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# Review of nitrogen cycling in temperate winter soil under climate change

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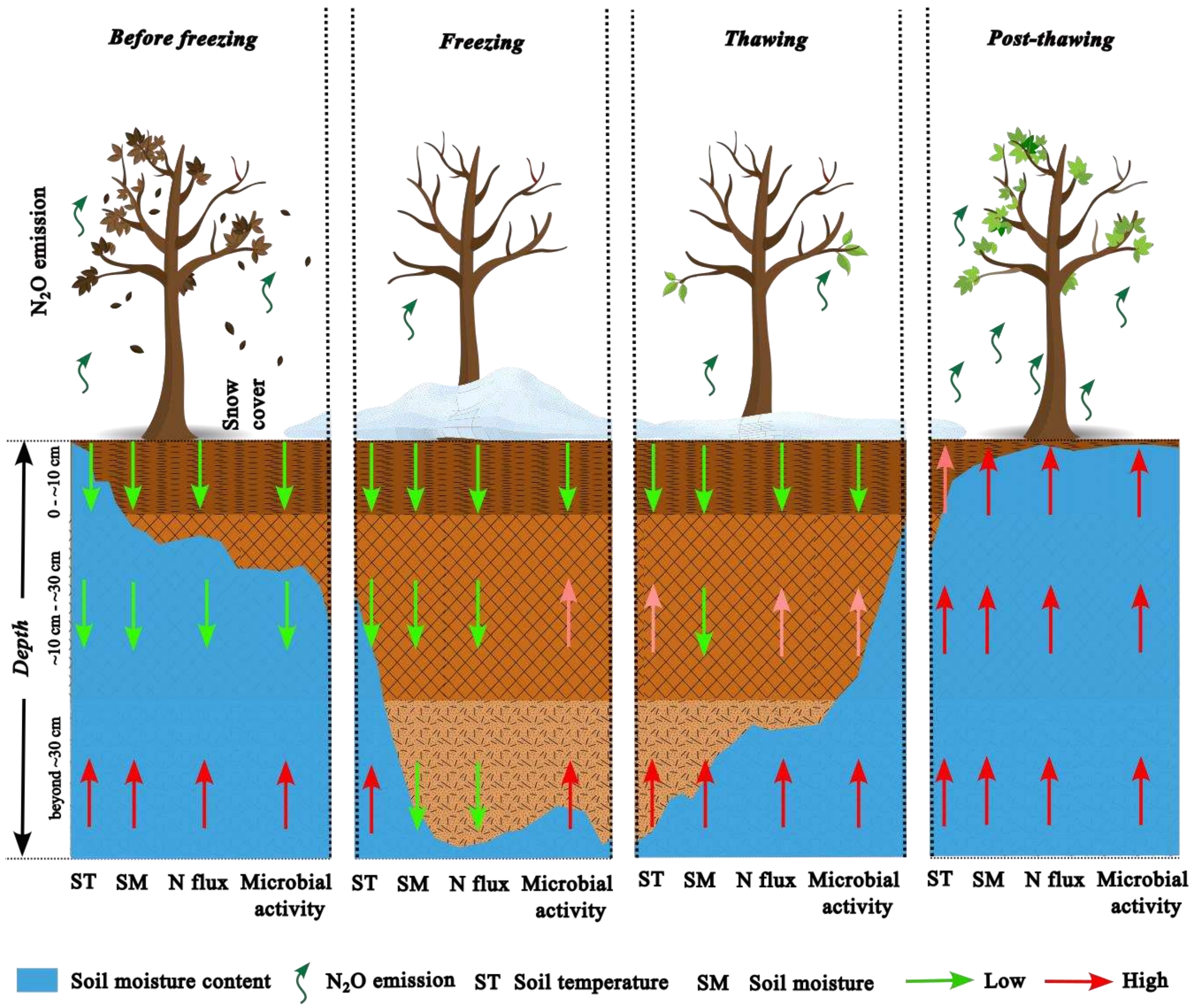
**Abstract**

In recent years the biogeochemical cycling of nitrogen (N) in soils under temperate climates during winter has received growing attention due to rising N emissions and the accumulation of N on the soil surface and in nearby water bodies. While the N cycle has traditionally been considered to slow during cold periods, recent studies show that freeze–thaw cycles (FTCs) can significantly reshape N dynamics by altering soil structure and stimulating microbial activity. This review synthesizes key abiotic drivers, such as soil moisture, temperature, and snow cover, along with anthropogenic influences that affect N transformations and transport in winter. We identified the key research gaps in the existing approaches and emphasized the need to incorporate winter N fluxes into annual N budgets to improve our understanding of terrestrial N cycling under climate change.

