Molecular Soil Biology 2024, Vol.15, No.3, 109-117
http://bioscipublisher.com/index.php/msb

Systematic Review Open Access

Snow Cover Dynamics: Impacts on Soil Moisture and Plant Growth in Temperate Ecosystems

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Molecular Soil Biology, 2024, Vol.15, No.3 doi: 10.5376/msb.2024.15.0012
Received: 17 Mar., 2024
Accepted: 29 Apr., 2024
Published: 14 May, 2024

Preferred citation for this article:
Cai S.Y., and Li Q.D., 2024, Snow cover dynamics: impacts on soil moisture and plant growth in temperate ecosystems, Molecular Soil Biology, 15(3): 109-117 (doi: 10.5376/msb.2024.15.0012)

Abstract Snow cover is a crucial natural phenomenon in temperate ecosystems, significantly influencing soil moisture regulation and plant growth cycles. With the intensification of global climate change, the seasonal patterns and distribution of snow cover are undergoing shifts that may have substantial long-term effects on ecosystem functionality and biodiversity. This study delves into the complex dynamics of snow cover, examining its seasonal variations and the multifaceted impacts of factors such as climate change and geographical differences. At its core, this research explores how snow cover aids in soil moisture retention, facilitates water infiltration through snowmelt mechanisms, and affects soil temperature regimes, thereby influencing plant dormancy and germination cycles. Through comprehensive analysis of case studies across different temperate regions and comparative assessments across various temperate zones, this study aims to highlight the critical role of snow in maintaining ecosystem functions and to inform future research directions and conservation practices.
Keywords Snow cover; Soil moisture; Plant growth; Climate change; Temperate ecosystems

1 Introduction

Snow cover plays a crucial role in temperate ecosystems, influencing a wide range of ecological and environmental processes. The accumulation and melting of snow determine ground temperature, light conditions, and moisture availability during winter, which in turn affect the timing of the growing season and the availability of nutrients for plants (Rixen et al., 2022). Snow cover dynamics are driven by various factors, including atmospheric conditions, wind-driven processes, and topographical features, which contribute to the spatial and temporal variability of snow accumulation and melt (Mott et al., 2018). Understanding these dynamics is essential for predicting the impacts of changing snow regimes on ecosystems.

In temperate ecosystems, snow cover acts as an insulating layer that protects soil and plant roots from extreme cold, thereby maintaining soil microbial activity and nutrient cycling during winter (Rumpf et al., 2014). The depth and duration of snow cover influence soil moisture levels, which are critical for plant growth and productivity in the subsequent growing season (Wang et al., 2018; Moriana-Armendariz et al., 2022). Changes in snow cover can lead to shifts in vegetation composition, plant phenology, and soil nutrient status, with cascading effects on the entire ecosystem. For instance, reduced snow depth often results in increased plant mortality and physical injury, while earlier snowmelt can advance spring phenology in plants and other organisms (Slatyer et al., 2020; Slatyer et al., 2021).

This study aims to synthesize the current knowledge on the effects of snow cover dynamics on soil moisture and plant growth in temperate ecosystems. Specifically, to study how changes in snow cover depth and melting time affect soil moisture levels and nutrient availability; Identify the mechanisms behind these responses and their impact on ecosystem functioning. By integrating the results of multiple studies, it is beneficial to fully understand the role of snow cover in temperate ecosystems and highlight research gaps that need to be addressed to improve the prediction of ecosystem responses to future climate change.

2 Snow Cover Dynamics

2.1 Definition and characteristics of snow cover

Snow cover refers to the layer of snow that accumulates on the ground surface during winter. It plays a crucial role in the climate system by influencing ground temperature, light conditions, and moisture availability. Snow cover acts as an insulating layer, protecting the soil and vegetation from extreme cold temperatures and maintaining soil moisture levels by reducing evaporation (Oppen et al., 2022). The characteristics of snow cover, such as depth and duration, are essential in determining its impact on the ecosystem. For instance, deeper snow cover can enhance soil moisture and stabilize plant community composition by providing a consistent water source during the early growing season (Li et al., 2020).

