significantly affected by latitude and climate. The effects of snow removal on winter soil available N and P were negatively correlated with latitude, while its effects on winter CH_4 uptake, NO_3^-, P, MBN, and fungal PLFA were positively correlated with elevation. The effects of snow removal on winter soil pH and available N were positively correlated with MAP, but its effects on winter soil moisture, frost, available N, and N_2O efflux were negatively correlated with experimental duration. Latitude, elevation, climate, and experimental duration had a minor impact the effects of snow addition on winter soil properties, but important moderators for the effects of snow removal on growing season DOC and snow addition on growing season NH_4^+ and NO_3^-.

4. Discussion

4.1. Warmer and more humid soil microclimate conditions induced by snow cover

Partially consistent with our first hypothesis, our results suggest that snow removal promoted colder soil microclimate conditions both in winter and in the following growing season, while snow addition induced warmer and humid conditions in winter but led to lower soil temperatures in the growing season. 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). Previous evidence suggest that a snow cover layer of 30-40 cm is sufficient for decoupling soil thermal changes from air temperature in most of the snowing regions (Steinweg et al., 2008). Most of the removed snow in our study had a depth > 30 cm, which would be sufficient to stimulate significant soil temperature decreases, and trigger variations in multiple soil properties. The thermal insulating effect of snow cover on soil temperature was further supported by our results that the negative effect of snow removal and positive effect of snow addition on soil temperature were enhanced with increases in snow depth (Fig. 3). The non-significant effects of snow removal on winter soil moisture may be attributed to the fact that the soil was frozen in both snow removal and natural snow plots. It could also be that snow was only removed for a short period of time at the beginning of the winter in some of the studies, which is just long enough to induce soil freezing without substantially altering the water balance. This is supported by our result that soil moisture was significantly decreased when assessed only using data from plots with snow free in the whole winter (Fig. S4). The significant positive effects of snow removal on growing season 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), while soil freezing induced by snow removal can also affect microbial and fine root cell lysis and leakage, contributing to a higher soil NO_3^- concentration (Callesen et al., 2007). 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) that agreed with our findings here, 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). Snow removal did not affect soil pH in winter, indicating that snow cover not only affects soil properties during winter, but also has legacy effects in the following growing season. In addition, our results showed that snow compaction only increased soil frost depth, suggesting the limited impacts of snow density in regulating soil microclimate.

4.2. Contrasting effects of snow cover on soil properties between winter and the following growing season

In contrast to our second hypothesis, we found that snow removal showed only limited effects on soil properties in winter but induced strong effects in the following growing season, while snow addition affected soil properties in both winter and growing season. 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 show positive effects of snow removal on growing season C, DOC, and C:N ratio, as well as positive effects of snow addition on winter C. Soil dissolved organic matter (DOM) may 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). However, our results suggested that these processes are not strong enough to induce differences in DOM between ambient snow cover and snow removal treatment in winter, while the loss of existing soil DOM by leaching along with snow melt in the following growing season may explain the significant effects of snow removal on growing season C and DOC.

Soil temperature is a major factor controlling soil microbial enzymatic activities and the availability of liquid water for microbes, and thus indirectly drive soil CO_2 and CH_4 fluxes (Schindlbacher et al., 2007; Puissant et al., 2015). Somewhat surprisingly, our results indicate that snow removal did not affect soil CO_2 efflux, microbial biomass, microbial diversity, or soil enzymatic activities neither in winter nor growing season, except for its negative effect on winter urease activity which may be the damage of lower soil temperature, despite the significant negative effects of snow removal on soil temperature. Previous studies have found that snow removal 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 resistance and resilience of soil microbial communities to changes in snow cover (Männistö et al., 2018). In contrast, snow addition significantly increased soil CO_2 efflux, MBC, and MBN, mainly because of the higher soil temperature and moisture under snow addition (Wipf and Rixen, 2010; Männistö et al., 2018). The divergent response of soil CO_2 efflux and microbial biomass to snow removal *vs.* snow addition may be that their responses to snow manipulation depend on ambient macroclimate conditions.

Snow removal significantly increased winter ammonification and nitrification rates and increased growing season NH_4^+ and N_2O efflux, while snow addition significantly increased NH_4^+ and NO_3^- both in winter and in the growing season, and available P in winter. With snow removal, 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 the ammonification and nitrification rates and the availability of inorganic N in the following growing season (van Bochove et al., 2000). Higher concentrations of inorganic N in the soil can in turn drive higher N_2O emissions via denitrification (Groffman et al., 2001b; Müller et al., 2003; Blankinship and Hart, 2012). On the other hand, a higher soil temperature induced by snow addition may also facilitate a higher abundance and diversity of N-cycling microbial communities that increase N mineralization (Jusselme et al., 2016; Xu et al., 2021), and thus increase the concentrations of soil NH_4^+ and NO_3^-. The positive effects of snow addition 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 increased snow cover, because anoxic conditions can help soil minerals to retain P otherwise will be susceptible to leaching, and anoxic events may potentially increase P bioavailability by decreasing the strength of P sorption (Lin et al., 2020).

4.3. Environmental variables regulate the effects of snow manipulation

Manipulated snow depth, soil depth of measurement, ecosystem type, latitude, and macroclimate are important moderator variables on the effects of snow manipulation. The effect of snow cover on soil biogeochemical properties was mainly attributed to its insulating effects, so understanding that the effects of snow removal or addition would increase with the manipulated snow depth is easy, and is also supported by our findings. It is noteworthy that snow water equivalent may be a better predictor than snow depth because it can also capture some variations of snow density. However, because of the limited data points, we were not able to assess the impacts of snow water equivalent here. The insulating effects of snow cover generally decrease with soil depth, and we found evidence that responses of several soil properties to snow manipulation significantly decreased with soil depth. Ecosystem type was also an important moderator variable regulating the effects of snow manipulation on several soil properties, with the strongest effects observed in deserts. 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, elevation, MAT, and MAP were all important factors controlling the effects of snow removal and snow addition on soil properties in both winter and the following growing seasons, but their moderating impacts varied among soil properties. In addition, experimental duration was generally negatively correlated with the effects of snow manipulation on soil properties, regardless of the season, indicating that snow manipulation effects diminish with experimental duration.

4.4. Major limitations and recommendations for future research

Despite the comprehensive analyses conducted in this study, several uncertainties and knowledge gaps still exist because of the limitations in experimental designs of the primary studies and the lack of a more complete dataset with sufficient information on the snow manipulation study. Firstly, the effects of snow cover and snow removal were rarely assessed in the same study using similar experimental protocols, with only the effects of snow removal or snow addition assessed in a particular study, which limited our ability to compare their effects using pairwise datasets. Secondly, the sample sizes for many soil variables were small, especially when data were divided into different subgroups such as ecosystem types. The small sample size can hamper our ability to draw a robust result of the snow cover effects and prevented us from evaluating the underling drivers of snow cover effects. Thirdly, most of the primary studies did not report background data such as the climate during the experiment period, snow characteristics such as snow water equivalent, and the frequency and intensity of snow manipulation, which reduced our ability to clearly evaluate the underlying mechanisms of snow cover effects on soil properties. Therefore, we suggest that well-designed and replicated snow manipulation experiments considering both snow removal and snow addition are needed to help us better understanding the ecological functions of snow cover in alpine and arctic regions. Also, future studies should clearly report the background information that is closely related to the assessment of snow cover effects, which will facilitate continuous and comprehensive synthesis studies.

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 removal had limited effects on winter soil properties but showed profound effects on the concentrations and fluxes of soil C and N in the following growing season. Snow addition affected soil properties both in winter and growing season, while snow compaction only increased soil frost depth. The effects of snow manipulation on several soil properties depended on ecosystem type, with the strongest effects found in deserts. Other moderator variables such as snow depth, latitude, elevation, MAT, MAP, and experimental 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 snow cover in regulating soil physicochemical and biotic properties in winter and the following growing season. 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 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, increasing 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 used in the study have been deposited in figshare with a DOI (https://doi.org/10.6084/m9.figshare.19822885.v1).

