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25 **Review of nitrogen cycling in temperate winter soil under climate change**

26 **Abstract**

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

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

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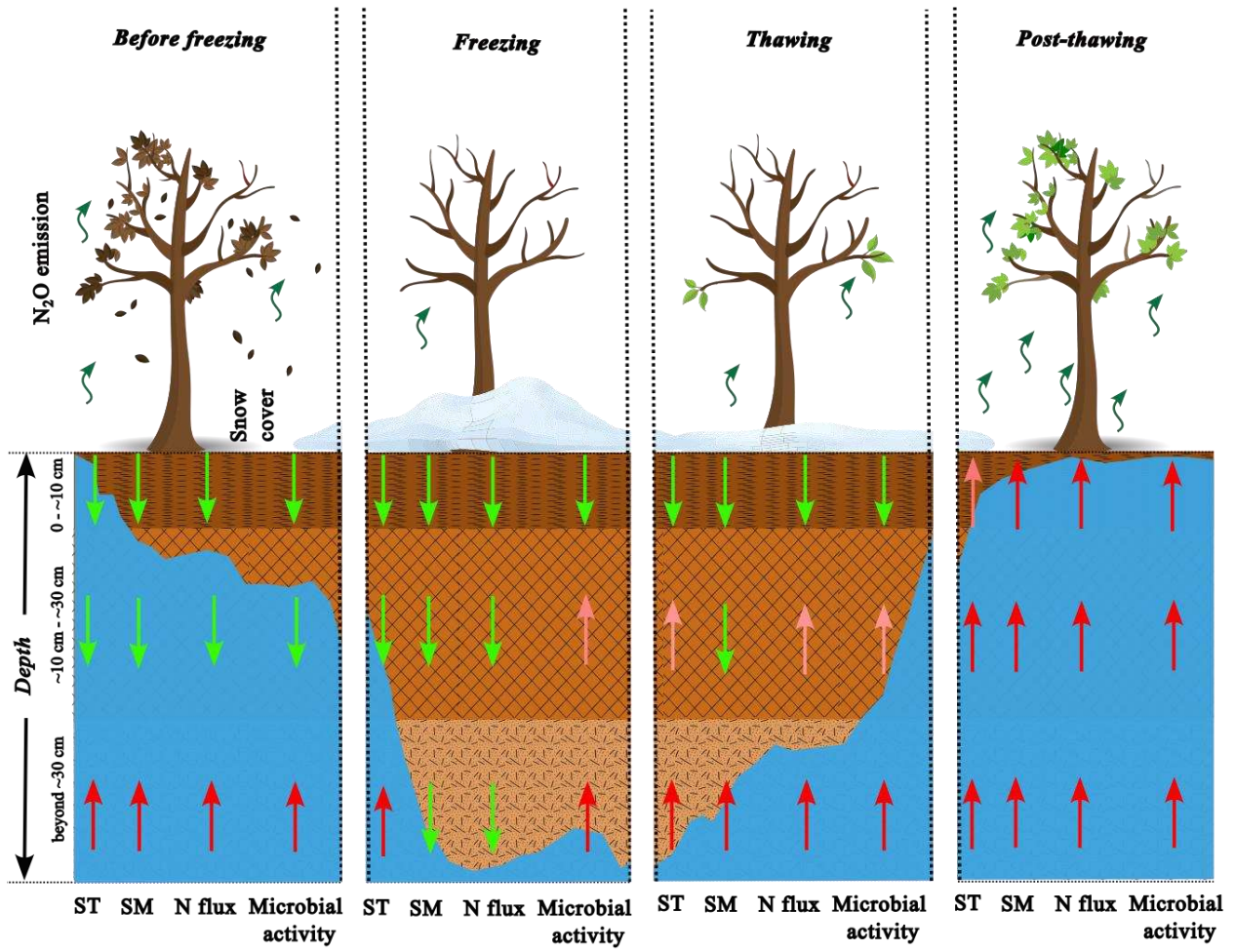
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Graphical Abstract