2.2 Seasonal variations in snow cover

Seasonal variations in snow cover are primarily driven by changes in temperature and precipitation patterns. During winter, snow accumulates and forms a protective layer over the soil and vegetation. As temperatures rise in spring, snow begins to melt, releasing stored water into the soil, which is crucial for the onset of the growing season (Chen et al., 2019). The timing of snowmelt can significantly influence plant phenology, with earlier snowmelt advancing the start of the growing season and potentially exposing plants to frost damage (Sanders and Templer, 2017). In contrast, delayed snowmelt can extend the period of soil moisture availability, benefiting plant growth and carbon uptake.

2.3 Factors influencing snow cover dynamics (e.g., climate change, geographical location)

Several factors influence snow cover dynamics, including climate change, geographical location, and local environmental conditions. Climate change is a significant driver, leading to alterations in snowfall patterns, snow depth, and the timing of snowmelt. Rising global temperatures are causing a shift from snow to rain in many regions, reducing snow cover duration and depth (Wipf et al., 2009; Slatyer et al., 2021). Geographical location also plays a crucial role, with high-latitude and high-altitude regions experiencing more pronounced changes in snow cover due to their sensitivity to temperature fluctuations (Wang et al., 2018). Additionally, local factors such as vegetation type, topography, and soil moisture can modulate the effects of snow cover on the ecosystem. For example, in temperate China, thicker snow cover and later snowmelt generally enhance soil moisture and lengthen the growing season, promoting higher carbon uptake (Chen et al., 2019). Conversely, in alpine tundra ecosystems, reduced snow depth and earlier snowmelt can lead to increased plant mortality and altered species composition.

3 Impacts on Soil Moisture

3.1 Role of snow cover in soil moisture retention

Snow cover plays a crucial role in soil moisture retention by acting as an insulating layer that prevents soil from freezing deeply and maintains higher soil moisture levels during winter. In temperate forests, reduced snow cover due to climate change can lead to increased soil freezing, which in turn affects soil moisture dynamics during the snowmelt period (Blankinship and Hart, 2012). Additionally, in arid grasslands, increased winter snowfall has been shown to enhance soil moisture in the early growing season, particularly in deeper soil layers, which is critical for plant growth and ecosystem stability (Li et al., 2020).

3.2 Mechanisms of snowmelt and water infiltration

The process of snowmelt significantly influences water infiltration into the soil. Snowmelt provides a steady supply of water that infiltrates the soil, replenishing soil moisture levels. In northern hardwood forests, snow depth manipulation experiments have demonstrated that reduced snow cover leads to lower soil moisture levels during the snowmelt period, as less snow results in less water available for infiltration (Christiansen et al., 2018). Similarly, in temperate China, thicker snow cover and later snowmelt have been associated with increased soil moisture, which positively impacts vegetation growth by extending the growing season (Chen et al., 2019).

3.3 Effects of snow cover duration and depth on soil moisture levels

The duration and depth of snow cover are critical factors that determine soil moisture levels. Longer and deeper snow cover periods generally result in higher soil moisture levels due to prolonged insulation and gradual water release during snowmelt. In Arctic ecosystems, increased snow depth and later snowmelt have been linked to improved soil and vegetation nutrient status, as well as higher soil moisture levels (Figure 1) (Moriana-Armendariz et al., 2022). Conversely, in temperate forests, shorter snow cover duration and reduced snow depth due to climate change can lead to increased soil freezing and lower soil moisture levels during the growing season.

