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Effects of winter pulsed warming and snowmelt on soil nitrogen cycling in agricultural soils: A lysimeter study

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In cold regions, climate change is expected to result in warmer winter temperatures and increased temperature variability. Coupled with changing precipitation regimes, these changes can decrease soil insulation by reducing snow cover, exposing soils to colder temperatures and more frequent and extensive soil freezing and thawing. Freeze-thaw events can exert an important control over winter soil processes and the cycling of nitrogen (N), with consequences for soil health, nitrous oxide (N_2O) emissions, and nearby water quality. These impacts are especially important for agricultural soils and practices in cold regions. We conducted a lysimeter experiment to assess the effects of winter pulsed warming, soil texture, and snow cover on N cycling in agricultural soils. We monitored the subsurface soil temperature, moisture, and porewater geochemistry together with air temperature, precipitation, and N_2O fluxes in four agricultural field-controlled lysimeter systems (surface area of 1 m^2 and depth of 1.5 m) at the University of Guelph's Elora Research Station over one winter (December 2020 to April 2021). The lysimeters featured two soil types (loamy sand and silt loam) which were managed under a corn-soybean-wheat rotation with cover crops. Additionally, ceramic infrared heaters located above two of the lysimeters were turned on after each snowfall event to melt the snow and then turned off to mimic snow-free winter conditions with increased soil freezing. Porewater samples collected from five depths in the lysimeters were analyzed for total dissolved nitrogen (TDN), nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+). N_2O fluxes were measured using automated soil gas chambers installed on each lysimeter. The results from the snow removed lysimeters were compared to those of lysimeters without heaters (with snow). As expected, the removal of the insulating snow cover resulted in more intense soil freeze-thaw events, causing increased dissolved N loss from the lysimeter systems as N_2O (from the silt loam system) and *via* NO_3^- leaching (from the loamy sand system). In the silt loam lysimeter, we attribute the freeze thaw-enhanced N_2O fluxes to *de novo* processes rather than gas build up and release. In the loamy sand lysimeter, we attribute the increased NO_3^- leaching to the larger pore size and therefore lower water retention capacity of this soil type. Overall, our study illustrates the important role of winter snow cover dynamics and soil freezing in modulating the coupled responses of soil moisture, temperature, and N cycling.

KEYWORDS

winter soil processes, cold regions, freeze-thaw cycles, agricultural soils, nitrogen cycling

1 Introduction

Historical data and projected climate trends for cold regions indicate that climate change has and will continue to contribute to warmer winters and fewer days with insulating snow cover, potentially causing increased soil freezing during the fall, winter, and spring (*i.e.,* the non-growing season) (Zhang et al., 2000; Henry, 2008; Natali et al., 2019; Rafat et al., 2022). Winter climate warming may expose soils to: 1) colder temperatures due to the loss of the insulating snowpack, 2) increased soil moisture content arising from increased precipitation and an increased frequency of intermittent snow melt events during winter, and 3) more frequent freeze-thaw cycles (FTC) (Zhang, 2005; Henry, 2008; Campbell et al., 2014). Previous studies conducted in natural and managed ecosystems have reported that microbial activity can be substantial in cold soils (Brooks et al., 1996; Yanai and Toyota, 2006; Wagner-Riddle et al., 2007; Nikrad et al., 2016). The repeated freezing and thawing of porewater in soil can impact soil structure and cause aggregate destruction, water redistribution, gas diffusivity alteration, and changes in soil microbial activity (Kay et al., 1981; Henry, 2007; Tatti et al., 2014; Gao et al., 2017; King et al., 2021). These changes also affect the chemical composition and biotic processes in seasonally snow-covered soils, which, in turn, cause changes in the turnover, retention, and export of nutrients as well as their associated water quality and ecological impacts (Henry, 2007 and, Henry, 2008; Hayashi, 2013; Kurylyk and Watanabe, 2013).

In agroecosystems, freezing and thawing cycles during the winter and spring seasons impact nitrogen (N) cycling in soils, leading to N losses in the form of nitrous oxide (N_2O) and nitrate (NO_3^-), and ultimately decreasing crop yield and contributing to increased greenhouse gas emissions and decreased water quality after runoff (Gao et al., 2017; Wagner-Riddle et al., 2017; King et al., 2021). During the winter, substantial amounts of inorganic N can be generated by soil microbes and then lost in late winter and early spring to leaching and denitrification (Ryan et al., 2000; Schimel et al., 2004). The net N mineralization observed over winter and early spring has been explained by various mechanisms, including carbon (C) limitation in the soil (as finite stocks of labile C are metabolized by the microbial community), reduced overall C:N ratios in the absence of actively growing plants (Lipson et al., 1999), the presence of a physical ice barrier limiting microbial access to new C sources (Schimel et al., 2004), and physical damage to plant roots by heavy soil freezing and subsequent reduced N uptake (Groffman et al., 2001; Tierney et al., 2001).

Limited oxygen (O_2) availability in snow-covered soils favours denitrification (*i.e.,* NO_3^- is used as an alternative electron acceptor for microbial metabolism and reduced to nitrite (NO_2^-), dinitrogen gas (N_2), nitric oxide (NO) or N_2O) (King et al., 2021). In contrast, soils that are not insulated by snow cover and are exposed to FTCs experience aggregate disruption that releases dissolved N that was previously inaccessible, which stimulates N_2O production (Matzner and Borken, 2008; King et al., 2021). In temperate agroecosystems, soil freezing and thawing during the winter and shoulder seasons (late fall and early spring) is an important control on N_2O emissions, and it is estimated 35–65% of annual N_2O emissions (Wagner-Riddle et al., 1997; Wagner-Riddle et al., 2007; Risk et al., 2013; Wagner-Riddle et al., 2017) and around 80% of N leaching losses (Jayasundara et al., 2007) can occur at these times. The projected and observed increasing frequency and intensity of FTCs could therefore result in increased N_2O production and release, contributing to climate change and ozone layer depletion (IPCC - Intergovernmental Panel on Climate Change, 2021). This hypothesis is supported by studies that have found that following extreme soil freezing during the non-growing season there are decreased concentrations of ammonium (NH_4^+) and NO_3^- in the soil coupled with decreased plant N uptake, which suggests that N is being lost due to NO_3^- leaching and N_2O release (Campbell et al., 2014). The environmental controls on these freeze-thaw-induced N_2O emissions, the relative contributions of nitrification *versus* denitrification, and the contributions by N_2O accumulated in the frozen soil *versus* N_2O produced *in situ* upon thaw, have still not been fully resolved (Risk et al., 2014; Brin et al., 2018; Congreves et al., 2018; Ghimire et al., 2020).