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Soil moisture content
 N₂O emission
 ST Soil temperature
 SM Soil moisture
 Low
 High

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57 1. Introduction

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

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

74 The global averaged temperature has reached approximately 1°C above pre-industrial
75 levels in 2017, increasing at $0.2^\circ\text{C}/\text{decade}$ according to Intergovernmental Panel for Climate
76 Change (IPCC) (Allen et al., 2018). Climate change-driven warming is expected to increase
77 the number of snow-free days, increase the frequency of freeze-thaw cycles (FTC), and
78 reduce the extent of frozen soils in mid- and high-latitudes (Henry, 2007; Peng et al., 2016;
79 Kreyling et al., 2019; Li et al., 2021). The accumulation and movement of N species through

80 the soil profile to groundwater may impact its quality over different timescales, depending
81 on the prevailing temperature dynamics (cycling frequency), soil biogeochemical properties
82 (reactive N content), catchment hydrology (residence time) and processes that attenuate N
83 compounds. It is crucial to identify the factors which affect winter N production and its
84 direction of movement within soil (Urakawa et al., 2014). This review focuses on the
85 biogeochemical cycling of N during winter, emphasizing both natural drivers and
86 anthropogenic practices that influence the fate and transport of soil N compounds under
87 present climate warming conditions.

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

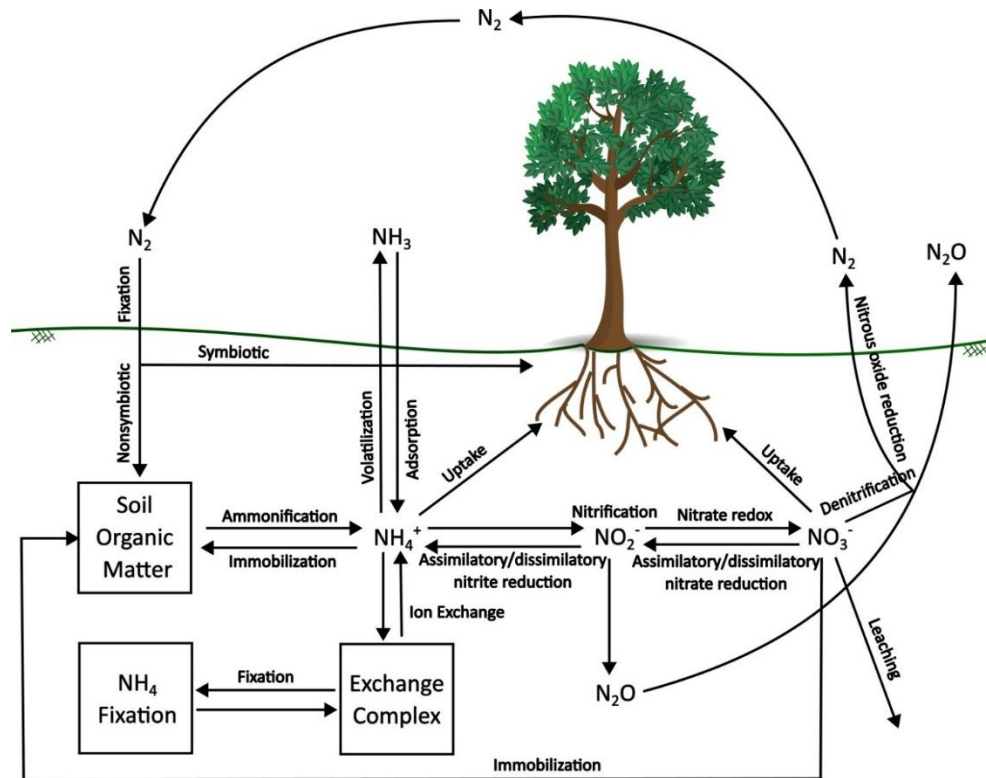


Fig. 1. Terrestrial nitrogen cycle (adapted from Marion, 1995; Kuypers et al., 2018).