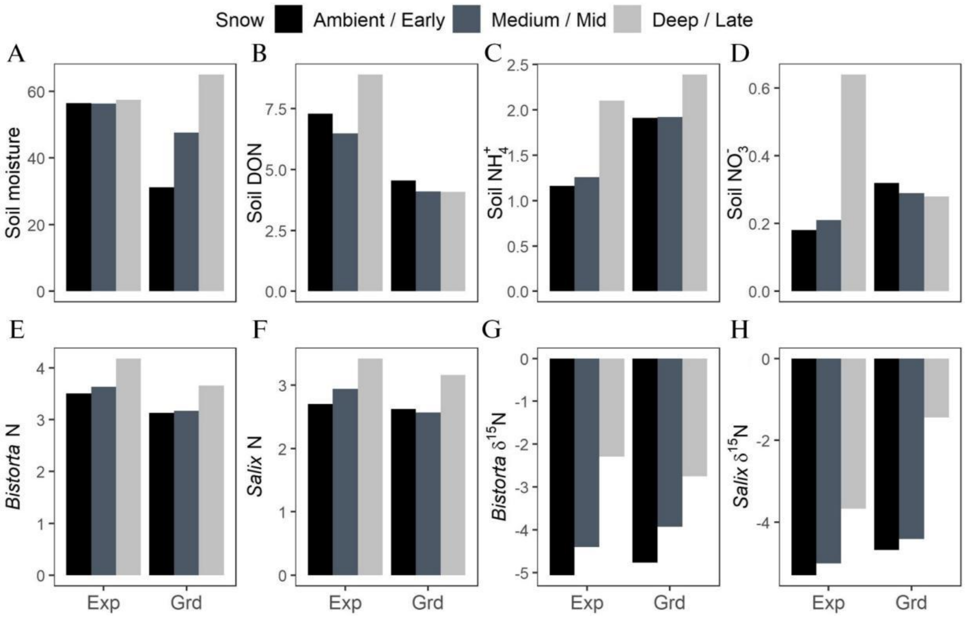

Figure 1 Comparison of estimates between gradient studies (based on snowmelt time) and experimental studies (based on snow depth) (Adopted from Moriana-Armendariz et al., 2022)

Image caption: (A) Soil moisture content as a percentage of soil moisture capacity. (B) Dissolved organic nitrogen (DON-N), (C) ammonium (NH4-N) and (D) nitrogen concentrations in the form of nitrate (NO^{+}_{3-}. N) is expressed as μgN per g of dry soil. The concentration of nitrogen in the leaves of (E) *Bistorta vivipara* and (F) *Salix polaris* is expressed as a percentage of leaf dry matter. The N of (G) *B. vivipara* and (H) *S. polaris* leaves is shown in ‰ (Adopted from Moriana-Armendariz et al., 2022)

The study by Moriana-Armendariz et al. (2022) showed the effect of snow cover duration and depth on soil moisture content (Figure 1A). In general, the deeper and longer the snow cover, the higher the moisture content of the soil. This suggests that the depth of snow cover and the time of snowmelt play an important role in regulating soil moisture, especially when the soil moisture content increases significantly at deeper or later snowmelt. This conclusion is further supported by the agreement between experimental data (Exp) and gradient studies (Grd).

3.4 Comparative analysis of soil moisture in snow-covered vs. snow-free periods

Comparative studies have shown that soil moisture levels are significantly higher during snow-covered periods compared to snow-free periods. In a study conducted in a temperate grassland, deepened winter snow cover was found to increase soil moisture in the early growing season, which in turn enhanced net ecosystem exchange of CO_2 and stabilized plant community composition and productivity (Li et al., 2020). In contrast, snow-free periods are often associated with lower soil moisture levels and increased soil freezing, which can negatively impact soil biogeochemical processes and plant growth (Chen et al., 2020).

4 Impacts on Plant Growth

4.1 Influence of snow cover on soil temperature

Snow cover acts as an insulating layer, significantly affecting soil temperature during winter. Increased snow depth can raise winter soil temperatures by approximately 3 °C, as observed in the Canadian Low Arctic mesic shrub tundra (Christiansen et al., 2018). This insulation effect can protect plant roots from extreme cold, thereby influencing plant survival and growth. Conversely, reduced snow cover can lead to lower soil temperatures, increasing the risk of frost damage to plant roots and affecting overall plant health (Drescher and Thomas, 2013; Chen et al., 2020).

4.2 Effects on plant dormancy and germination

Snow cover plays a crucial role in the dormancy and germination of plants. For cold-temperate tree species, increased snow cover has been shown to enhance post-winter sapling survival by protecting roots from frost heaving. However, the effects on seed germination can vary; some species experience decreased germination rates with increased snow cover, particularly those that disperse seeds in summer or fall (Darrouzet-Nardi et al., 2019). This variability highlights the complex relationship between snow cover and plant reproductive success.

4.3 Impact of snowmelt timing on plant growth cycles

The timing of snowmelt is critical for the initiation of plant growth cycles. Earlier snowmelt can advance the start of the growing season, but it may also expose plants to late frost events, which can negate the benefits of a longer growing season. In the Arctic, earlier snowmelt without additional spring warming has been associated with smaller plant sizes, indicating that the timing of snowmelt must coincide with favorable temperature conditions to benefit plant growth (Rumpf et al., 2014). Additionally, changes in snowmelt timing can affect soil moisture availability, further influencing plant growth dynamics (Li et al., 2020).