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Table 1 Mixed-effects meta-regression modeling assessing the effects of moderator variables [latitude, elevation, mean annual temperature (MAT), mean annual precipitation (MAP), and duration] on the effect sizes (lnRR) of soil properties in response to snow removal in winter. Estimates (slop) are shown, and values in bold indicate significant effects. Several variables were not assessed here because of limited number of observations, and the number of observations and studies (in parentheses) used for analyses for each variable are shown. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Soil property	*n*	Winter – snow removal				
		Latitude	Elevation	MAT	MAP	Duration
Temperature	362 (50)	**-0.004****	0.002	0.001	0.001	-0.001
Moisture	153 (26)	-0.088	0.069	-0.021	0.084	**-0.129****
Frost	75 (13)	0.332	-0.142	0.087	-0.284	**-0.428*****
pH	30 (9)	-0.008	0.005	0.003	**0.012***	-0.004
C	37 (11)	-0.106	0.068	0.011	0.094	-0.019
DOC	46 (10)	-0.019	0.002	-0.017	-0.024	0.016
CO_2 efflux	109 (18)	-0.114	0.175	0.012	-0.132	0.047
CH_4 uptake	21 (6)	0.002	**0.154***	**0.122****	0.160	0.069
C:N ratio	21 (5)	-0.002	0.017	-0.034	0.011	-0.014
N	32 (10)	-0.120	0.081	0.003	0.117	-0.031
Available N	20 (5)	**-0.176****	0.095	0.037	**0.169****	**-0.192****
DON	40 (7)	-0.137	0.137	-0.043	-0.091	0.047
NH_4^+	106 (18)	-0.026	0.014	0.002	0.177	-0.144
NO_3^-	134 (17)	-0.129	**0.256***	-0.018	0.176	-0.098
N_2O efflux	51 (8)	**0.239****	**-0.441****	0.178	**-0.320****	**-0.342*****
Ammonification rate	10 (3)	-1.299	1.497	-1.446	-1.616	1.037
Nitrification rate	28 (6)	-0.489	0.490	-0.530	-0.509	0.160
P	7 (3)	**-0.338***	**0.325***	-0.282	0.312	0.028
Available P	31 (5)	-0.113	0.084	-0.284	0.317	-0.182
MBC	141 (21)	-0.022	0.037	-0.019	0.027	-0.024
MBN	118 (16)	-0.024	**0.070***	**-0.076***	0.029	-0.009
MBC:MBN ratio	14 (2)	0.043	-0.044	0.016	-0.018	0.034
PLFA	11 (4)	0.056	0.073	0.038	0.082	0.012
Bacterial PLFA	10 (3)	0.065	0.080	-0.067	0.087	-0.055
Fungal PLFA	8 (2)	0.099	**0.118***	-0.100	0.112	-0.046
R_m	14 (2)	-0.072	0.064	0.070	0.071	-0.067
Invertase activity	37 (5)	-0.021	0.017	0.042	0.026	-0.044
Urease activity	38 (5)	-0.036	0.039	0.049	0.034	**-0.103***

C, total carbon; DOC, dissolved organic carbon; N, total nitrogen; DON, dissolved organic nitrogen; P, total phosphorus; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; MBP, microbial biomass phosphorus; PLFA, phospholipid fatty acid; R_m, microbial respiration.

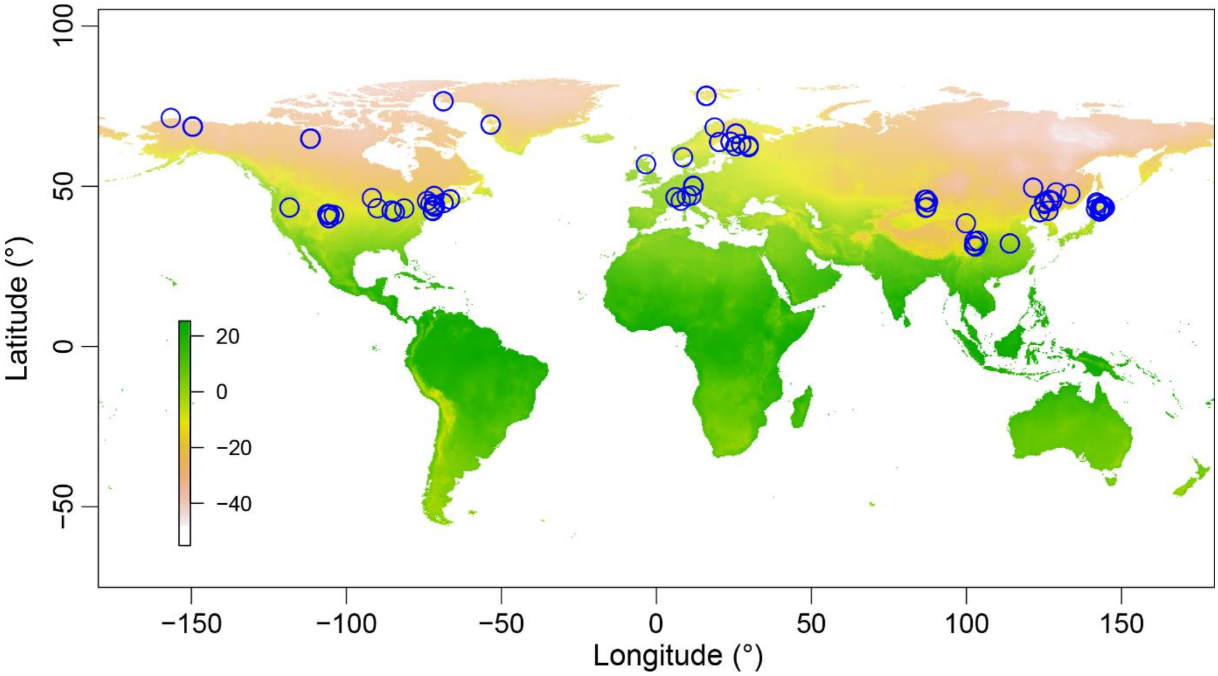


Figure 1 The distribution of paired observations (blue circles) of the responses of soil properties to snow manipulation collected from the 99 publications. The color scale indicates the long-term (1970-2000) minimum temperature (°C) of the coldest month derived from *WorldClim* (https://www.worldclim.org).