*Keywords- Soil temperature, soil moisture content, snow cover thickness, terrestrial nitrogen cycle, climate warming*

## Graphical Abstract



## 1. Introduction

Global warming is expected to affect overall weather patterns in temperate and high latitude regions, with particularly significant impacts on winter conditions. Soils in these regions may experience disturbances in microbial communities and soil structure. Regions that previously exhibited stable winter soil temperatures are now increasingly affected by warmer, more variable, and wetter conditions (Kreyling et al., 2020). These changes influence the release and mobility of nutrients in the environment. Because biogeochemical cycles are temperature-sensitive, they may be substantially altered under shifting winter climate regimes.

The release of nutrients, particularly nitrogen (N) and phosphorus (P), along with carbon (C), has been widely observed in temperate regions during winter. Elevated seasonal concentrations of nitrate ($NO_3^-$) in water bodies, surface accumulation of nitrates and other salts, and enhanced emissions of nitrous oxide ($N_2O$) in early spring point to intriguing dynamic processes driving these patterns (Gao et al., 2015; Johnson and Stets, 2020; Kreyling et al., 2020; Gao et al., 2021). The accumulation and movement of N into groundwater could potentially impair water quality. Therefore, identifying the key factors which influence winter N production and its transport within soil strata is essential.

The global averaged temperature has reached approximately 1ºC above pre-industrial levels in 2017, increasing at 0.2ºC/decade according to Intergovernmental Panel for Climate Change (IPCC) (Allen et al., 2018). Climate change-driven warming is expected to increase the number of snow-free days, increase the frequency of freeze-thaw cycles (FTC), and reduce the extent of frozen soils in mid- and high-latitudes (Henry, 2007; Peng et al., 2016; Kreyling et al., 2019; Li et al., 2021). The accumulation and movement of N species through the soil profile to groundwater may impact its quality over different timescales, depending on the prevailing temperature dynamics (cycling frequency), soil biogeochemical properties (reactive N content), catchment hydrology (residence time) and processes that attenuate N compounds. It is crucial to identify the factors which affect winter N production and its direction of movement within soil (Urakawa et al., 2014). This review focuses on the biogeochemical cycling of N during winter, emphasizing both natural drivers and anthropogenic practices that influence the fate and transport of soil N compounds under present climate warming conditions.

The soil N cycle (Fig. 1) is largely influenced by factors such as soil moisture content, organic matter, pH, porosity, and soil temperature. During winter decreases in air and soil temperatures and the freezing of soil moisture tend to slow N transformations. However, soil FTCs are known to alter the N cycle significantly (Marion, 1995; Li et al., 2017; Wang et al., 2020; Yin et al., 2024). FTCs can: (i) change the soil aggregate structure, modifying porosity and hydraulic conductivity; (ii) increase solute concentrations in soil pore water; and (iii) influence microbial activity (Wang et al., 2020).