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.

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

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

140 **2. Effect of FTCs on different stages of the N cycle**

141 Nitrogen transformation during a FTC occurs in three distinct stages: freezing, thawing
142 and post-thawing ([Müller et al., 2002](#)). The freezing stage is characterized by a decrease of
143 the soil temperature below 0°C, with the formation of ice crystals in pore spaces creating a
144 downward movement of the freezing front. At this stage the soil layers below the freezing
145 front still contain unfrozen soil pore water ([Brooks et al., 2011](#)). In this stage, ammonium
146 (NH_4^+) and NO_3^- concentrations can increase as unfrozen soil moisture, along with solutes,
147 is drawn towards the freezing front ([Müller et al., 2002](#); [Liu et al., 2022](#)). Soil freezing is
148 considered analogous to soil drying and creates a strong sink for the upward movement of
149 water. Chemical potentials of water due to gradients in hydrostatic pressure, solute

150 concentration and temperature create a strong thermodynamic sink for water at the freezing
151 front (Marion, 1995; Congreves et al., 2018; Li et al., 2023).

152 The thawing stage occurs as the soil temperature approaches 0°C and ice within the
153 soil matrix starts to melt. Under these conditions NO₃⁻ is no longer released but the NH₄⁺
154 concentration can increase due to mineralization of the soil organic matter (Marion, 1995).
155 During the post-thawing period the temperature rises above 0°C and the rate of N
156 mineralization tends to decrease, while nitrification rates increase substantially. Nitrification
157 during post-thawing conditions has been related to both autotrophic and heterotrophic
158 processes (Müller et al., 2002; Yang et al., 2020). N₂O is produced in deeper soil layers and
159 is converted to N₂ by the time it reaches the soil surface. The depletion of NH₄⁺ and organic
160 N occurs during the post-thaw stage. High soil moisture content from snow melt leads to soil
161 saturation and the development of anaerobic conditions (Peng et al., 2019; Ekwunife et al.,
162 2022). NO₃⁻ is mobilized with soil moisture and may accumulate at the soil surface or be
163 transported to adjacent water bodies (Liu et al., 2022). In addition, thawing and post-thawing
164 stages result in an increase in infiltration and subsurface flow. As much as 86% of thawed
165 water has been observed to contribute to subsurface flow from 30 cm depth (Zhang et al.,
166 2024). During this stage, leaching of NO₃⁻ to groundwater is likely to occur (Taylor and
167 Parkinson, 1988; Joseph and Henry, 2008). Understanding both the direction and magnitude
168 of the nitrogen flux during FTCs is critical for effective nutrient management. The
169 commonly identified factors influencing N transformation and transport under these
170 conditions are discussed in the following subsections.

171 **2.1. Soil moisture and soil temperature**

172 Unfrozen water moves from a high-moisture zone to low-moisture zone carrying
173 solutes (NO_3^- and other salts) during a FTC (Marion, 1995). A high moisture content due to
174 thawing or the presence of antecedent moisture can result in anaerobic conditions, which
175 lead to the production N_2O through denitrification (Congreves et al., 2018; Sennett et al.,
176 2024). During freezing solutes move upwards towards the freezing front by convection,
177 while a concentration gradient of the unfrozen soil water between the frozen and unfrozen
178 area drives downward diffusion of solutes. Convection and diffusion mechanisms induce the
179 movement of soil solutes in opposite directions, with the final direction of soil solutes
180 determined by the relative strength of the two processes (Wang et al., 2022). A coupled heat
181 and water model study by Zhang et al. (2021) showed upward moisture migration from a
182 depth of 1.5 m. Soil moisture is an important driver of overall microbial activity. Microbial
183 biomass has been reported to vary along moisture gradients at a catchment scale (Brockett
184 et al., 2012). Studies made in agricultural fields with dry and wet conditions under FTCs
185 showed a higher release of NH_4^+ and NO_3^- for wet fields than in dry fields (Zhao et al., 2017;
186 Kong et al., 2023).