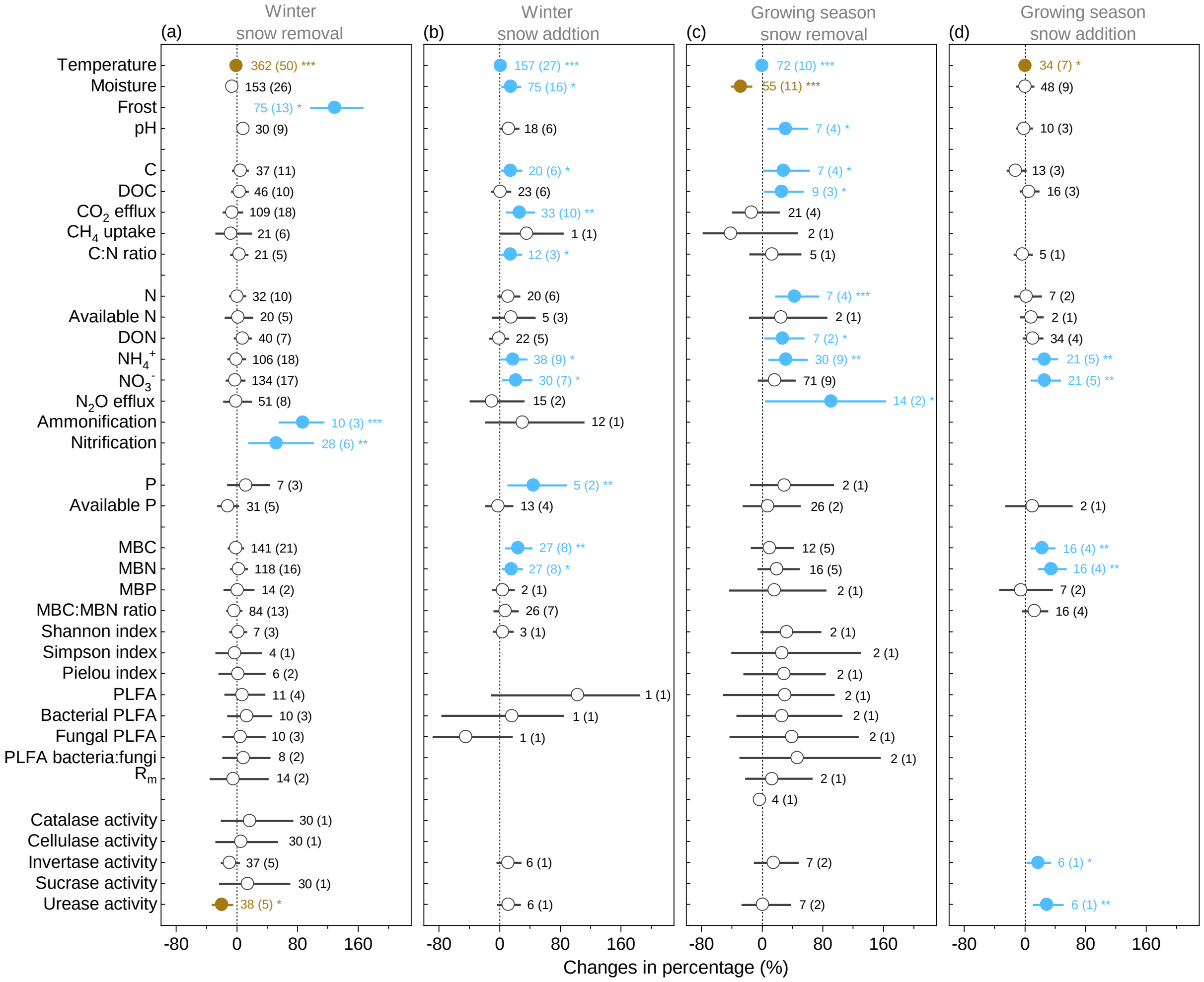


Figure 2 Effects of snow removal and addition on soil properties during winter and growing season. Values indicate means with 95% confidence intervals, and the number of observations and studies (in parentheses) for each variable of soil properties are shown. Empty circles indicate non-significant effects, and solid blue and brown circles indicate significant positive and negative effects, respectively. C, total carbon; DOC, dissolved organic carbon; N, total nitrogen; DON, dissolved organic nitrogen; P, total phosphorus; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; PLFA, phospholipid fatty acid; R_m, microbial respiration. ${}^{*}p < 0.05$; ${}^{**}p < 0.01$; ${}^{***}p < 0.001$.

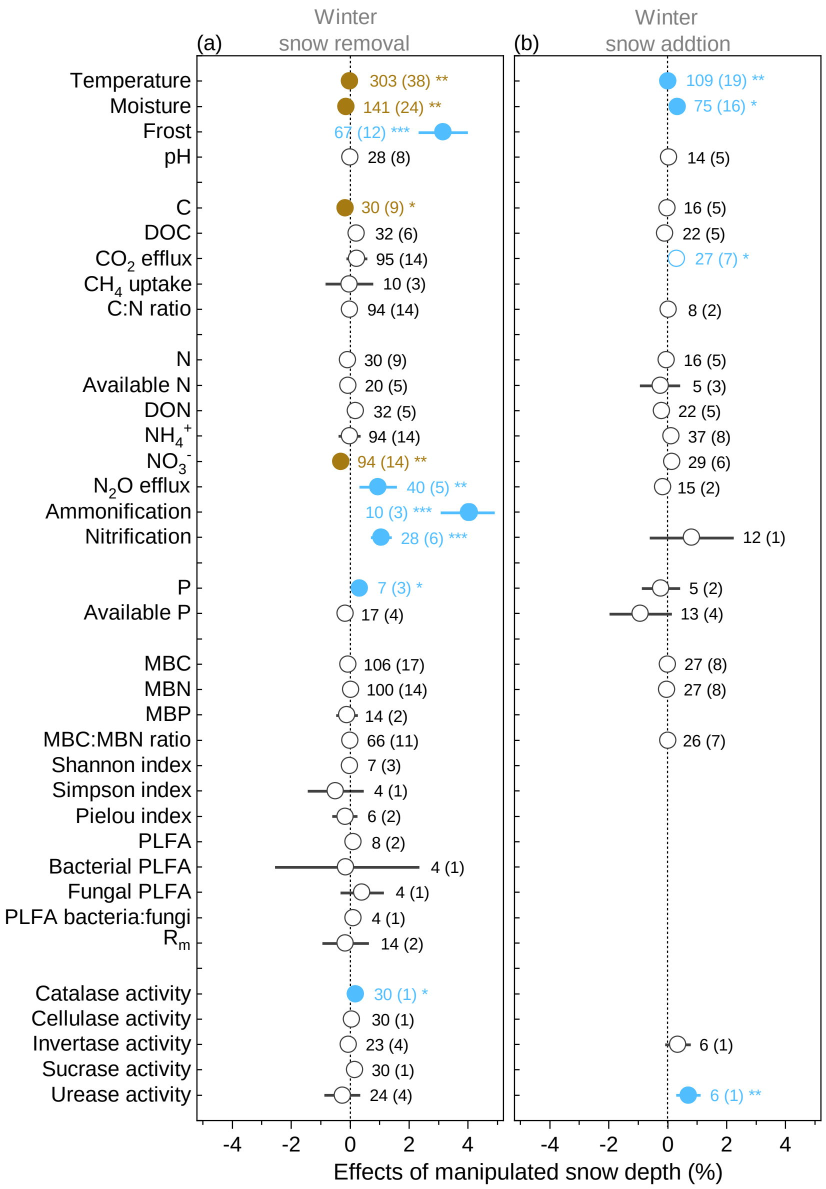


Figure 3 Influences of manipulated snow depth on the responses of soil properties to snow manipulation. Values indicate means with 95% confidence intervals, and the number of observations and studies (in parentheses) for each variable of the soil properties are shown in parentheses. Empty circles indicate non-significant effects, and solid blue and brown circles indicate significant positive and negative effects, respectively. Negative (positive) effects indicate that the presence of snow negatively (positively) affected the soil property. C, total carbon; DOC, dissolved organic carbon; N, total nitrogen; DON, dissolved organic nitrogen; P, total phosphorus; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; PLFA, phospholipid fatty acid; R_m, microbial respiration. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