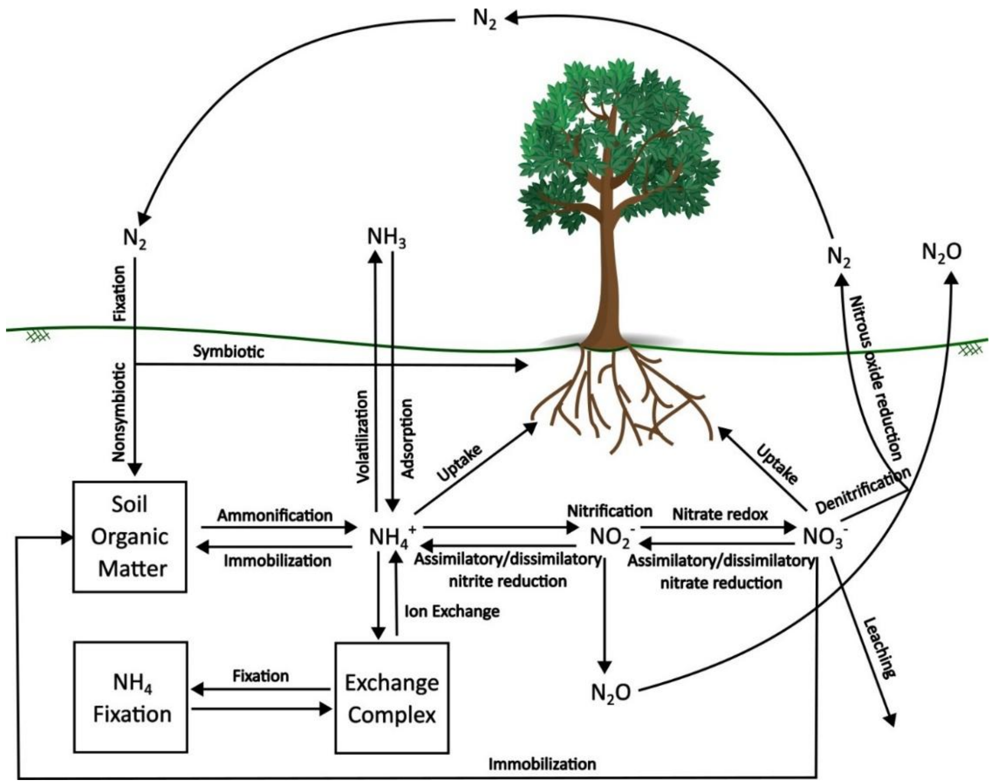



Fig. 1. Terrestrial nitrogen cycle (adapted from Marion, 1995; Kuypers et al., 2018).

The porous structure of the soil undergoes repeated phase transitions and chemical reactions during FTCs. The formation and expansion of ice crystals during freezing can enlarge pore spaces, impacting saturated hydraulic conductivity, bulk density, infiltration rates and soil aggregate stability (Wang et al., 2012; Lai et al., 2017). These physical changes, combined with chemical and microbial responses, affect the N distribution. Although microbial activity is typically reduced in frozen soils, it is not entirely halted as enzymatic processes can persist at subzero temperatures (Ekwunife et al., 2022).

This review aims to integrate these perspectives, with a specific focus on how winter climate change and FTCs influence *in situ* nitrogen biotransformation and the export of nitrogen species to the environment.

- Section 2 outlines the physicochemical and biological factors that influence nitrogen fluxes under FTCs.

- Sections 3 and 4 discuss the role of land use and anthropogenic activities.
- Section 5 presents identified research gaps, recommendations, and suggestions for future work.

While existing reviews and meta-analyses have addressed microbial processes, chemical transformations and physical mechanisms affecting N dynamics individually (Matzner and Borken, 2008; Kurylyk et al., 2014; Liu et al., 2024), others have focused on the effects of land use, meteorological factors (e.g., precipitation and snow fall), presence or absence of vegetation, plant root N uptake, and snow cover in late winter/early spring (Rennenberg et al., 2009; Ollivier et al., 2011; Williams et al., 2015; Zhu et al., 2015). This review integrates these perspectives, with a specific focus on how winter climate change and FTCs influence *in situ* N biotransformation and the export of nitrogen species to the environment.

## 2. Effect of FTCs on different stages of the N cycle

Nitrogen transformation during a FTC occurs in three distinct stages: freezing, thawing and post-thawing (Müller et al., 2002). The freezing stage is characterized by a decrease of the soil temperature below 0ºC, with the formation of ice crystals in pore spaces creating a downward movement of the freezing front. At this stage the soil layers below the freezing front still contain unfrozen soil pore water (Brooks et al., 2011). In this stage, ammonium ($NH_4^+$) and $NO_3^-$ concentrations can increase as unfrozen soil moisture, along with solutes, is drawn towards the freezing front (Müller et al., 2002; Liu et al., 2022). Soil freezing is considered analogous to soil drying and creates a strong sink for the upward movement of water. Chemical potentials of water due to gradients in hydrostatic pressure, solute concentration and temperature create a strong thermodynamic sink for water at the freezing front (Marion, 1995; Congreves et al., 2018; Li et al., 2023).