4.4 Case studies of plant species affected by snow cover dynamics

Several studies have documented species-specific responses to changes in snow cover. For instance, in the Swiss Alps, earlier snowmelt reduced aboveground growth in three out of four dwarf-shrub species studied, with only *Loiseleuria procumbens* benefiting from the advanced snowmelt. In the Arctic, deeper snow with later melt-out had varied effects on different plant species, underscoring the importance of species-level investigations (Wang et al., 2018). In temperate grasslands, increased winter snowfall stabilized plant community composition and productivity, particularly benefiting grasses by enhancing root biomass and soil moisture during the early growing season. These case studies illustrate the diverse and complex impacts of snow cover dynamics on plant species across different ecosystem.

5 Interrelationship Between Snow Cover, Soil Moisture, and Plant Growth

5.1 Integrated effects on ecosystem productivity

Snow cover plays a crucial role in determining soil moisture levels, which in turn significantly impacts plant growth and overall ecosystem productivity. In temperate regions, thicker snow cover and later snowmelt generally result in increased soil moisture, which can enhance the start date of the growing season (SGS) and subsequently increase spring carbon uptake (Chen et al., 2019). This is particularly important in water-limited areas where the additional moisture from snowmelt can extend the growth period and boost gross primary production (GPP). Similarly, in temperate grasslands, deepened winter snow has been shown to increase soil moisture in the early growing season, particularly in deeper soil layers, which enhances net ecosystem exchange (NEE) and stabilizes plant community composition and productivity (Li et al., 2020). However, the effects of snow cover on ecosystem productivity can vary depending on the specific environmental conditions and the timing of snowmelt.

5.2 Feedback mechanisms between snow cover and vegetation

The relationship between snow cover and vegetation is characterized by complex feedback mechanisms. For instance, increased snow depth can lead to higher soil moisture levels, which promote plant growth and extend the growing season. This, in turn, can enhance photosynthesis and carbon uptake, creating a positive feedback loop (Wang et al., 2018). However, in wetter regions, thicker snow cover with later snowmelt can delay the start of the growing season, reducing spring GPP and potentially leading to water stress during the summer if subsequent precipitation is insufficient. Additionally, changes in snow cover can influence plant community structure. For example, deepened winter snow in arid grasslands has been found to stabilize plant community composition by reducing resource competition and promoting coexistence between different plant functional groups. These feedback mechanisms highlight the intricate interplay between snow cover, soil moisture, and vegetation dynamics.

5.3 Long-term ecological impacts of changing snow cover patterns

Long-term changes in snow cover patterns due to climate change are expected to have profound ecological impacts. In Arctic and alpine tundra ecosystems, altered snow conditions can affect vegetation, plant-animal interactions, permafrost conditions, microbial processes, and biogeochemical cycling. For example, long-term deepened snow in tundra regions has been shown to promote the growth of evergreen shrubs, increase aboveground vascular plant biomass, and reduce soil carbon and nutrient pools (Christiansen et al., 2018). These changes can have cascading effects on ecosystem structure and function, potentially altering carbon and nutrient cycling processes. Additionally, reduced snow cover and earlier snowmelt can lead to advanced spring phenology in plants and increased mortality or physical injury in some species, fundamentally changing the environment and affecting ecosystem resilience (Slatyer et al., 2021).

6 Case Studies and Regional Analysis

6.1 Analysis of snow cover dynamics in different temperate regions

Snow cover dynamics significantly influence temperate ecosystems, affecting soil moisture, plant growth, and overall ecosystem productivity. In temperate China, changes in winter snow depth and snowmelt dates have been shown to impact vegetation gross primary production (GPP). Thicker snow cover and later snowmelt generally result in earlier start dates for the growing season (SGS) due to increased soil moisture, enhancing spring carbon uptake in water-limited areas (Chen et al., 2019). Conversely, in wetter regions, thicker snow cover can delay SGS, reducing spring GPP (Figure 2). In semi-arid regions of China, increased winter snowfall has been found to enhance soil moisture in early spring, stabilize plant community composition, and increase net ecosystem exchange of CO_2 (NEE).