In this study, four lysimeter systems were used to determine the impact of winter warming and FTCs on N cycling in agricultural soils, comparing the impact on two soil textures, loamy sand and silt loam. This was achieved by imposing winter pulsed warming using infrared ceramic heaters to remove the snow cover from the surfaces of half the lysimeters for each soil type over the winter and comparing the concentrations of N species and gas fluxes to the lysimeters with ambient snow cover. Specifically, we investigated the effects of pulsed snow removal and soil texture on soil moisture and temperature and the subsequent impacts on soil N cycling responses, with a focus

TABLE 1 Physical and chemical properties of the soil in the four lysimeters (Brown, 2021).

Lysimeter	Mineral soil horizons	Sand (%)	Silt (%)	Clay (%)	Textural class	Bulk density (g cm^{-3})	Porosity (%)	Total carbon (% dry)	Inorganic carbon (% dry)	Organic carbon (% dry)	Total nitrogen (% dry)
SL-SR	Ap1	38.0	54.5	7.5	silt loam	1.53 ± 0.12	42.3 ± 4.4	2.71	0.21	2.50	0.24
	Ap2	38.0	54.5	7.5	silt loam	1.53 ± 0.12	42.3 ± 4.4	3.46	0.27	3.18	0.31
	B	44.7	40.3	15.0	loam	1.71 ± 0.08	35.6 ± 2.9	1.54	0.55	0.99	0.09
	Ck	49.4	38.1	12.5	loam	1.78 ± 0.11	32.9 ± 4.0	3.79	3.40	0.39	0.03
SL-WS	Ap1	38.0	54.5	7.5	silt loam	1.53 ± 0.12	42.3 ± 4.4	2.73	0.18	2.55	0.26
	Ap2	38.0	54.5	7.5	silt loam	1.53 ± 0.12	42.3 ± 4.4	2.27	0.11	2.15	0.21
	B	44.7	40.3	15.0	loam	1.71 ± 0.08	35.6 ± 2.9	0.48	0.04	0.43	0.03
	Ck	49.4	38.1	12.5	loam	1.78 ± 0.11	32.9 ± 4.0	1.44	1.21	0.22	<0.02
LS-SR	Ap1	79.2	17.5	3.3	loamy sand	1.71 ± 0.11	35.5 ± 4.1	0.91	0.19	0.71	0.08
	Ap2	79.2	17.5	3.3	loamy sand	1.71 ± 0.11	35.5 ± 0.41	0.79	0.05	0.74	0.08
	B	82.0	13.0	5.0	loamy sand	1.68 ± 0.09	36.6 ± 3.5	0.34	0.03	0.30	0.03
	Ck	88.8	8.7	2.5	sand	1.64 ± 0.07	38.3 ± 2.6	3.37	3.13	0.23	<0.02
LS-WS	Ap1	79.2	17.5	3.3	loamy sand	1.71 ± 0.11	35.5 ± 4.1	0.91	0.07	0.83	0.09
	Ap2	79.2	17.5	3.3	loamy sand	1.71 ± 0.11	35.5 ± 0.4	0.77	0.06	0.71	0.08
	B	82.0	13.0	5.0	loamy sand	1.68 ± 0.09	36.6 ± 3.5	0.38	0.09	0.29	0.03
	Ck	88.8	8.7	2.5	sand	1.64 ± 0.07	38.3 ± 2.6	4.20	4.28	<0.005	<0.02

on NO_3^- leaching to groundwater and N_2O emissions. We hypothesized that winter pulsed warming and the resulting increase in freeze-thaw cycles would increase NO_3^- leaching and N_2O emission. We further hypothesized that the larger pore size and lower water retention capacity of the loamy sand would result in increased NO_3^- leaching compared to in the silt loam.

2 Materials and methods

2.1 Study site

This study was performed at an agricultural site within the University of Guelph's Elora Research Station (43°38′14.9″N, 80°22′55.0″W) located in Elora, Ontario, Canada. The environmental parameters, including air temperature, precipitation, and snowfall, were recorded hourly at the Environment and Climate Change Canada Elora Weather Station. Our experiment occurred between 1 December 2020 and 30 April 2021. During this phase, air temperatures ranged from -19.7°C (21 February 2021) to 22.1°C (8 April 2021). The average air temperatures during February and April were -7.7°C and 6.4°C, respectively.

2.2 Lysimeter system

The Elora Research Station contains 18 cylindrical weighing lysimeters (Meter Scientific, Meter GmbH, Munich, Germany) installed within a 0.1 ha agricultural field. Each lysimeter is positioned in a 3 m × 10 m plot, arranged in nests of six lysimeters. The lysimeters are 1 m^2 in diameter and 1.5 m in depth and are suspended onto load cells in concrete wells, with their weights monitored every minute with ±10 g resolution. The lysimeters vary in soil type, crop rotation, and application of winter warming. For a more detailed explanation of the lysimeter systems at Elora Research Station, the reader is referred to Brown et al. (2021).