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

195 As temperatures rise during thawing and post-thawing stages, concentrations of NH_4^+
196 and NO_3^- in pore water can increase due to enhanced release from soil organic matter
197 (Ouyang et al., 2013; Wang et al., 2020). Soil moisture and temperature directly affect the
198 size of microbial populations, thus influencing soil enzyme activity (Wu, 2020; Lin and
199 Hernandez-Ramirez, 2022). Soil microbial activities are reported to be functional during
200 FTCs. During the freezing stage, N_2O emissions can result from soil enzyme activities.
201 However, as the soil temperature increases during the thawing stage, the release of microbial
202 biomass nitrogen (MBN) due to microbial lysis can subsequently add to the N_2O production
203 due to high microbial activity (Peng et al., 2019). Mild cooling temperature ($\geq -5^\circ\text{C}$) during
204 FTCs do not generate significant N products (Zhang et al., 2022c). Laboratory-based FTC
205 studies usually freeze soil at $\geq -20^\circ\text{C}$, which can stop microbial activity (Ejack and Whalen,
206 2021). Microbial communities show higher sensitivity to rapid freezing compared to slower
207 freezing rates (Xu et al., 2016; Gao et al., 2021). Soil temperature fluctuations can damage
208 plant roots and, together with microbial lysis, result in excess nutrient release. Reduced root
209 uptake may result in the movement of N products with soil moisture (Kreyling et al., 2020).

210 2.2. *Snow cover*

211 The presence or absence of snow cover can impact soil temperature and moisture
212 content, which in turn affect microbial activity and the biogeochemical cycling of N (Rixen
213 et al., 2008; Zhao et al., 2018; Green et al., 2022; Xu, 2022). Snow cover is a thermal
214 insulator and dissociates soil temperature from the atmospheric temperature (Brooks et al.,
215 2011). Soil microbes slowly adapt to low temperatures (Smith et al. 2010). Soil temperature,
216 number of FTCs and net N mineralization are closely correlated with the depth and duration
217 of winter snow cover (Mellander et al., 2007; Ekwunife et al., 2022).

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

224 2.3. *Soil pH and salinity*

225 Soil pH along with moisture content, temperature, and frequency and duration of FTCs
226 controls soil microbial N transformation ([Shibata, 2016](#)). Soil N_2O emissions are positively
227 correlated with pH during FTCs ([Osei et al., 2024](#)). [Deng et al. \(2024\)](#) suggested that pH
228 increased with decrease in soil moisture content. Frozen soil inhibits soil microbial activity
229 thus leading to increase in pH. Alternately FTCs have been found to increase the quantity of
230 exchangeable $\text{NH}_4\text{-N}$; freezing increases adsorbed bases, thus increasing pH during the
231 freezing stage than in subsequent stages ([Marion, 1995](#)).

232 Salt accumulation in shallow soil layers due to upward migration of solutes during
233 FTCs increases the soil salinity ([Cary and Mayland, 1972](#); [Gray and Granger, 1986](#); [Liu et
234 al., 2021](#); [Wang et al., 2022](#)). In this context, evaporation during post-thawing enables salt
235 migration to the soil surface ([Liu et al., 2021](#)). The constituent salts in the soil pore water
236 can have different eutectic temperatures, such that salts with a higher eutectic temperature
237 in the solution precipitate, while salts with lower eutectic point temperature remain in the
238 solution. FTCs thus affect soil quality as well as soil structure. Soils undergoing freezing \leq
239 -10°C may precipitate Na_2SO_4 (eutectic temperature -1.2°C), while salts like NaCl (eutectic
240 temperature -21.2°C) may exist in the solution ([Wang et al., 2022](#)).