The thawing stage occurs as the soil temperature approaches 0°C and ice within the soil matrix starts to melt. Under these conditions $NO_3^-$ is no longer released but the $NH_4^+$ concentration can increase due to mineralization of the soil organic matter (Marion, 1995). During the post-thawing period the temperature rises above 0°C and the rate of N mineralization tends to decrease, while nitrification rates increase substantially. Nitrification during post-thawing conditions has been related to both autotrophic and heterotrophic processes (Müller et al., 2002; Yang et al., 2020). $N_2O$ is produced in deeper soil layers and is converted to $N_2$ by the time it reaches the soil surface. The depletion of $NH_4^+$ and organic N occurs during the post-thaw stage. High soil moisture content from snow melt leads to soil saturation and the development of anaerobic conditions (Peng et al., 2019; Ekwunife et al., 2022). $NO_3^-$ is mobilized with soil moisture and may accumulate at the soil surface or be transported to adjacent water bodies (Liu et al., 2022). In addition, thawing and post-thawing stages result in an increase in infiltration and subsurface flow. As much as 86% of thawed water has been observed to contribute to subsurface flow from 30 cm depth (Zhang et al., 2024). During this stage, leaching of $NO_3^-$ to groundwater is likely to occur (Taylor and Parkinson, 1988; Joseph and Henry, 2008). Understanding both the direction and magnitude of the nitrogen flux during FTCs is critical for effective nutrient management. The commonly identified factors influencing N transformation and transport under these conditions are discussed in the following subsections.

### ***2.1. Soil moisture and soil temperature***

Unfrozen water moves from a high-moisture zone to low-moisture zone carrying solutes ($NO_3^-$ and other salts) during a FTC (Marion, 1995). A high moisture content due to thawing or the presence of antecedent moisture can result in anaerobic conditions, which lead to the production $N_2O$ through denitrification (Congreves et al., 2018; Sennett et al., 2024). During freezing solutes move upwards towards the freezing front by convection, while a concentration gradient of the unfrozen soil water between the frozen and unfrozen area drives downward diffusion of solutes. Convection and diffusion mechanisms induce the movement of soil solutes in opposite directions, with the final direction of soil solutes determined by the relative strength of the two processes (Wang et al., 2022). A coupled heat and water model study by Zhang et al. (2021) showed upward moisture migration from a depth of 1.5 m. Soil moisture is an important driver of overall microbial activity. Microbial biomass has been reported to vary along moisture gradients at a catchment scale (Brockett et al., 2012). Studies made in agricultural fields with dry and wet conditions under FTCs showed a higher release of $NH_4^+$ and $NO_3^-$ for wet fields than in dry fields (Zhao et al., 2017; Kong et al., 2023).

A study by Kaštovská et al. (2022) in an Alpine meadow found that even a short-term increase in air temperature of 2°C can accelerate nutrient cycling. Air temperature can directly influence soil temperature at shallow depth (approx. 5 cm) in the absence of vegetation or snow cover (Edwards et al., 2006; Soong et al., 2020). Soils within mid- and high-latitudes experience a warm winter temperature, thus influencing nutrient cycling (Kreyling et al., 2019; Sahoo, 2022). Soil temperature influences soil moisture distribution and migration during FTCs (Wu et al., 2015a). Soil temperature gradients greater than 0 can be observed between 0-100 cm depth (Wu et al., 2023).

As temperatures rise during thawing and post-thawing stages, concentrations of $NH_4^+$ and $NO_3^-$ in pore water can increase due to enhanced release from soil organic matter (Ouyang et al., 2013; Wang et al., 2020). Soil moisture and temperature directly affect the size of microbial populations, thus influencing soil enzyme activity (Wu, 2020; Lin and Hernandez-Ramirez, 2022). Soil microbial activities are reported to be functional during FTCs. During the freezing stage, $N_2O$ emissions can result from soil enzyme activities. However, as the soil temperature increases during the thawing stage, the release of microbial biomass nitrogen (MBN) due to microbial lysis can subsequently add to the $N_2O$ production due to high microbial activity (Peng et al., 2019). Mild cooling temperature (≥ -5ºC) during FTCs do not generate significant N products (Zhang et al., 2022c). Laboratory-based FTC studies usually freeze soil at ≥-20ºC, which can stop microbial activity (Ejack and Whalen, 2021). Microbial communities show higher sensitivity to rapid freezing compared to slower freezing rates (Xu et al., 2016; Gao et al., 2021). Soil temperature fluctuations can damage plant roots and, together with microbial lysis, result in excess nutrient release. Reduced root uptake may result in the movement of N products with soil moisture (Kreyling et al., 2020).