In the High Arctic, natural variations in snow depth and snowmelt timing influence soil and plant nutrient status and vegetation composition. Areas with later snowmelt have wetter soils, higher pH, and higher nutrient concentrations in plant leaves, leading to distinct vegetation compositions compared to areas with earlier snowmeltm (Moriana-Armendariz et al., 2022). Similarly, in the Canadian Low Arctic, long-term deepened snow experiments have shown increased winter soil temperatures and enhanced growth of evergreen shrubs, although this also led to reduced soil carbon and nutrient pools (Blankinship et al., 2012).

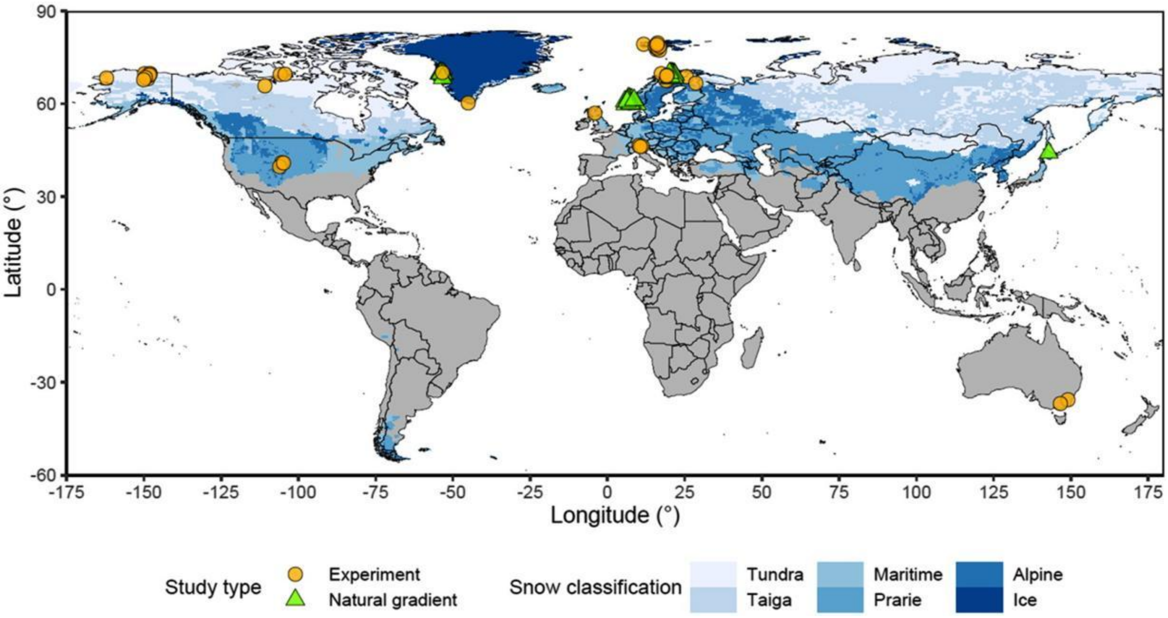

Figure 2 Study of early, middle, or late snowmelt sites of natural snowmelt (Adopted from Rixen et al., 2022)

Image caption: The yellow dots indicate snow manipulation experiments, and the green triangles indicate studies conducted along natural snow gradients. The darkest to lightest blue represents ice, mountains, grasslands, oceans, coniferous forests and tundra (Adopted from Rixen et al., 2022)

6.2 Case studies highlighting specific impacts on local ecosystems

A study from 2001 to 2015 investigated the effects of winter snow depth and snowmelt date on GPP across temperate China. It was found that thicker snow cover and later snowmelt increased soil moisture, leading to earlier SGS and enhanced spring carbon uptake in water-limited areas. However, in wetter regions, these conditions delayed SGS and reduced spring GPP. A 5-year snow manipulation experiment in a temperate grassland showed that deepened winter snow increased soil moisture in early growing season, particularly in deeper soil layers. This led to increased NEE and stabilized plant community composition, with a significant increase in root biomass (Li et al., 2020).