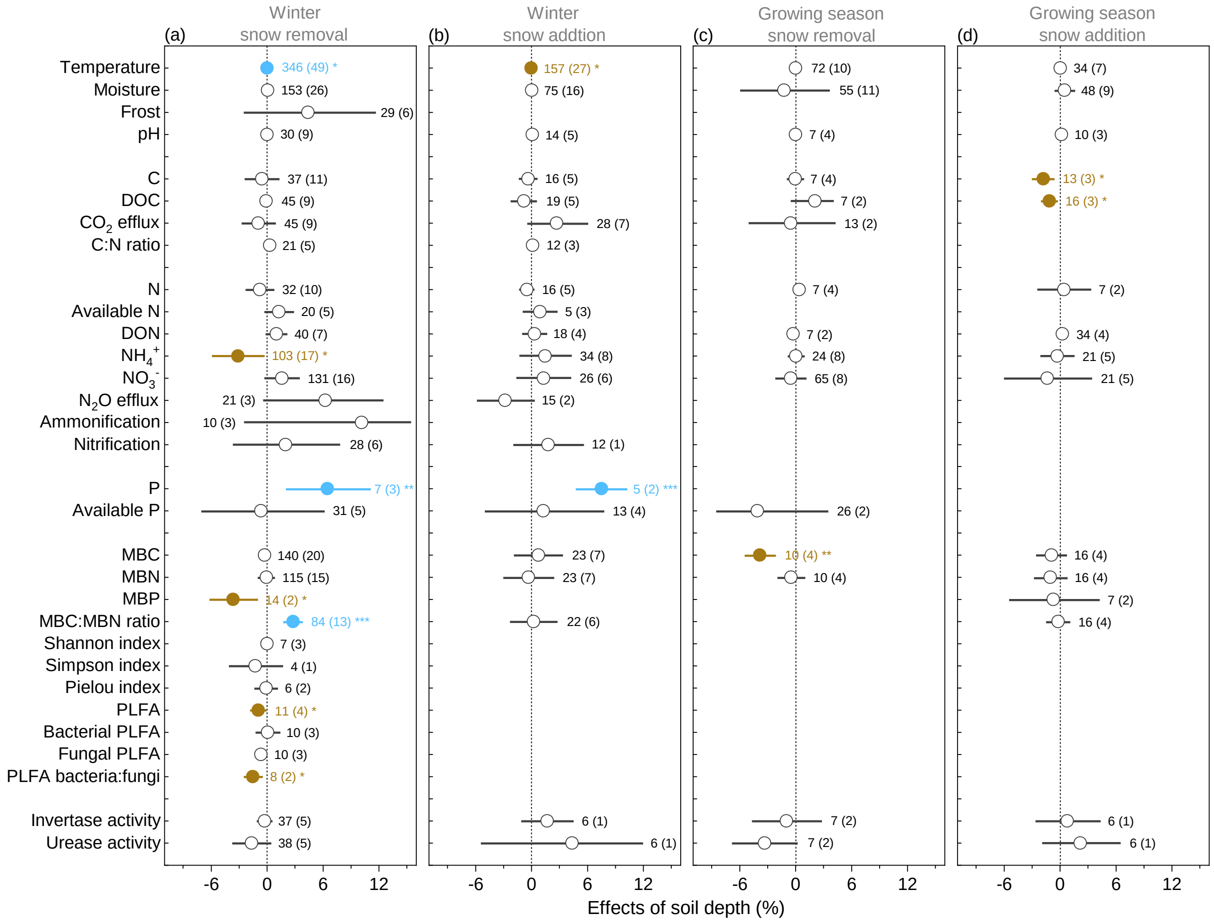


Figure 4 Effects of soil depth on the responses of soil properties to snow manipulation. Values indicate means with 95% confidence intervals, and the number of observations for each variable of the soil properties are shown in parentheses. Empty circles indicate non-significant effects, and solid blue and brown circles indicate significant positive and negative effects, respectively. Negative (positive) effects indicate that the presence of snow negatively (positively) affected the soil property. C, total carbon; DOC, dissolved organic carbon; N, total nitrogen; DON, dissolved organic nitrogen; P, total phosphorus; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; PLFA, phospholipid fatty acid. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

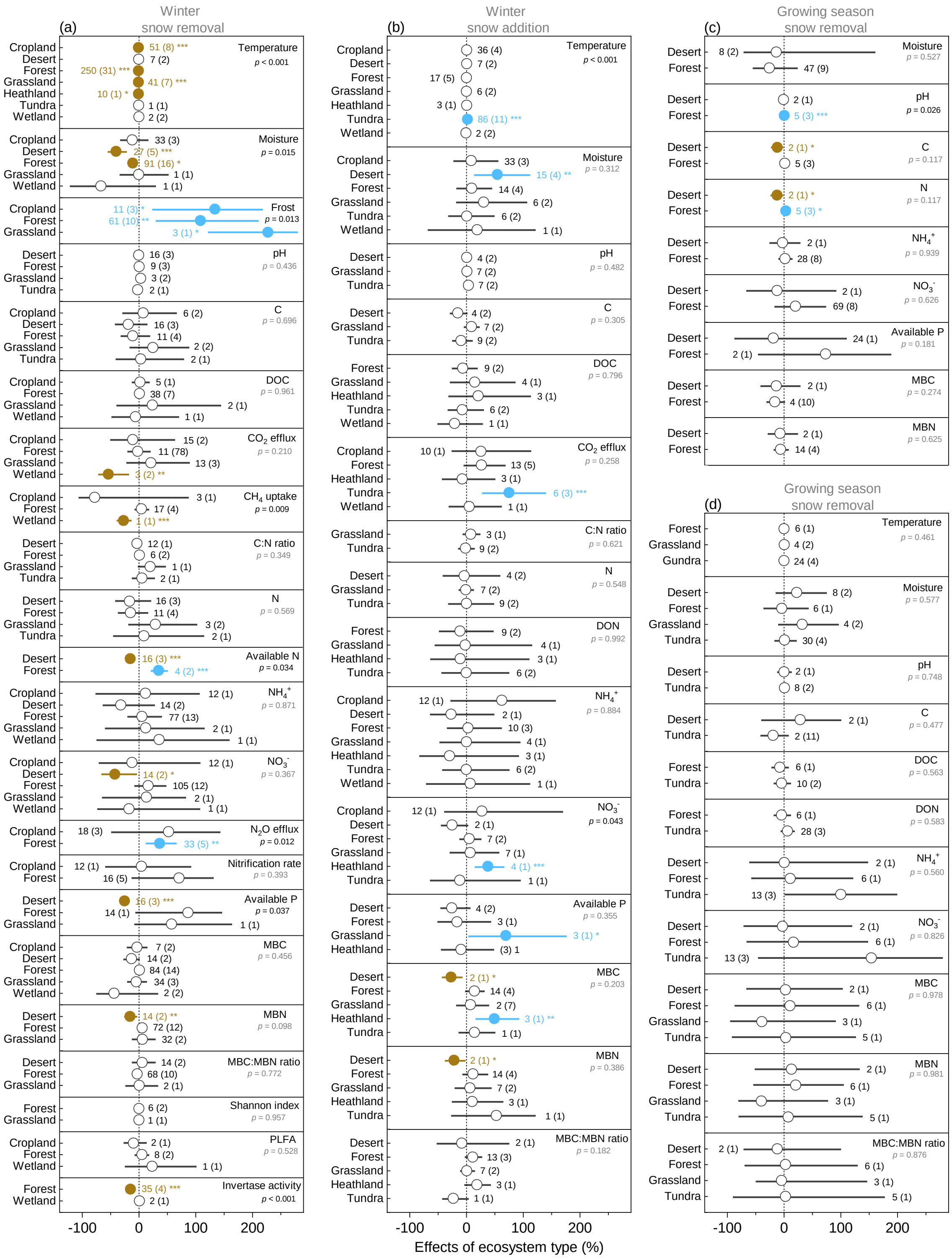


Figure 5 Effects of ecosystem type on the responses of soil properties to snow manipulation. Values indicate means with 95% confidence intervals, and the number of observations and studies (in parentheses) for each variable of soil properties are shown in parentheses. Empty circles indicate non-significant effects, and solid blue and brown circles indicate significant positive and negative effects, respectively. C, total carbon; DOC, dissolved organic carbon; N, total nitrogen; DON, dissolved organic nitrogen; P, total phosphorus; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; PLFA, phospholipid fatty acid concentration. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