### *2.2. Snow cover*

The presence or absence of snow cover can impact soil temperature and moisture content, which in turn affect microbial activity and the biogeochemical cycling of N (Rixen et al., 2008; Zhao et al., 2018; Green et al., 2022; Xu, 2022). Snow cover is a thermal insulator and dissociates soil temperature from the atmospheric temperature (Brooks et al., 2011). Soil microbes slowly adapt to low temperatures (Smith et al. 2010). Soil temperature, number of FTCs and net N mineralization are closely correlated with the depth and duration of winter snow cover (Mellander et al., 2007; Ekwunife et al., 2022).

Studies by Brooks et al. (2011) and Shibata et al. (2013) have shown that thick snow cover can facilitate microbial N mineralization. Microbial activity continued below the freezing front and surface snow cover protects it from extreme low temperatures (Coxson and Parkinson, 1987). In contrast, snow-free winters have been associated with increased $NH_4^+$ and $NO_3^-$ concentrations in soil, as well as elevated $N_2O$ emissions (Matzner and Borken, 2008; Brooks et al., 2011; Zhao et al., 2018; Yin et al., 2024).

### *2.3. Soil pH and salinity*

Soil pH along with moisture content, temperature, and frequency and duration of FTCs controls soil microbial N transformation (Shibata, 2016). Soil $N_2O$ emissions are positively correlated with pH during FTCs (Osei et al., 2024). Deng et al. (2024) suggested that pH increased with decrease in soil moisture content. Frozen soil inhibits soil microbial activity thus leading to increase in pH. Alternately FTCs have been found to increase the quantity of exchangeable $NH_4$-N; freezing increases adsorbed bases, thus increasing pH during the freezing stage than in subsequent stages (Marion, 1995).

Salt accumulation in shallow soil layers due to upward migration of solutes during FTCs increases the soil salinity (Cary and Mayland, 1972; Gray and Granger, 1986; Liu et al., 2021; Wang et al., 2022). In this context, evaporation during post-thawing enables salt migration to the soil surface (Liu et al., 2021). The constituent salts in the soil pore water can have different eutectic temperatures, such that salts with a higher eutectic temperature in the solution precipitate, while salts with lower eutectic point temperature remain in the solution. FTCs thus affect soil quality as well as soil structure. Soils undergoing freezing ≤ -10°C may precipitate $Na_2SO_4$ (eutectic temperature -1.2°C), while salts like NaCl (eutectic temperature -21.2°C) may exist in the solution (Wang et al., 2022).

### *2.4. Soil texture*

Soil texture and antecedent moisture content affect infiltration rates. FTCs can influence infiltration rates by affecting soil structure (Yang et al., 2023). The finer the soil texture, the greater the capillary rise height and water migration during FTCs (Lyu et al., 2023). Studies by Gray and Granger (1986) and Wu et al. (2015b) examining various soil solute fluxes under FTCs showed that large fluxes can occur in light-textured soils (e.g., silt loam). Dry clay soil exhibits higher infiltration rates than other soil during FTCs, but structural disturbances caused in the process may result in clogging of pores, thus reducing soil permeability (Fouli et al., 2013).

### *2.5. Organic matter content and microbial activity*

Decomposition of soil organic matter by microbes during winter is the primary source of N products (Freppaz et al., 2007; Li et al., 2017; Kreyling et al., 2020; Tang et al., 2022; Wang and Hu, 2024). The quality and quantity of organic matter affects N mineralization (Congreves et al., 2018). Frequent and rapid FTCs can have a damaging effect on the soil microbial community (Han et al., 2018). The ability of the microbial community in nitrogen fixation and denitrification is drastically impacted over repeated FTCs, gradually decreasing the microbial biomass. The soil biotic composition of warmer regions has shown adaptability and is relatively less responsive to high temperature fluctuations during FTCs (Kreyling et al., 2020). FTCs occurring in organic matter-rich soil within mid- and high-latitude zones are reported to increase N production compared to soils in warmer regions (Kreyling et al., 2020; Kazmi et al., 2023).

Nitrogen fixation and denitrification processes are dependent on microbial activity. Soil temperature and moisture directly affect the size of the microbial population and their enzyme activity during FTCs (Wu, 2020). Yang et al. (2020) found winter drought can decrease microbial biomass. During the freezing stage, temperature-sensitive microbes in the topsoil (0-10 cm) perish (Zhao and Hu, 2023). Snow cover provides an insulation during the freezing stage and a substantial number of microbes can survive and maintain relatively high activity under snow cover (Groffman et al., 2011; Shibata et al., 2013; Li et al., 2017; Isobe et al., 2022; Jiang et al., 2024; Kaštovská et al., 2022).