Long-term snowfence experiments increased snow depth, resulting in higher winter soil temperatures and enhanced growth of the evergreen shrub *Rhododendron subarcticum*. However, this also led to reduced soil carbon and nutrient pools, indicating complex interactions between snow cover and ecosystem processes. A 2-year field experiment above the treeline investigated the effects of decreased snow depth and earlier snowmelt on plant phenology and growth. Earlier snowmelt advanced the start of the growing season but also increased the number of low-temperature events experienced by plants, reducing aboveground growth in most species studied (Wipf et al., 2009).

6.3 Comparison of snow cover effects across various temperate zones

Comparing the effects of snow cover across different temperate zones reveals both commonalities and region-specific responses. In temperate China, thicker snow cover generally enhances soil moisture and spring carbon uptake in water-limited areas, while in wetter regions, it can delay the growing season and reduce productivity (Christiansen et al., 2018). In semi-arid regions like Inner Mongolia, increased winter snowfall stabilizes plant communities and enhances belowground biomass, contributing to greater ecosystem stability.

In the High Arctic, later snowmelt leads to higher soil moisture and nutrient concentrations, resulting in distinct vegetation compositions compared to areas with earlier snowmelt. Similarly, in the Canadian Low Arctic, long-term deepened snow experiments promote the growth of evergreen shrubs but reduce soil carbon and nutrient pools, highlighting the complex interactions between snow cover and ecosystem processes.

7 Mitigation and Adaptation Strategies

7.1 Approaches to mitigate the impacts of reduced snow cover

Mitigating the impacts of reduced snow cover in temperate ecosystems involves several strategies aimed at preserving soil moisture and protecting plant health. One effective approach is the manipulation of snow cover through artificial means, such as snow fences or snow redistribution techniques, which can help maintain adequate snow depth and insulation for the soil. For instance, long-term snow manipulation experiments have shown that increased snow cover can enhance soil moisture and stabilize plant community composition, thereby mitigating the adverse effects of reduced natural snowfall (Ósvaldsson et al., 2022).

Another approach is the use of mulching and other ground cover techniques to simulate the insulating effects of snow. These methods can help reduce soil freezing and maintain soil moisture levels during winter months, thereby protecting plant roots and promoting healthy growth during the growing season (Sorensen et al., 2016; Ósvaldsson et al., 2022).

7.2 Adaptation strategies for maintaining soil moisture and plant health

Adaptation strategies focus on enhancing the resilience of ecosystems to changing snow cover patterns. One key strategy is the selection and cultivation of plant species that are more tolerant to soil freezing and moisture variability. For example, certain evergreen shrubs have shown increased growth and stability under conditions of deepened snow cover, suggesting that these species may be more resilient to changes in snow dynamics (Christiansen et al., 2018).

Additionally, improving soil structure and organic matter content can enhance soil moisture retention and reduce the negative impacts of soil freezing. Practices such as adding compost or organic mulches can improve soil health and water-holding capacity, thereby supporting plant growth even in the absence of consistent snow cover (Kreyling et al., 2012).

7.3 Role of conservation practices in temperate ecosystems

Conservation practices play a crucial role in maintaining ecosystem stability and resilience in the face of reduced snow cover. One important practice is the management of grazing intensity to prevent overgrazing, which can reduce vegetation cover and snow accumulation, leading to lower soil moisture levels in the spring. Studies have shown that reducing grazing intensity or leaving some plots ungrazed can significantly increase snow accumulation and spring soil water content, thereby supporting plant health and ecosystem function (Yan et al., 2019).

Another conservation practice is the protection and restoration of natural vegetation, which can enhance snow capture and soil moisture retention. Maintaining diverse plant communities and protecting key species that contribute to snow accumulation and soil health can help buffer ecosystems against the impacts of reduced snow cover (Blume-Werry et al., 2016; Wang et al., 2018).

8 Future Research Directions

8.1 Identifying knowledge gaps and research needs

Despite significant advancements in understanding snow cover dynamics and their impacts on soil moisture and plant growth, several knowledge gaps remain. One critical area is the need for a comprehensive overview of how altered snow conditions will affect various ecosystems, particularly in the context of climate change. Additionally, there is a lack of understanding of the generality of soil biogeochemical responses to snow depth changes during the growing season and the driving mechanisms across different sites (Gavazov et al., 2017). The spatial heterogeneity in the impact of winter snow water equivalent (SWE) on vegetation greenness also needs further exploration to improve terrestrial carbon cycle models. Moreover, the long-term effects of deepened snow on plant community structure and soil biogeochemistry are not well understood, especially in tundra ecosystems. Finally, the interactions between snow cover, soil freeze-thaw cycles, and root-microbe interactions require more detailed investigation to understand their implications for soil nutrient availability and plant-soil interactions.