Figure 1

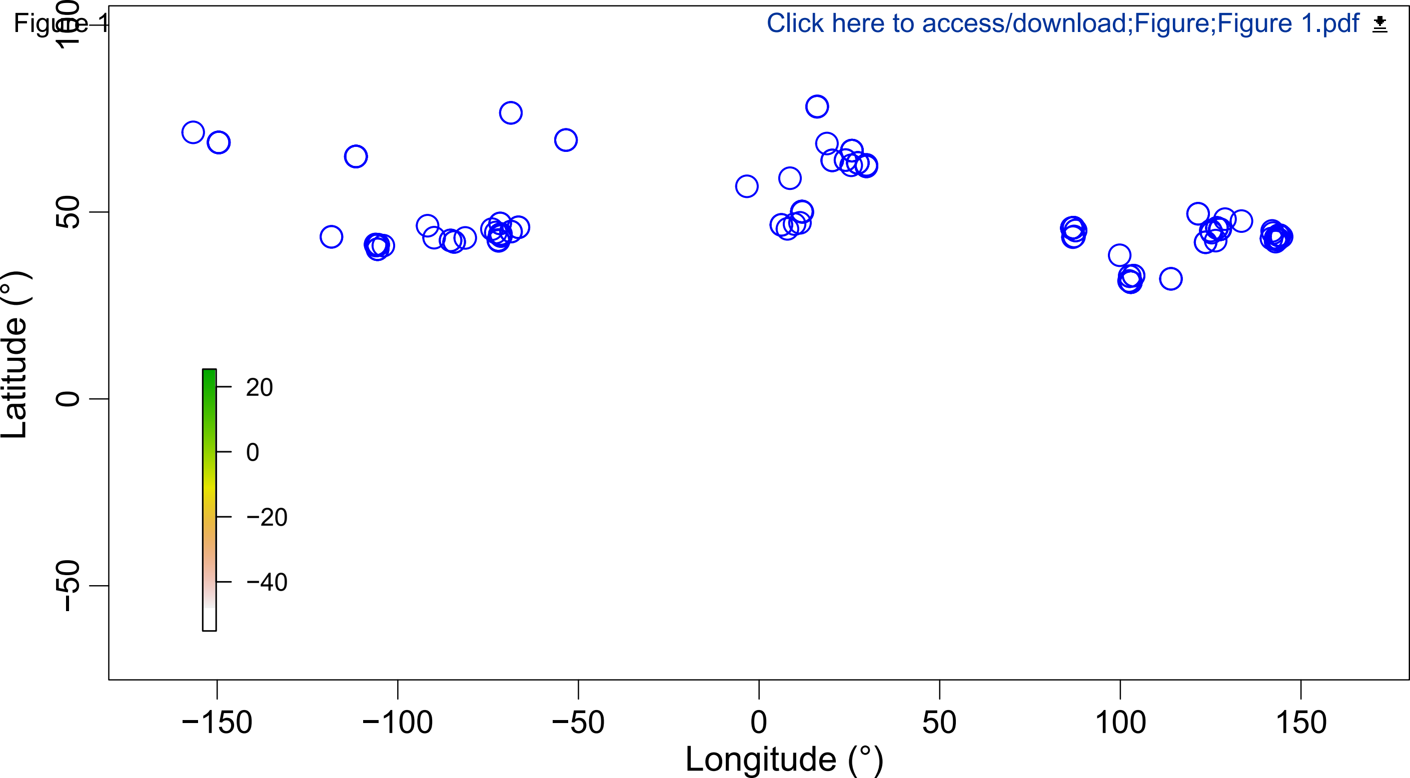
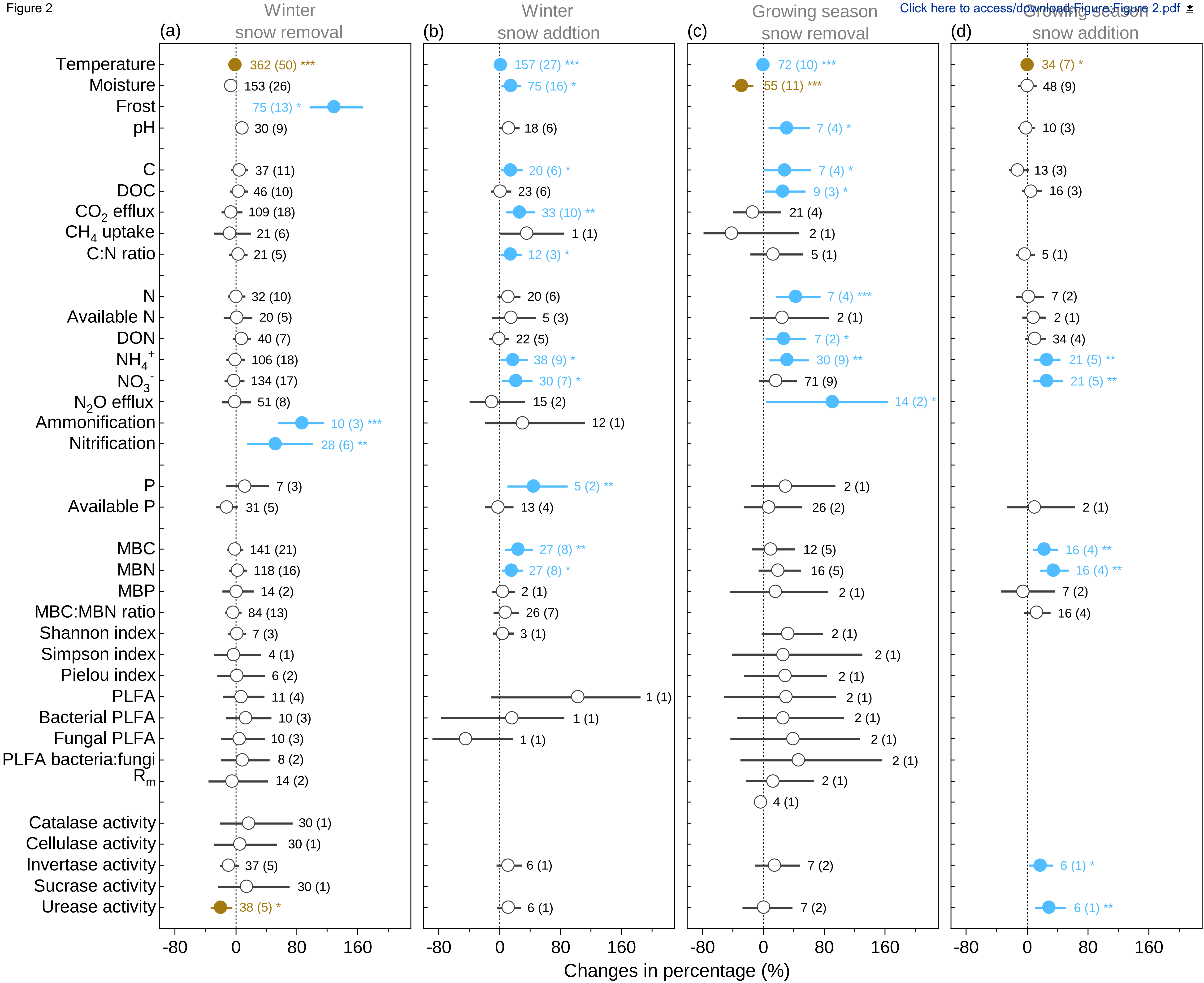