Microorganisms active during winter are classified into winter-adapted, snowmelt-specialist and spring-adapted by Sorensen et al. (2020), based on their population during the three stages of a FTC. Different microorganisms contribute to the overall N biogeochemical process during winter. Soil fungi are reported to be more active than bacteria during FTCs in deep soil layers (Starke et al., 2016; Sorensen et al., 2018; Sorensen et al., 2020; Jiang et al., 2024). Isobe et al. (2018) observed an increase in the population of nitrifying bacteria in mid-winter and in denitrifying bacteria and fungi during thawing and post-thawing stages in temperate forests.

### *2.6. Frequency and duration of FTCs*

Climate change-induced warming is expected to increase the frequency and magnitude of FTCs, thus leading to the disturbance of the soil biota and release of nutrients (Kreyling et al., 2020). Frequent FTCs can reduce the soil snow cover, which can enhance $N_2O$ emissions and even $NO_3^-$ leaching to groundwater (Peng et al., 2019; Green et al., 2022; Pastore et al., 2023). Soil texture may be affected due to frequent freezing and thawing of pore water. Increases in permeability due to the disturbance of the soil pore structure can result in preferential flow and an increase in the extent of groundwater and surface water contamination by N compounds (Fouli et al., 2013).

The first thaw cycle has been reported to have a higher mineralization rate than later FTCs (Otgonsuren et al., 2020; Kong et al., 2025). Repeated FTCs accelerate the decomposition of above ground litter, and induce changes in microbial activity (Coxson and Parkinson, 1987; Taylor and Parkinson, 1988; Congreves et al., 2018). Studies by Teepe et al. (2001), Gao et al. (2015), Sanders-DeMott et al., (2018) and Gao et al. (2021) indicate that prolonged intervals between freezing and thawing can suppress soil enzymatic activity and delay $N_2O$ flux peaks, which often drop within one to two days after thawing.

## 3. Impact of FTCs on different types of land use

Biogeochemical cycling of N during winter has been examined across various land-use types in mid- and high-latitude regions. Table 1 summarizes the key factors identified in the literature as influencing N fluxes during FTCs in this context. The most important factors are the winter soil moisture and soil temperature, which influence soil microbial activity (as discussed in Section 2). Different land-use patterns vary in their organic matter content, thus affecting the microbial activity and in turn create significantly different rates of N cycling. Furthermore, anthropogenic activities may add to the accelerated N production and flux. The following sections discuss common anthropogenic activities which have been reported to influence N production during winter.

Table 1. Summary of FTC effects across different land-use types and soil types, and the most influential factors associated with N flux during winter

| Type of Land Use | Soil type | Factors influencing N flux during winter | References |
|---|---|---|---|
| Agriculture land | MP | Soil moisture, soil temperature | Wang et al. (2020) |
| | Silt loam | Soil moisture, salt content | Wu et al. (2015b) |
| | Silt loam | Soil temperature, microbial activity | Souriol and Henry (2024) |
| | Silt clay loam | Microbial activity | Hu et al. (2024) |
| | MP | Soil moisture, microbial activity | Wang et al. (2020) |