241 **2.4. *Soil texture***

242 Soil texture and antecedent moisture content affect infiltration rates. FTCs can
243 influence infiltration rates by affecting soil structure (Yang et al., 2023). The finer the soil
244 texture, the greater the capillary rise height and water migration during FTCs (Lyu et al.,
245 2023). Studies by Gray and Granger (1986) and Wu et al. (2015b) examining various soil
246 solute fluxes under FTCs showed that large fluxes can occur in light-textured soils (e.g., silt
247 loam). Dry clay soil exhibits higher infiltration rates than other soil during FTCs, but
248 structural disturbances caused in the process may result in clogging of pores, thus reducing
249 soil permeability (Fouli et al., 2013).

250 **2.5. *Organic matter content and microbial activity***

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

262 Nitrogen fixation and denitrification processes are dependent on microbial activity.
263 Soil temperature and moisture directly affect the size of the microbial population and their

264 enzyme activity during FTCs (Wu, 2020). Yang et al. (2020) found winter drought can
265 decrease microbial biomass. During the freezing stage, temperature-sensitive microbes in
266 the topsoil (0-10 cm) perish (Zhao and Hu, 2023). Snow cover provides an insulation during
267 the freezing stage and a substantial number of microbes can survive and maintain relatively
268 high activity under snow cover (Groffman et al., 2011; Shibata et al., 2013; Li et al., 2017;
269 Isobe et al., 2022; Jiang et al., 2024; Kaštovská et al., 2022).

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

278 **2.6. Frequency and duration of FTCs**

279 Climate change-induced warming is expected to increase the frequency and magnitude
280 of FTCs, thus leading to the disturbance of the soil biota and release of nutrients (Kreyling
281 et al., 2020). Frequent FTCs can reduce the soil snow cover, which can enhance N₂O
282 emissions and even NO₃⁻ leaching to groundwater (Peng et al., 2019; Green et al., 2022;
283 Pastore et al., 2023). Soil texture may be affected due to frequent freezing and thawing of
284 pore water. Increases in permeability due to the disturbance of the soil pore structure can
285 result in preferential flow and an increase in the extent of groundwater and surface water
286 contamination by N compounds (Fouli et al., 2013).

287 The first thaw cycle has been reported to have a higher mineralization rate than later
 288 FTCs (Otgonsuren et al., 2020; Kong et al., 2025). Repeated FTCs accelerate the
 289 decomposition of above ground litter, and induce changes in microbial activity (Coxson and
 290 Parkinson, 1987; Taylor and Parkinson, 1988; Congreves et al., 2018). Studies by Teepe et
 291 al. (2001), Gao et al. (2015), Sanders-DeMott et al., (2018) and Gao et al. (2021) indicate
 292 that prolonged intervals between freezing and thawing can suppress soil enzymatic activity
 293 and delay N₂O flux peaks, which often drop within one to two days after thawing.

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

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

304 Table 1. Summary of FTC effects across different land-use types and soil types, and the most
 305 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)
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(MP = multiple sample points)

306 **3.1. Movement of N fluxes due to FTCs**

307 Thawing and post-thawing stages are associated with high export of NO_3^- into water
 308 bodies by overland flow (Liu et al., 2022; Zhao et al., 2017). The topography of a region
 309 plays an important role in controlling the discharge of snowmelt runoff (Park et al., 2010).
 310 Changes in stream chemistry during the thawing stage can be observed due to N inputs from
 311 land. Dissolved N may leach into groundwater, eventually reaching streams as subsurface
 312 discharge. Alternatively, NO_3^- can accumulate in groundwater as legacy N (Green et al.,
 313 2022).

314 In parallel, N_2O emissions to the atmosphere enhance the greenhouse effect (Liu et al.,
 315 2023; Peng et al., 2019). In addition, FTCs may result in the release of amino acids in soils
 316 during early spring, which can be subsequently used by plants as an N source (Inselsbacher
 317 et al., 2014).