Figure 2


(a)
Winter snow removal
(b)
Winter snow addtion
(c)
Growing season snow removal
(d)
Growing season snow addition
Temperature
Moisture
Frost
pH
C
DOC
CO_2 efflux
CH_4 uptake
C:N ratio
N
Available N
DON
NH_4^+
NO_3^-
N_2O efflux
Ammonification
Nitrification
P
Available P
MBC
MBN
MBP
MBC:MBN ratio
Shannon index
Simpson index
Pielou index
PLFA
Bacterial PLFA
Fungal PLFA
PLFA bacteria:fungi
R_m
Catalase activity
Cellulase activity
Invertase activity
Sucrase activity
Urease activity
362 (50) ***
153 (26)
75 (13) *
30 (9)
37 (11)
46 (10)
109 (18)
21 (6)
21 (5)
32 (10)
20 (5)
40 (7)
106 (18)
134 (17)
51 (8)
10 (3) ***
28 (6) **
7 (3)
31 (5)
141 (21)
118 (16)
14 (2)
84 (13)
7 (3)
4 (1)
6 (2)
11 (4)
10 (3)
10 (3)
8 (2)
14 (2)
30 (1)
30 (1)
37 (5)
30 (1)
38 (5) *
157 (27) ***
75 (16) *
18 (6)
20 (6) *
23 (6)
33 (10) **
1 (1)
12 (3) *
20 (6)
5 (3)
22 (5)
38 (9) *
30 (7) *
15 (2)
12 (1)
5 (2) **
13 (4)
27 (8) **
27 (8) *
2 (1)
26 (7)
3 (1)
1 (1)
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72 (10) ***
55 (11) ***
7 (4) *
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48 (9)
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16 (4) **
7 (2)
16 (4)
6 (1) *
6 (1) **
-80
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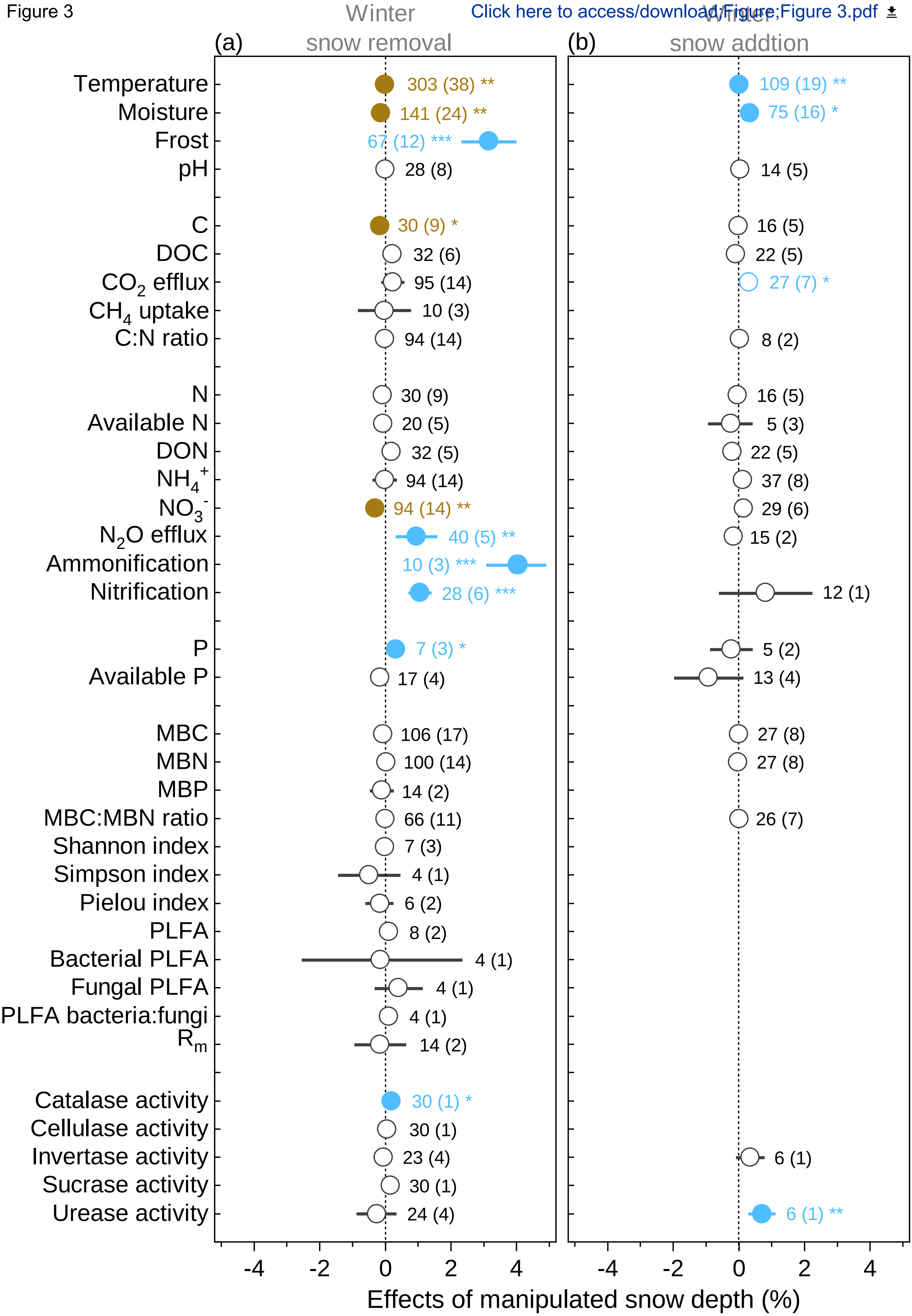
80
160
-80
0
80
160
-80
0
80
160
-80
0
80
160
Changes in percentage (%)

Figure 3


(a)
Winter
snow removal
(b)
Winter
snow addtion
Temperature
Moisture
Frost
pH
C
DOC
CO_2 efflux
CH_4 uptake
C:N ratio
N
Available N
DON
NH_4^+
NO_3^-
N_2O efflux
Ammonification
Nitrification
P
Available P
MBC
MBN
MBP
MBC:MBN ratio
Shannon index
Simpson index
Pielou index
PLFA
Bacterial PLFA
Fungal PLFA
PLFA bacteria:fungi
R_m
Catalase activity
Cellulase activity
Invertase activity
Sucrase activity
Urease activity
303 (38) **
141 (24) **
67 (12) ***
28 (8)
30 (9) *
32 (6)
95 (14)
10 (3)
94 (14)
30 (9)
20 (5)
32 (5)
94 (14)
94 (14) **
40 (5) **
10 (3) ***
28 (6) ***
7 (3) *
17 (4)
106 (17)
100 (14)
14 (2)
66 (11)
7 (3)
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8 (2)
4 (1)
4 (1)
4 (1)
14 (2)
30 (1) *
30 (1)
23 (4)
30 (1)
24 (4)
109 (19) **
75 (16) *
14 (5)
16 (5)
22 (5)
27 (7) *
8 (2)
16 (5)
5 (3)
22 (5)
37 (8)
29 (6)
15 (2)
12 (1)
5 (2)
13 (4)
27 (8)
27 (8)
26 (7)
6 (1)
6 (1) **
-4
-2
0
2
4
-4
-2
0
2
4
Effects of manipulated snow depth (%)