Four of the 18 lysimeters were used for the experiment to study the impact of winter warming on two soil textures: Silt Loam—With Snow (SL-WS), Silt Loam—Snow Removed (SL-SR), Loamy Sand—With Snow (LS-WS), Loamy Sand—Snow Removed (LS-SR). Two (SL-WS and SL-SR) contained silt loam (Gleyed Gray-Brown Luvisol, with 42.5 ± 5.1% sand, 46.9 ± 8.2% silt, and 10.6 ± 3.4% clay) extracted from the Elora Research Station (43°38′20″N, 80°24′37″W) which had bulk densities of 1.53 ± 0.12 to 1.78 ± 0.11 g cm^{-3} and total porosities of 35.6 ± 2.90 to 42.3 ± 4.4% (Table 1). The other two (LS-WS and LS-SR) contained loamy sand soil (Eluviated Melanic Brunisol, with 82.3 ± 4.2% sand, 14.2 ± 3.9% silt, and 3.5 ± 0.9% clay) extracted from a farm in Cambridge, Ontario, Canada (43°27′28″N, 80°20′48″W) which had bulk densities of 1.64 ± 0.07 to 1.71 ± 0.11 g cm^{-3} and total porosities of 35.5 ± 4.1 to 38.3 ± 2.6% (Table 1). Total C, inorganic C, organic C, and N of the soils in the four lysimeters are presented in Table 1, with higher C and N contents in the silt loam lysimeters (SL-WS and SL-SR) compared to in the loamy sand lysimeters (LS-WS and LS-SR).

Pulsed warming was applied during the winter frozen period to two of the lysimeters (SL-SR and LS-SR) (one loamy sand and one silt loam) using an infrared heater containing 1000 W 120v ceramic heating elements (Mor Electric ALEX Radiant Fixtures, Comstock, Michigan, United States) positioned 1 m above each lysimeter. Heaters were turned on to melt fallen snow then turned off to allow soil to freeze between 27 January 2021 and 3 March 2021. Tensiometers (Meter T8), soil moisture probes (Decagon MPS-6), and TDR sensors (Time-Pico 32) were installed in the lysimeters at -5, -10, -30, -60, and -90 cm below the soil surface to monitor soil moisture content, matric potential, and water potential, respectively, with measurements taken every 10 min. Automatic chambers (Biomet CH-V5) were installed on each lysimeter to measure surface N_2O fluxes for 20 min every 2 hours, with a trace gas analyzer (Campbell Scientific TGA200A) measuring N_2O concentrations in sampled air. The N_2O concentrations were measured using a sampling and return air system that brings air to the trace gas analyzer from the chamber while replacing it with ambient air of known concentration. Addition of ambient air to the chamber headspace causes a dilution of N_2O, which is considered when calculating the N_2O flux of the system using the ambient air concentration and flow rate. Porewater samples were collected from the depths of -5, -10, -30, -60, and -90 cm from each lysimeter every week (or less often depending on drainage events) using a suction cup (Meter Legacy SIC20) with a Meter Legacy VS. Pro applying negative pressure. The collected porewater samples ranged in volume from 0 to 25 ml, depending on the soil moisture content. The samples were frozen immediately after collection and transported in a cooler to the laboratory, where they were stored at −20°C prior to chemical analyses (Section 2.3).

A diversified crop rotation (*Glycine* max (soybean), *Triticum aestivum* (winter and spring wheat), then *Zea mays* (corn)) with cover crops was applied to each lysimeter plot starting in 2017, with the rotation of crops planted annually in the spring/summer. The diverse crop rotation began with spring wheat planted and 67 kg Nha^{-1} urea applied on 26 April 2017. After the spring wheat harvest in August 2017, cover crops were planted and 50 kg Nha^{-1} urea was applied. The cover crops consisted of a four-species mixture after winter wheat (*Secale cereale* (cereal rye), *Avena sativa* (oats), *Raphanus sativus* (radish), and *Trifolium incarnatum* (crimson clover)). On 18 May 2018, corn was planted and urea applied at 130 kg Nha^{-1} and in June 2018, corn was interseeded with cover crop (a two-way mixture of rye grass and crimson clover) followed by application of 77 kg Nha^{-1} urea. In 2019, soybean was planted and 15 kg Nha^{-1} fertilizer was applied on 7 June and wheat was planted on 8 October, followed by 89 kg Nha^{-1} urea application on 2 April 2020.

2.3 Porewater geochemistry and analytical techniques

The porewater samples collected from each depth of the four lysimeters were thawed at 4°C for approximately 24 h prior to subsampling for analysis. The samples were filtered through a 0.45 µm pore size membrane filter (polypropylene syringe filters, VWR) into 50 ml centrifuge tubes. Two milliliters of filtered porewater were transferred into 5 ml centrifuge tubes for NH_4^+ analysis, which was performed using a Gallery Discrete Analyzer (±10% error and ±3% precision). Seven milliliters of filtered porewater were acidified with 20 µl 1M hydrochloric acid (HCl) and analyzed for total dissolved nitrogen (TDN) using a total organic carbon (TOC) analyzer (Shimadzu TOC-LCPH/CPN; method detection limit: 6 µM). One milliliter of porewater was further filtered through a 0.2 µm pore size polysulfone membrane filter (Thermo Fischer Scientific) and was analyzed for NO_3^- and NO_2^- using ion chromatography (IC, Dionex ICS-5000 with a capillary IonPac® AS18 column; ± 3.0% error and ±1.6% precision) and all standards were prepared from certified multi-anion standards (Sigma-Aldrich).