318 **3.2. Management practices before and during winter which contribute to N fluxes**

319 ***Fertilizer application and snow removal***

320 Fertilizer application during autumn is a common practice in prairie states, such as
 321 those in the United States. Nitrogen amendments increase N mineralization and soil
 322 respiration. However, elevated rates of winter N mineralization in the absence of plant
 323 demand may result in the loss of this N from the system (Contosta et al., 2011; Zong et al.,
 324 2018; Geng et al., 2019; Zhang et al., 2022b).

325 Snow removal has been shown to increase NO_3^- and NH_4^+ concentrations in soil pore
 326 water (Viglietti et al., 2014; Zhao et al., 2018). Snowpack acts as an insulation layer,
 327 protecting the soil from extreme cold and thus maintaining a relatively warm environment

328 for soil microbial activity (see Section 2.2). Bokhorst et al. (2013) and [Li et al. \(2017\)](#)
329 observed that snow removal increased the mortality of fine plant roots and soil microbes. In
330 addition, plots without snow cover exhibited lower denitrification enzyme activity compared
331 to those under snow, indicating the importance of snowpack in sustaining microbial nitrogen
332 transformation during winter.

333 *Cover crops*

334 Studies by [Zhang et al. \(2022a\)](#) and [Heuchan et al. \(2024\)](#) on adding crop residues to
335 soil after the autumn harvest showed that FTCs significantly changed the microbial
336 community in the straw-amended soil considered. Soil microbes in the amended soil were
337 less resistant to freeze-thaw stress and perished, releasing nutrients to the soil. These findings
338 highlight the potential for organic amendments to modify soil biogeochemistry under winter
339 conditions. Cover crops were found to retain soil N under FTC conditions. [Lu et al. \(2015\)](#)
340 investigated the influence of grassland management practices on nitrogen dynamics during
341 FTCs. Grazing was found to reduce N₂O production by 36.8%, while mowing enhanced
342 emissions during FTCs. This contrast was attributed to a greater increase in microbial
343 population in mowed plots compared to grazed areas, which likely stimulated microbial
344 activity and nitrogen transformation during FTCs. Cover crops (or frost-tolerant crops) have
345 been used as a best management practice in regions which witness mild winters ($\leq -4^{\circ}\text{C}$).
346 However, growing cover crops in heavy frosted regions ($\geq -18^{\circ}\text{C}$) may not prove to be
347 beneficial during FTCs owing to damage of plant cells and increase in emission of N₂O
348 ([Cober et al., 2018](#); [Olofsson and Ernfors, 2022](#)).

349 *Artificial soil warming and the application of biochar*

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

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

359 4. Other abiotic factors affecting N fluxes during FTCs

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

367 Winter drought can also be a major abiotic stressor affecting N dynamics. Yang et al.
368 (2020) found severe drought during winter can alter microbial community structure in
369 temperate semi-arid grasslands. Decreased snow cover can damage the below ground root
370 system and microbial biomass (See Section 2.2). Most of the inorganic N surplus may be
371 recycled via enhanced heterotrophic microbial assimilation of NO_3^- and NH_4^+ under winter
372 drought conditions.

373 5. Conclusions

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

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

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

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

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

393 These research gaps offer opportunities to advance our understanding of N cycling
394 during winter. Climate change-induced warming has led to higher availability of N in winter
395 across temperate latitudes. While this increased N may be short-lived and limited to the early

396 growing season, the associated N fluxes to the atmosphere and waterbodies could have lasting
397 impacts.

398 This review highlighted the most common biotic and abiotic factors influencing N
399 dynamics during winter. Most existing studies have focused on single FTC events, limiting
400 our understanding of how the duration and intensity of temperature fluctuations shape N
401 cycling. The thickness and persistence of snow cover emerge as dominant controls on these
402 processes. While many studies have addressed N₂O emissions and microbial activity in this
403 context, broader measurements of N cycle products would provide a more comprehensive
404 view of winter soil biogeochemistry.

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

409

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

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720 **Competing interests**

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