Figure 4

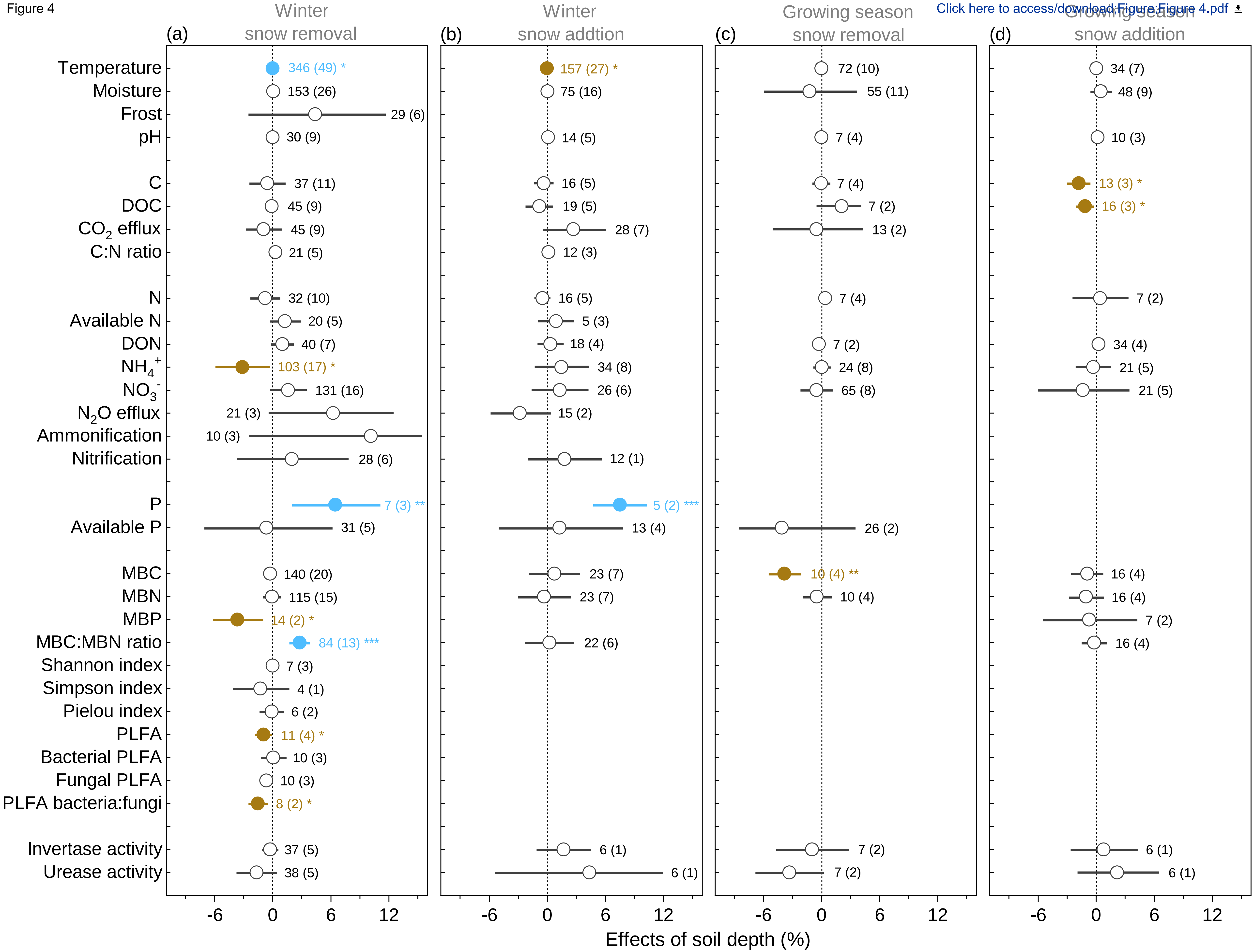
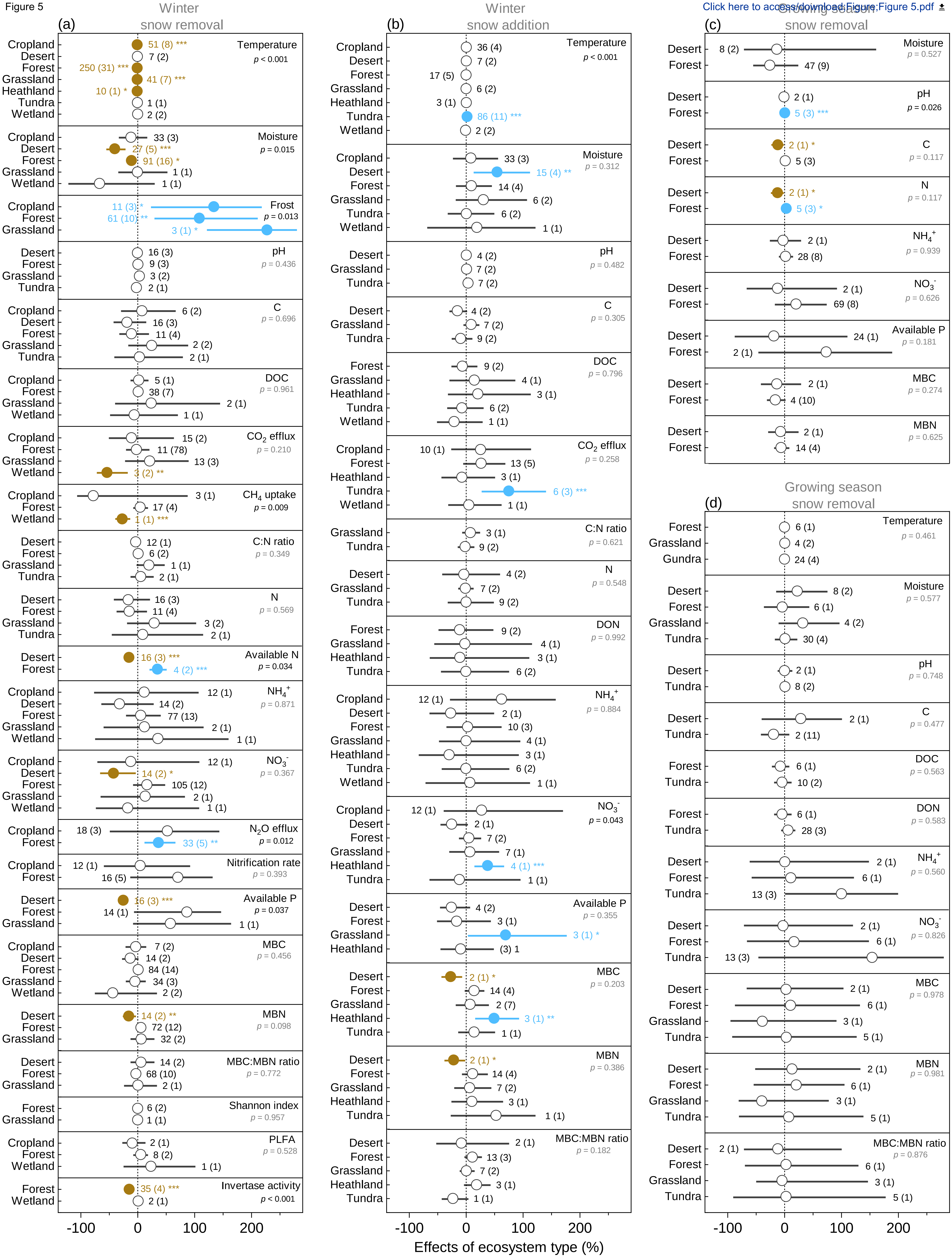

(a)
Winter
snow removal
(b)
Winter
snow addtion
(c)
Growing season
snow removal
(d)
Growing season
snow addition
Temperature
Moisture
Frost
pH
C
DOC
CO_2 efflux
C:N ratio
N
Available N
DON
NH_4^+
NO_3^-
N_2O efflux
Ammonification
Nitrification
P
Available P
MBC
MBN
MBP
MBC:MBN ratio
Shannon index
Simpson index
Pielou index
PLFA
Bacterial PLFA
Fungal PLFA
PLFA bacteria:fungi
Invertase activity
Urease activity
346 (49) *
153 (26)
29 (6)
30 (9)
37 (11)
45 (9)
45 (9)
21 (5)
32 (10)
20 (5)
40 (7)
103 (17) *
131 (16)
21 (3)
10 (3)
28 (6)
7 (3) **
31 (5)
140 (20)
115 (15)
14 (2) *
84 (13) ***
7 (3)
4 (1)
6 (2)
11 (4) *
10 (3)
10 (3)
8 (2) *
37 (5)
38 (5)
157 (27) *
75 (16)
14 (5)
16 (5)
19 (5)
28 (7)
12 (3)
16 (5)
5 (3)
18 (4)
34 (8)
26 (6)
15 (2)
12 (1)
5 (2) ***
13 (4)
23 (7)
23 (7)
22 (6)
6 (1)
6 (1)
72 (10)
55 (11)
7 (4)
7 (4)
7 (2)
13 (2)
7 (4)
7 (2)
24 (8)
65 (8)
26 (2)
10 (4) **
10 (4)
7 (2)
7 (2)
34 (7)
48 (9)
10 (3)
13 (3) *
16 (3) *
7 (2)
34 (4)
21 (5)
21 (5)
16 (4)
16 (4)
7 (2)
16 (4)
6 (1)
6 (1)
-6
0
6
12
Effects of soil depth (%)