| | | | |
|---|---|---|---|
| | MP | Soil moisture | Liu et al. (2022) |
| | Clay | Soil moisture, microbial activity | Lin and Hernandez-Ramirez (2022) |
| | MP | Soil moisture, soil texture, microbial activity | Ekwunife et al. (2022) |
| | Sandy loam | Soil moisture, soil temperature, precipitation, snow cover | Sennett et al. (2024) |
| | MP | Soil moisture, soil temperature, soil texture | Gray and Granger (1986) |
| | Sandy loam | Duration and frequency of FTCs, microbial activity | Ejack and Whalen (2021) |
| | - | Soil moisture, soil temperature, duration of FTCs | Zhao et al. (2017) |
| | Clay and loam | Soil moisture, soil temperature | Wang et al. (2022) |
| | | | |
| Grassland | MP | pH, soil texture, temperature, duration and depth of FTCs, microbial activity | Deng et al. (2024) |
| | MP | Microbial activity | Wang and Hu (2024) |
| | MP | Soil moisture, pH, microbial activity | Jiang et al. (2024) |
| | MP | Intensity and frequency of FTCs | Gao et al. (2015) |
| | MP | Soil moisture, soil temperature, organic matter, microbial activity | Andrade-Linares et al. (2021) |
| | MP | Snow cover, microbial activity | Gavazov et al. (2017) |
| | | | |
| Forest | MP | Snow cover, microbial activity | Li et al. (2017) |
| | MP | Soil moisture, soil temperature, snow cover, microbial activity | Wu (2020) |
| | MP | Soil moisture, soil temperature, microbial activity | Kazmi et al. (2023) |
| | MP | Microbial activity | Peng et al. (2019) |
| | MP | Intensity and frequency of FTCs | Gao et al. (2021) |
| | Sand | Soil temperature, snow cover, microbial activity | Mellander et al. (2007) |
| | - | Microbial activity | Lí et al. (2024) |
| | Sandy silt, silty sand | Soil moisture, soil temperature, microbial activity | Weigel et al. (2021) |
| | - | Snow cover | Wipf et al. (2009) |
| | | | |
| Desert | MP | Snow cover, frequency of FTCs | Yin et al. (2024) |
| | MP | Snow cover, microbial activity | Zhao et al. (2018) |
| | MP | Microbial activity | Kimura and Okuro (2024) |
| | | | |

| | | | |
|---|---|---|---|
| Wetland | - | Soil temperature, snow cover, precipitation, microbial activity | Ding et al. (2023) |

(MP = multiple sample points)

### 3.1. Movement of N fluxes due to FTCs

Thawing and post-thawing stages are associated with high export of $NO_3^-$ into water bodies by overland flow (Liu et al., 2022; Zhao et al., 2017). The topography of a region plays an important role in controlling the discharge of snowmelt runoff (Park et al., 2010). Changes in stream chemistry during the thawing stage can be observed due to N inputs from land. Dissolved N may leach into groundwater, eventually reaching streams as subsurface discharge. Alternatively, $NO_3^-$ can accumulate in groundwater as legacy N (Green et al., 2022).

In parallel, $N_2O$ emissions to the atmosphere enhance the greenhouse effect (Liu et al., 2023; Peng et al., 2019). In addition, FTCs may result in the release of amino acids in soils during early spring, which can be subsequently used by plants as an N source (Inselsbacher et al., 2014).

### 3.2. Management practices before and during winter which contribute to N fluxes

#### Fertilizer application and snow removal

Fertilizer application during autumn is a common practice in prairie states, such as those in the United States. Nitrogen amendments increase N mineralization and soil respiration. However, elevated rates of winter N mineralization in the absence of plant demand may result in the loss of this N from the system (Contosta et al., 2011; Zong et al., 2018; Geng et al., 2019; Zhang et al., 2022b).

Snow removal has been shown to increase $NO_3^-$ and $NH_4^+$ concentrations in soil pore water (Viglietti et al., 2014; Zhao et al., 2018). Snowpack acts as an insulation layer, protecting the soil from extreme cold and thus maintaining a relatively warm environment for soil microbial activity (see Section 2.2). Bokhorst et al. (2013) and Li et al. (2017) observed that snow removal increased the mortality of fine plant roots and soil microbes. In addition, plots without snow cover exhibited lower denitrification enzyme activity compared to those under snow, indicating the importance of snowpack in sustaining microbial nitrogen transformation during winter.

***Cover crops***

Studies by Zhang et al. (2022a) and Heuchan et al. (2024) on adding crop residues to soil after the autumn harvest showed that FTCs significantly changed the microbial community in the straw-amended soil considered. Soil microbes in the amended soil were less resistant to freeze-thaw stress and perished, releasing nutrients to the soil. These findings highlight the potential for organic amendments to modify soil biogeochemistry under winter conditions. Cover crops were found to retain soil N under FTC conditions. Lu et al. (2015) investigated the influence of grassland management practices on nitrogen dynamics during FTCs. Grazing was found to reduce $N_2O$ production by 36.8%, while mowing enhanced emissions during FTCs. This contrast was attributed to a greater increase in microbial population in mowed plots compared to grazed areas, which likely stimulated microbial activity and nitrogen transformation during FTCs. Cover crops (or frost-tolerant crops) have been used as a best management practice in regions which witness mild winters (≤-4°C). However, growing cover crops in heavy frosted regions (≥-18°C) may not prove to be beneficial during FTCs owing to damage of plant cells and increase in emission of $N_2O$ (Cober et al., 2018; Olofsson and Ernfors, 2022).