2.4 NO_3^- leaching rates

Instantaneous daily NO_3^- leaching rates were calculated for each lysimeter for the days when porewater NO_3^- concentrations at the -90 cm depth were measured. The NO_3^- leaching rate was calculated by taking the daily sum of discharges measured by the drainage tank method and multiplying this daily discharge rate by the NO_3^- concentration at 90 cm measured on that date. Following the formula reported by LaPierre et al. (2022), we calculated NO_3^- leaching rates using:

$$R_{NO_3^- leach} = Discharge \times C_{NO_3^- -90cm} \times 0.01$$

where $R_{NO_3^- leach}$ is the NO_3^- leaching rate in units of mmol NO_3^- d^{-1}, $Discharge$ is the mean discharge measured by the drainage tank method in units of L m^{-2} d^{-1}, $C_{NO_3^- -90cm}$ is the NO_3^-concentration at 90 cm depth in mmol L^{-1}, and 0.01 is a conversion factor to convert the leaching rate from m^{-2} to ha^{-1}.

2.5 Statistical analysis

A *t*-test was used to compare the mean N_2O flux and mean daily discharge between the snow removed treatments (WS and SR) within the soil types (SL and LS) and the three phases (pre-snow, winter with/without snow cover, and spring-thaw). We were unable to use a statistical test to compare the mean NO_3^- leaching rates because of the low number of data points, which was less than 10 within each soil type and period group. The results of the *t*-test are summarized in Table 2.

TABLE 2 *p*-values of one-way *t*-test comparing the mean N_2O flux and mean daily discharge between the snow removal treatments (WS and SR) within the soil types (SL and LS) and the three phases (Pre-Snow, Winter with/without snow cover, and Spring-thaw). Bold values indicated $p \leq 0.05$.

Phase	SL	LS
Discharge *p*-values 2020/2021		
Pre-snow (December 1–January 27)	**<0.01**	**<0.01**
Winter with/without snow cover (January 27–March 3)	**<0.01**	**<0.01**
Spring-thaw phase (March 3–April 30)	**<0.01**	**<0.01**
N_2O flux *p*-values 2020/2021		
Pre-snow (December 1–January 27)	0.81	**<0.01**
Winter with/without snow cover (January 27–March 3)	**<0.01**	**<0.01**
Spring-thaw phase (March 3–April 30)	**<0.01**	**<0.01**

The *t*-test results were considered significant when $p \leq 0.05$. The *t*-test calculations were performed using R 4.1.2 (R Core Team, 2021).

3 Results

We categorized the experimental period into three phases based on the winter snow cover: the pre-snow phase (1 December 2020 to 27 January 2021), the winter with/without snow cover phase (27 January 2021 to 3 March 2021), and the spring-thaw phase (3 March 2021 to 30 April 2021). These three phases are distinguished by shading in all of the time series figures to visualize and highlight the snow cover controls on temperature, moisture, and N species concentrations.

3.1 Soil temperature and moisture dynamics

Changes in soil temperature at different depths within each lysimeter were directly influenced by air temperature and snow removal from the surface of SL-SR and LS-SR (Figure 1). The soil

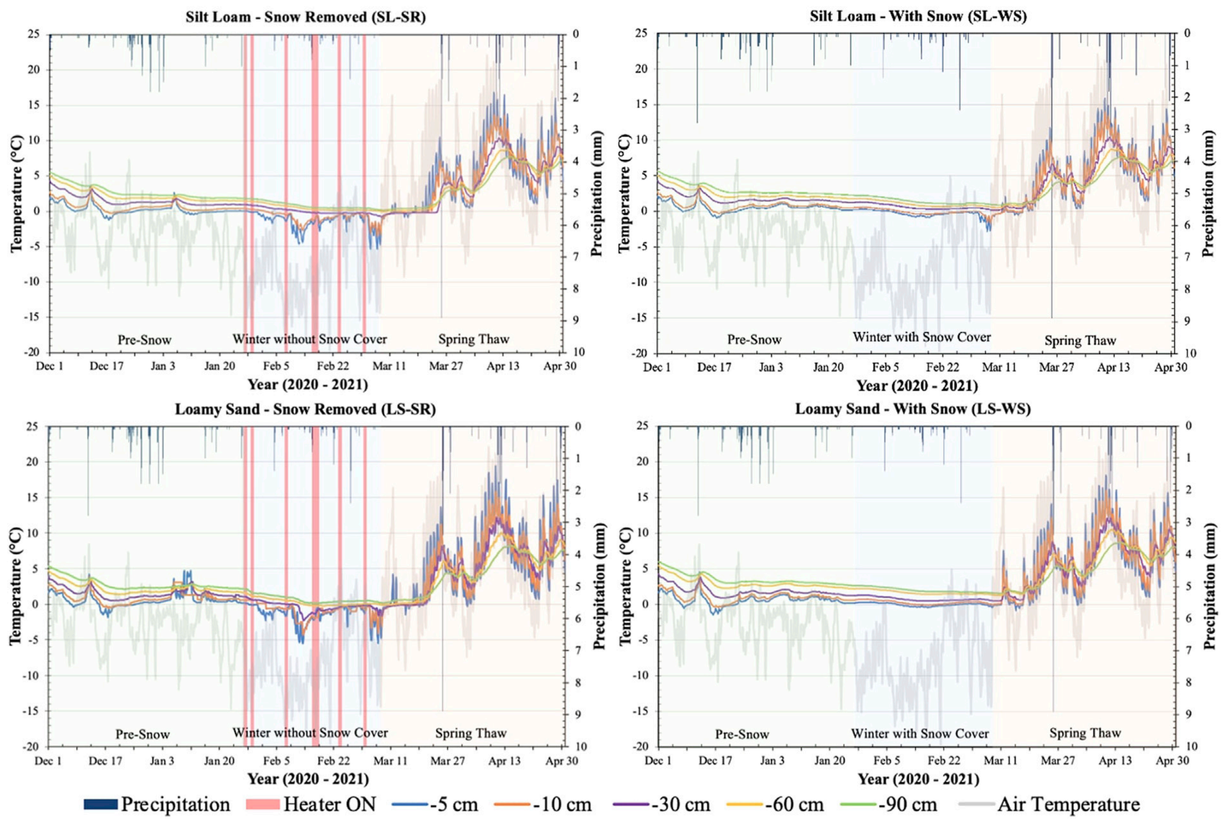

FIGURE 1
Soil temperature (primary *y*-axis) measured at -5, -10, -30, -60, and -90 cm depths in four lysimeters between 1 December 2020, and 30 April 2021. Soil temperature is plotted with air temperature (primary *y*-axis) and precipitation (secondary *y*-axis) recorded from the Environment Canada Elora Weather Station. The graphs for SL-SR and LS-SR also show when the heaters were turned on and off during the winter to melt snow on the lysimeter surface (red bars on winter without snow cover phase). The graphs are divided into three phases, pre-snow, winter with/without snow, and spring-thaw, to determine the patterns of change during each of the experimental phases.