Figure 5


(a)
Winter
snow removal
Temperature
$p < 0.001$
Cropland 51 (8) ***
Desert 7 (2)
Forest 250 (31) ***
Grassland 41 (7) ***
Heathland 10 (1) *
Tundra 1 (1)
Wetland 2 (2)
Moisture
$p = 0.015$
Cropland 33 (3)
Desert 27 (5) ***
Forest 91 (16) *
Grassland 1 (1)
Wetland 1 (1)
Frost
$p = 0.013$
Cropland 11 (3) *
Forest 61 (10) **
Grassland 3 (1) *
pH
$p = 0.436$
Desert 16 (3)
Forest 9 (3)
Grassland 3 (2)
Tundra 2 (1)
C
$p = 0.696$
Cropland 6 (2)
Desert 16 (3)
Forest 11 (4)
Grassland 2 (2)
Tundra 2 (1)
DOC
$p = 0.961$
Cropland 5 (1)
Forest 38 (7)
Grassland 2 (1)
Wetland 1 (1)
CO_2 efflux
$p = 0.210$
Cropland 15 (2)
Forest 11 (78)
Grassland 13 (3)
Wetland 3 (2) **
CH_4 uptake
$p = 0.009$
Cropland 3 (1)
Forest 17 (4)
Wetland 1 (1) ***
C:N ratio
$p = 0.349$
Desert 12 (1)
Forest 6 (2)
Grassland 1 (1)
Tundra 2 (1)
N
$p = 0.569$
Desert 16 (3)
Forest 11 (4)
Grassland 3 (2)
Tundra 2 (1)
Available N
$p = 0.034$
Desert 16 (3) ***
Forest 4 (2) ***
NH_4^+
$p = 0.871$
Cropland 12 (1)
Desert 14 (2)
Forest 77 (13)
Grassland 2 (1)
Wetland 1 (1)
NO_3^-
$p = 0.367$
Cropland 12 (1)
Desert 14 (2) *
Forest 105 (12)
Grassland 2 (1)
Wetland 1 (1)
N_2O efflux
$p = 0.012$
Cropland 18 (3)
Forest 33 (5) **
Nitrification rate
$p = 0.393$
Cropland 12 (1)
Forest 16 (5)
Available P
$p = 0.037$
Desert 16 (3) ***
Forest 14 (1)
Grassland 1 (1)
MBC
$p = 0.456$
Cropland 7 (2)
Desert 14 (2)
Forest 84 (14)
Grassland 34 (3)
Wetland 2 (2)
MBN
$p = 0.098$
Desert 14 (2) **
Forest 72 (12)
Grassland 32 (2)
MBC:MBN ratio
$p = 0.772$
Desert 14 (2)
Forest 68 (10)
Grassland 2 (1)
Shannon index
$p = 0.957$
Forest 6 (2)
Grassland 1 (1)
PLFA
$p = 0.528$
Cropland 2 (1)
Forest 8 (2)
Wetland 1 (1)
Invertase activity
$p < 0.001$
Forest 35 (4) ***
Wetland 2 (1)
-100
0
100
200
(b)
Winter
snow addition
Temperature
$p < 0.001$
Cropland 36 (4)
Desert 7 (2)
Forest 17 (5)
Grassland 6 (2)
Heathland 3 (1)
Tundra 86 (11) ***
Wetland 2 (2)
Moisture
$p = 0.312$
Cropland 33 (3)
Desert 15 (4) **
Forest 14 (4)
Grassland 6 (2)
Tundra 6 (2)
Wetland 1 (1)
pH
$p = 0.482$
Desert 4 (2)
Grassland 7 (2)
Tundra 7 (2)
C
$p = 0.305$
Desert 4 (2)
Grassland 7 (2)
Tundra 9 (2)
DOC
$p = 0.796$
Forest 9 (2)
Grassland 4 (1)
Heathland 3 (1)
Tundra 6 (2)
Wetland 1 (1)
CO_2 efflux
$p = 0.258$
Cropland 10 (1)
Forest 13 (5)
Heathland 3 (1)
Tundra 6 (3) ***
Wetland 1 (1)
C:N ratio
$p = 0.621$
Grassland 3 (1)
Tundra 9 (2)
N
$p = 0.548$
Desert 4 (2)
Grassland 7 (2)
Tundra 9 (2)
DON
$p = 0.992$
Forest 9 (2)
Grassland 4 (1)
Heathland 3 (1)
Tundra 6 (2)
NH_4^+
$p = 0.884$
Cropland 12 (1)
Desert 2 (1)
Forest 10 (3)
Grassland 4 (1)
Heathland 3 (1)
Tundra 6 (2)
Wetland 1 (1)
NO_3^-
$p = 0.043$
Cropland 12 (1)
Desert 2 (1)
Forest 7 (2)
Grassland 7 (1)
Heathland 4 (1) ***
Tundra 1 (1)
Available P
$p = 0.355$
Desert 4 (2)
Forest 3 (1)
Grassland 3 (1) *
Heathland (3) 1
MBC
$p = 0.203$
Desert 2 (1) *
Forest 14 (4)
Grassland 2 (7)
Heathland 3 (1) **
Tundra 1 (1)
MBN
$p = 0.386$
Desert 2 (1) *
Forest 14 (4)
Grassland 7 (2)
Heathland 3 (1)
Tundra 1 (1)
MBC:MBN ratio
$p = 0.182$
Desert 2 (1)
Forest 13 (3)
Grassland 7 (2)
Heathland 3 (1)
Tundra 1 (1)
-100
0
100
200
Effects of ecosystem type (%)
(c)
Growing season
snow removal
Moisture
$p = 0.527$
Desert 8 (2)
Forest 47 (9)
pH
$p = 0.026$
Desert 2 (1)
Forest 5 (3) ***
C
$p = 0.117$
Desert 2 (1) *
Forest 5 (3)
N
$p = 0.117$
Desert 2 (1) *
Forest 5 (3) *
NH_4^+
$p = 0.939$
Desert 2 (1)
Forest 28 (8)
NO_3^-
$p = 0.626$
Desert 2 (1)
Forest 69 (8)
Available P
$p = 0.181$
Desert 24 (1)
Forest 2 (1)
MBC
$p = 0.274$
Desert 2 (1)
Forest 4 (10)
MBN
$p = 0.625$
Desert 2 (1)
Forest 14 (4)
(d)
Growing season
snow removal
Temperature
$p = 0.461$
Forest 6 (1)
Grassland 4 (2)
Gundra 24 (4)
Moisture
$p = 0.577$
Desert 8 (2)
Forest 6 (1)
Grassland 4 (2)
Tundra 30 (4)
pH
$p = 0.748$
Desert 2 (1)
Tundra 8 (2)
C
$p = 0.477$
Desert 2 (1)
Tundra 2 (11)
DOC
$p = 0.563$
Forest 6 (1)
Tundra 10 (2)
DON
$p = 0.583$
Forest 6 (1)
Tundra 28 (3)
NH_4^+
$p = 0.560$
Desert 2 (1)
Forest 6 (1)
Tundra 13 (3)
NO_3^-
$p = 0.826$
Desert 2 (1)
Forest 6 (1)
Tundra 13 (3)
MBC
$p = 0.978$
Desert 2 (1)
Forest 6 (1)
Grassland 3 (1)
Tundra 5 (1)
MBN
$p = 0.981$
Desert 2 (1)
Forest 6 (1)
Grassland 3 (1)
Tundra 5 (1)
MBC:MBN ratio
$p = 0.876$
Desert 2 (1)
Forest 6 (1)
Grassland 3 (1)
Tundra 5 (1)
-100
0
100
200