***Artificial soil warming and the application of biochar***

Artificial soil warming during winter has been shown to promote N mineralization due to the increase in soil temperature (Zong et al., 2018). However, due to low-temperature conditions in the atmosphere, microbial retention of nutrients is limited, increasing the risk of N losses through leaching or gaseous emissions (Liu et al., 2023).

Biochar amendment has been proposed as a strategy to modulate N cycling during FTCs. Fu et al. (2019) and Wang et al. (2024) found that applying approximately 2% biochar by weight to soil can help maintain the inorganic N content of the soil, affecting the N mineralization rate and ultimately plant growth. Biochar application was found to inhibit soil water migration, reduce $NH_4^+$ concentrations, and increase $NO_3^-$ levels during FTCs.

## 4. Other abiotic factors affecting N fluxes during FTCs

Winter rain events can reduce or delay snow accumulation, leading to so-called 'Rain on Snow (ROS)' events. These events alter the insulating properties of snow cover and delay its establishment on the soil surface. Viglietti et al. (2014) observed that late snow accumulation can cause a significant increase in soil pore water $NO_3^-$ during the spring and summer seasons, suggesting a possible reduction in plant uptake caused by root damage. FTCs coupled with winter rain events can loosen the soil structure, subsequently eroding nutrient-rich sediments (Inamdar et al., 2018; Tang et al., 2019).

Winter drought can also be a major abiotic stressor affecting N dynamics. Yang et al. (2020) found severe drought during winter can alter microbial community structure in temperate semi-arid grasslands. Decreased snow cover can damage the below ground root system and microbial biomass (See Section 2.2). Most of the inorganic N surplus may be recycled via enhanced heterotrophic microbial assimilation of $NO_3^-$ and $NH_4^+$ under winter drought conditions.

## 5. Conclusions

This review has focused specifically on studies conducted in temperate climates. Research related to permafrost regions and the effects of climate warming on biogeochemical processes in these zones requires a separate and dedicated analysis, which is beyond the scope of the present review.

Understanding how climate warming influences the fate and transport of N in soil is of critical importance. Based on the reviewed literature, several key research gaps emerge:

1. *Disciplinary separation of winter N transport research*: most studies approach winter N transport either from a hydrogeological or a biogeochemical perspective. However, N dynamics during winter seasons are influenced by a combination of physical, chemical, and biological processes. A more integrated approach that accounts for these interactions would improve predictions of soil N availability in temperate region soils.

2. *Limited studies on multiple FTCs*: research on how repeated FTCs affect soil structure and microbial communities remains scarce. Since soils often undergo multiple FTCs during winter, understanding their cumulative effects is essential for accurately assessing winter N fluxes.

3. *Neglect of flux directionality*: the direction in which N moves (e.g. toward groundwater, surface runoff or atmospheric emission) has received limited attention. Investigating how climatic and soil conditions influence the N flux direction could help inform better soil and water resource management strategies.

These research gaps offer opportunities to advance our understanding of N cycling during winter. Climate change-induced warming has led to higher availability of N in winter across temperate latitudes. While this increased N may be short-lived and limited to the early growing season, the associate N fluxes to the atmosphere and waterbodies could have lasting impacts.

This review highlighted the most common biotic and abiotic factors influencing N dynamics during winter. Most existing studies have focused on single FTC events, limiting our understanding of how the duration and intensity of temperature fluctuations shape N cycling. The thickness and persistence of snow cover emerge as dominant controls on these processes. While many studies have addressed $N_2O$ emissions and microbial activity in this context, broader measurements of N cycle products would provide a more comprehensive view of winter soil biogeochemistry.

Interdisciplinary collaborative research will be essential to address these complexities. Given the variability in soil properties across regions, further studies on FTCs across diverse soil types are needed to understand how climate change affects terrestrial processes that regulate N export from soils to both surface water and groundwater systems.

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## Authors' contributions

*Conceptualization, writing, reviewing, and editing:* M. Sahoo, D. Baù, and S. Thornton; *Supervision:* D. Baù and S. Thornton.

**Competing interests**

The authors declare that they have no known competing interests that could influence the work reported in this paper.

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