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temperature trends and magnitude during the pre-snow and spring-thaw phases were almost identical in each set of two lysimeters. Throughout the pre-snow phase, soil temperatures increased with increasing depth below the surface for each of the four lysimeters. During the spring-thaw phase, as air temperatures began to increase, the trend was reversed, and soil temperatures decreased with increasing depth. During the winter with/without snow cover phase, SL-SR and LS-SR experienced lower soil temperatures at all soil depths in comparison to SL-WS and LS-WS. SL-SR and LS-SR also had soil temperatures drop to below 0°C at depths of −5, −10, and −30 cm at multiple times over the winter months when air temperatures dropped significantly (−14°C), reaching temperatures of less than −5°C at −5 cm depth (Figure 1). SL-WS and LS-WS also experienced temperatures below 0°C at the −5 and −10 cm depths, however these temperature drops were less pronounced and occurred less frequently. Thus, the pulsed warming applied to SL-SR and LS-SR induced more freeze-thaw cycles than what was experienced by SL-WS and LS-WS.

Soil moisture varied between each of the four lysimeters and was directly influenced by precipitation and snowmelt (see Supplementary Figure S1). TDR sensors only measure liquid water, so a decrease in water content is a sign that water is moving from the liquid to solid phase. Soil moisture generally increased with an increase in depth for all lysimeters due to the drainage of water through the soil column. SL-SR had a constant soil moisture of ~35–38% (fully saturated; total porosity of 35.6 ± 2.90 to 42.3 ± 4.4%) at the -90 cm depth. The 5 and 10 cm depths followed the same patterns in soil moisture during the experiment period, beginning with decreases from ~35% to 18% at 5 cm and 22% at 10 cm depths on 17 December then increase back to ~35%. This was followed by a decrease to 10% at 5 cm and 32% at -10 cm depths on 12 January, an increase to 53% at the beginning of the winter without snow cover phase, and a decrease to 10–18% at -5 cm and 14–21% at -10 cm depths during the winter without snow cover phase, followed by an increase in soil moisture during the spring-thaw phase. SL-WS had a constant soil moisture of ~35% (fully saturated) at the depths of -30, -60, and -90 cm and stayed constant over the experimental period. At -10 cm, soil moisture had fluctuations similar to SL-SR. LS-SR had lower soil moisture compared to SL-WS and SL-SR (total porosity of 35.5 ± 4.1 to 38.3 ± 2.61%). At the -10 and -30 cm depths, the moisture began at 27% and stayed relatively constant during the pre-snow phase (there was a decrease to 10%) then increased around mid-December. Both the -10 and -30 cm depths had a decrease in soil moisture to ~9% during the winter without snow cover phase and then an increase to 29% (with small fluctuations) during the spring-thaw phase. The -60 cm depth remained between 15–26% soil moisture during the pre-snow phase, with a decrease in moisture during the winter without snow cover phase to a minimum value of 12%. At -90 cm, the soil moisture remained between 19–27%, decreased to 20%, and increased to 35% during the pre-snow, winter without snow cover, and spring-thaw phases, respectively. In LS-SR, the moisture content at -60 cm was notably lower than the moisture at -10 and -30 cm. Increased silt and clay content at -10 and -30 cm could have promoted water retention at those depths, thereby reducing the soil moisture measured at -60 cm. The moisture levels at -60 cm increased to levels above the values observed at -10 and -30 cm in LS-SR after the spring-thaw due to the drainage of porewater as it melted. LS-WS had relatively constant soil moistures at -5 and -10 cm depths, remaining between 6–28% with fluctuations during the experiment period. The soil moisture at -90 cm remained between 16–20% before increasing during the spring-thaw to a maximum value of 32%.

3.2 Trends in dissolved nitrogen species

Porewater NO_3^- concentrations in all four lysimeters remained relatively low and constant during the pre-snow and winter with/without snow cover phases and increased with the spring-thaw (Figure 2). For the lysimeters containing silt loam (SL-SR and SL-WS), NO_3^- concentrations at the depths of -5 and -10 cm were relatively low (0–0.2 mmol L^{-1}) and increased during the spring-thaw phase to concentrations of ~1.0 and 0.6 mmol L^{-1} at -5 cm and -10 cm depths, respectively, in SL-SR, and to a concentration of ~0.7 mmol L^{-1} at both the -5 cm and -10 cm depths in SL-WS. SL-WS also had an increase in NO_3^- concentration at the -30 cm depth at the beginning of the spring-thaw phase and the concentrations at -5, -10, and -30 cm depths decreased in the mid spring-thaw phase. The remaining depths (-60 and -90 cm) contained low and constant NO_3^- concentrations throughout the experimental period, with only small fluctuations. LS-SR and LS-WS had much lower NO_3^- concentrations and remained relatively low and close to zero during the pre-snow and winter with/without snow cover at all depths, with a small increase to a maximum value of 0.1–0.25 mmol L^{-1} at -30, -60, and -90 cm depths in LS-SR during the spring-thaw phase.