8.2 Potential impacts of future climate scenarios on snow cover dynamics

Future climate scenarios predict significant changes in snow cover dynamics, which will have profound impacts on temperate ecosystems. For instance, global warming is expected to alter winter snowfall patterns, leading to more shallow and discontinuous snowpacks (Blankinship and Hart, 2012). This change will likely affect soil temperature and moisture, influencing plant phenology and productivity. In mountain forests, changes in snow dynamics are expected to impact soil temperature and moisture, which are crucial for tree growth and functioning (Sanmiguel-Vallelado et al., 2021). Additionally, the reduction in snow cover is projected to increase soil freeze-thaw cycles, adversely affecting tree roots and microbial interactions. These changes will also influence greenhouse gas emissions, as variations in snow regimes and freeze-thaw dynamics contribute to differences in CO_2 and N_2O efflux between different land-use types (Chen et al., 2020).

8.3 Innovative methods for monitoring and managing snow cover impacts

To address the challenges posed by changing snow cover dynamics, innovative methods for monitoring and managing these impacts are essential. Satellite observations and climate data can be used to monitor vegetation greenness and soil moisture, providing valuable insights into the effects of winter SWE on vegetation activity (Wang et al., 2018). Experimental snow manipulation studies, such as snow addition and removal experiments, can help quantify soil biogeochemical responses and identify the variables that best explain changes in greenhouse gas emissions and nutrient concentrations. Long-term snow manipulation experiments can also provide insights into the effects of deepened snow on plant community structure and ecosystem carbon flux. Additionally, in situ studies combined with soil incubations under controlled conditions can help assess the effects of snow removal and advanced spring conditions on soil microbial communities and nutrient cycling (Gavazov et al., 2017). Finally, understanding the role of forest cover in regulating snow regimes and freeze-thaw dynamics can inform land-use management practices to mitigate the impacts of changing snow cover on soil and plant processes.

9 Conclusion

This study has highlighted the significant role of snow cover dynamics in influencing soil moisture and plant growth in temperate ecosystems. Key findings from the reviewed studies indicate that snow cover affects various ecological processes, including soil temperature, moisture availability, and nutrient cycling. For instance, deepened winter snow cover has been shown to enhance soil moisture during the early growing season, stabilize plant community composition, and increase root biomass in temperate grasslands. Conversely, reduced snow cover can lead to increased soil freeze-thaw cycles, adversely affecting root-microbe interactions and decreasing nitrification rates in northern hardwood forests. Additionally, snow cover changes can alter the timing of snowmelt, which in turn affects plant phenology and growth, as observed in alpine tundra ecosystems.

The findings underscore the importance of considering snow cover dynamics in ecosystem management and conservation strategies. Enhanced snow accumulation can stabilize arid grassland systems by reducing resource competition and promoting coexistence between plant functional groups, thereby mitigating the impacts of chronic drought during the growing season. In contrast, reduced snow cover and the resulting soil freeze-thaw cycles can impair microbial metabolism and soil organic matter cycling, potentially affecting soil nutrient availability and plant-soil interactions in mountain grasslands. Therefore, adaptive management practices that account for changing snow cover patterns are crucial for maintaining ecosystem stability and function in the face of climate change.

Snow cover plays a critical role in temperate ecosystems by regulating soil moisture, temperature, and nutrient dynamics, which in turn influence plant growth and ecosystem productivity. The reviewed studies collectively highlight the complex and multifaceted impacts of snow cover changes on ecological processes. As global climate change continues to alter snowfall patterns and snowmelt timing, understanding these dynamics becomes increasingly important for predicting and managing the future health and productivity of temperate ecosystems. Continued research and monitoring are essential to develop effective conservation strategies that can mitigate the adverse effects of changing snow cover on these vital ecosystems.

Acknowledgments

Our publisher greatly appreciates the professional opinions of the two peer reviewers.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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