Porewater TDN trends during the three phases in the lysimeters and the response to with/without snow cover conditions showed similar patterns as NO_3^- (Supplementary Figure S2). The NH_4^+ concentrations at all depths in the four lysimeters remained relatively constant with concentrations ranging between ~0.5–16 μmol L^{-1}, except the -30 cm depth in LS-SR experienced an increase in concentration during the spring-thaw phase to a maximum value of 54 μmol L^{-1} and then decreased to the low concentration range observed at other depths (Figure 3). The NO_2^- concentration in all lysimeters remained relatively low and below the detection limit throughout each phase. An increase in NO_2^- concentration was also observed at -30 cm in LS-SR during the spring-thaw (Supplementary Figure S3).

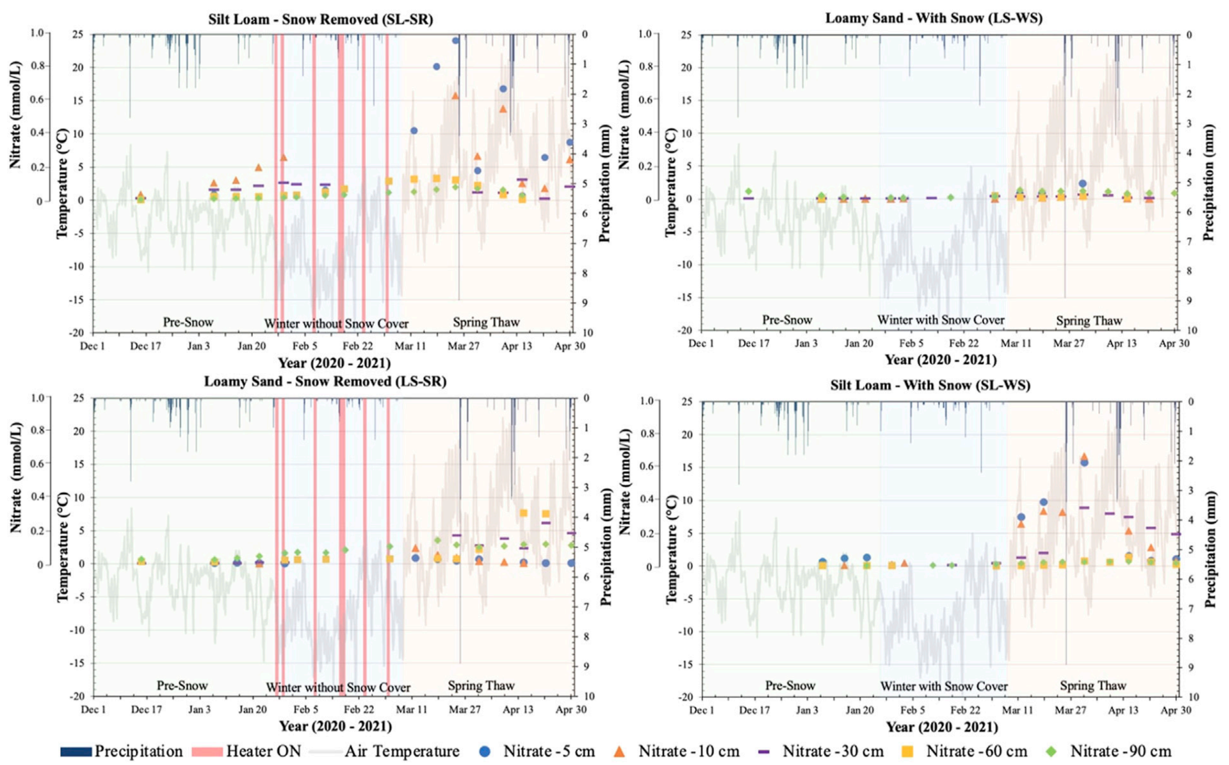

FIGURE 2
Porewater nitrate (NO_3^-) concentration (tertiary *y*-axis) measured at -5, -10, -30, -60, and -90 cm depths in four lysimeters between 1 December 2020, and 30 April 2021. NO_3^- concentration is plotted with air temperature (primary *y*-axis) and precipitation (secondary *y*-axis) recorded from the Environment Canada Elora Weather Station. The graphs for SL-SR and LS-SR also show when the heaters were turned on and off during the winter to melt snow on the lysimeter surface (red bars on winter without snow cover phase). The graphs are divided into three phases, pre-snow, winter with/without snow, and spring-thaw, to determine the patterns of change during each of the experimental phases.

3.3 N_2O fluxes

N_2O fluxes were measured throughout the experiment period with a baseline of approximately 0 mmol m^{-2} day^{-1}. SL-SR and SL-WS had low N_2O fluxes of 0.09 and 0.13 mmol m^{-2} day^{-1}, respectively, in the pre-snow phase after the first freeze and thaw cycle at the depths of -5 and -10 cm (Figure 4). There were also low N_2O fluxes (~0.21 and 0.1 mmol m^{-2} day^{-1}, respectively) in mid-February when the -5 and -10 cm soil depths froze. When the soil thawed in mid-March (spring-thaw phase), there was a large flux of N_2O up to maximum of 1.6 and 0.5 mmol m^{-2} day^{-1} in SL-SR and SL-WS, respectively. LS-SR had N_2O fluxes throughout the pre-snow and winter without snow cover phases, with a maximum value of ~0.2 mmol m^{-2} day^{-1} followed by lower fluxes of ~0.1 mmol m^{-2} day^{-1} after the soil thawed in the spring. LS-WS experienced the same pattern of N_2O fluxes throughout the experimental period; however, the pre-snow and winter with snow phase fluxes reached a maximum value of 0.1 mmol m^{-2} day^{-1} and the spring-thaw fluxes were ~0.4 mmol m^{-2} day^{-1}.

3.4 Discharge rates, NO_3^- leaching rates, and N_2O fluxes

We visualized the distributions of the discharge rates, NO_3^- leaching rates, and N_2O fluxes in all four lysimeters for each of the three seasonal periods using boxplots (Figures 5, 6). In lysimeters containing silt loam (SL-SR and SL-WS), snow removal resulted in high N_2O fluxes in the winter and spring-thaw phases, low NO_3^- leaching rates and discharge rates in the winter phase, and high NO_3^- leaching rates and discharge rates in the spring-thaw phase (Figure 5). In lysimeters containing loamy sand (LS-SR and LS-WS), snow removal resulted in low N_2O fluxes and high NO_3^- leaching rates in the winter and spring-thaw phases, high discharge rates in the winter phase, and low discharge rates in the spring-thaw phase. The results of the t-tests indicate that all differences in the discharge rates and N_2O fluxes between the SR and WS lysimeters were significant ($p \leq 0.05$) in the winter with/without snow cover and spring-thaw phases (Table 2).

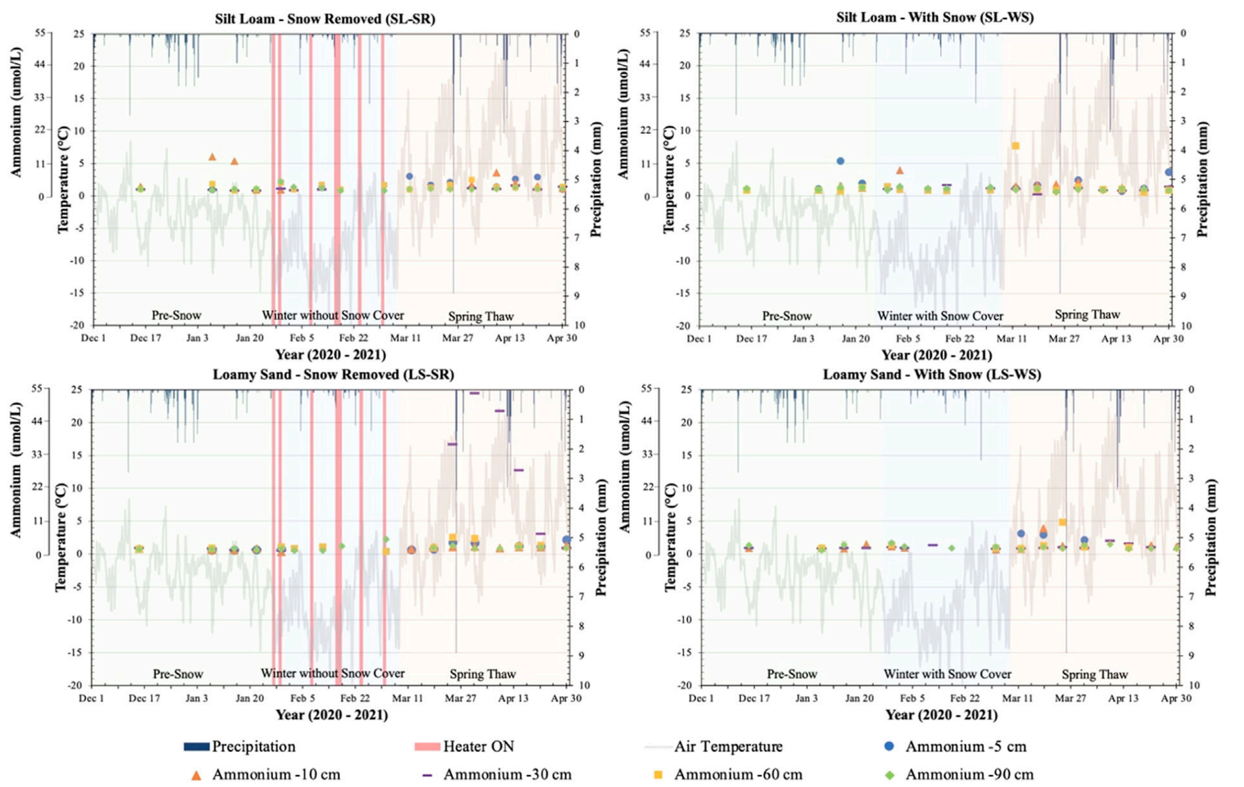

FIGURE 3
Porewater ammonium (NH_4^+) concentration (tertiary *y*-axis) measured at -5, -10, -30, -60, and -90 cm depths in four lysimeters between 1 December 2020 and 30 April 2021. NH_4^+ concentration is plotted with air temperature (primary *y*-axis) and precipitation (secondary *y*-axis) recorded from the Environment Canada Elora Weather Station. The graphs for SL-SR and LS-SR also show when the heaters were turned on and off during the winter to melt snow on the lysimeter surface (red bars on winter without snow cover phase). The graphs are divided into three phases, pre-snow, winter with/without snow, and spring-thaw, to determine the patterns of change during each of the experimental phases.

4 Discussion

4.1 Soil texture controls on temperature, moisture, and N dynamics

Our results showed that soil type (*i.e.,* the differences in texture and mineral particle size) influenced soil temperature and moisture, dissolved N species concentrations, discharge, NO_3^- leaching rates, and N_2O fluxes in the lysimeters. Soil moisture and temperature in SL-SR and SL-WS (silt loam) showed greater variability in comparison to the moisture and temperature levels of LS-SR and LS-WS (loamy sand) (see Figure 1 and Supplementary Figure S1), which can be attributed to differences in the physical and hydraulic properties of the soil in each lysimeter. SL-SR and SL-WS contain silt loam that consists of 42.5 ± 5.1% sand, 46.9 ± 8.2% silt, and 10.6 ± 3.4% clay (Table 1). LS-SR and LS-WS contain loamy sand which consists of 82.3 ± 4.2% sand, 14.2 ± 3.9% silt, and 3.5 ± 0.9% clay (Table 1). The loamy sand lysimeters had coarser texture and larger pores, lower water retention capacity, higher hydraulic conductivity, and higher levels of leaching in comparison to the silt loam lysimeters. During the winter with/without snow cover phase, the porewater froze as the soil temperatures fell below 0°C, which resulted in stable soil moisture levels until the thaw occurred and precipitation events led to an increase in soil moisture.

The silt loam has a higher ability to hold water and therefore also the nutrients dissolved in the water, which explains in part the higher NO_3^- concentrations in the lysimeters containing silt loam compared to the more permeable loamy sand lysimeters (Figure 2). The silt loam soil likely has a higher sorption capacity for NH_4^+ due to its higher clay content (10.6% vs. 3.5% in the loamy sand; Table 1) (Jarecki et al., 2008; Cambouris et al., 2016). Although we did not measure the NH_4^+ sorption capacity of the two soils, this higher clay content and presumed higher NH_4^+ sorption capacity likely drove the higher N_2O fluxes observed in the silt loam compared to the loamy sand for the lysimeters with the same snow cover treatments and within the same seasonal periods. The higher total organic C content, which likely also resulted in higher dissolved organic C concentrations in the soil

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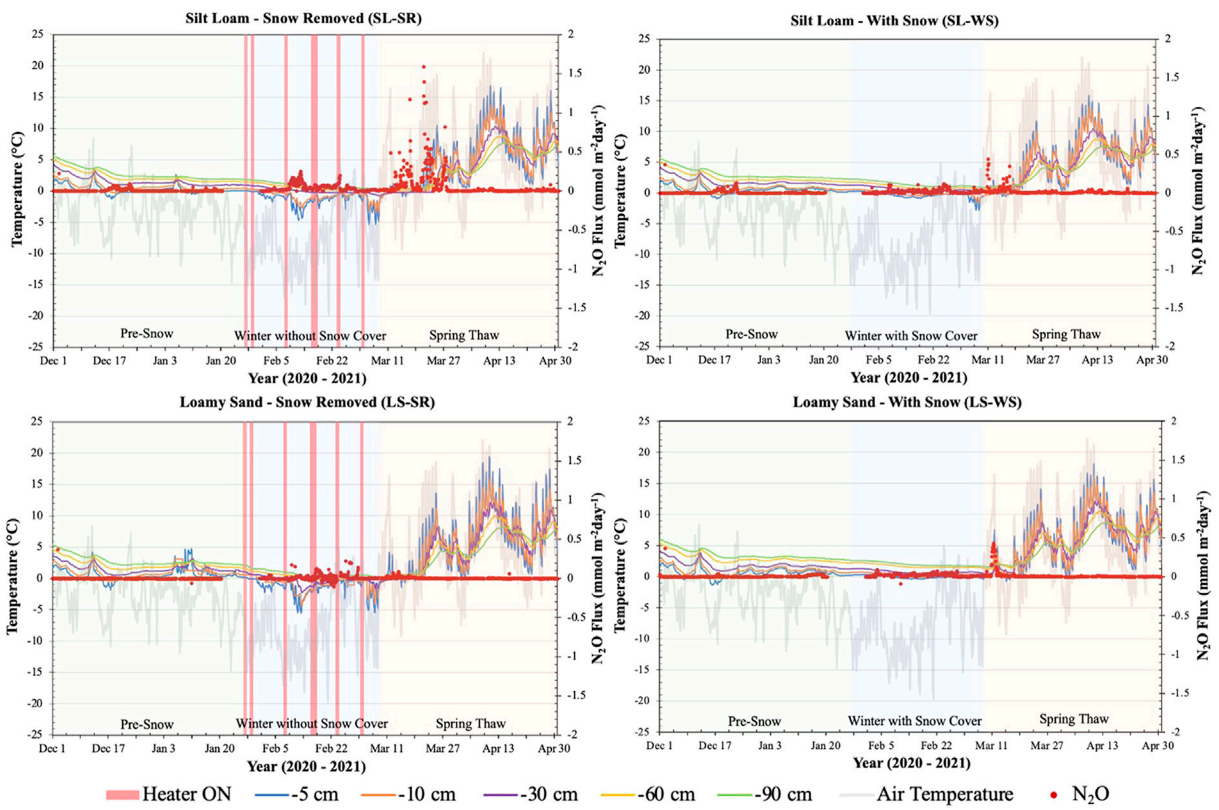

FIGURE 4
Nitrous oxide (N_2O) fluxes (secondary *y*-axis) measured at the soil surface in four lysimeters between 1 December 2020, and 30 April 2021. N_2O fluxes are plotted with soil temperature at -5, -10, -30, -60–90 cm depths and air temperature recorded from the Environment Canada Elora Weather Station. The graphs SL-SR and LS-SR also show when the heaters were turned on and off during the winter to melt snow on the lysimeter surface (red bars on winter without snow cover phase). The graphs are divided into three phases, pre-snow, winter with/without snow, and spring-thaw, to determine the patterns of change during each of the experimental phases.

porewater, in the SL *versus* LS soils may have also contributed to the higher N_2O fluxes observed, given that dissolved organic C is the main electron donor used for N_2O production *via* denitrification (*i.e.,* the reduction of NO_3^- and NO_2^-) (Li Y. et al., 2021). Another explanation for the lower N_2O fluxes observed in the loamy sand could be the larger pore spaces, higher aeration rates, and thus higher O_2 concentrations in the soil pore spaces compared to the silt loam (Osman, 2013), which would in turn decrease denitrification, contributing to less N_2O production (Kasimir-Klemedtsson et al., 1997; Song et al., 2019).

4.2 Snow cover controls on soil temperature, moisture, and N dynamics

Snow cover influences the soil temperature and moisture content which, in turn, affects microbial activity and the production, speciation, and transport of key bioactive elements, including N, in agricultural soils. The pulsed warming events imposed during the winter phase in both snow removed lysimeters (SL-SR and LS-SR) exposed the upper soil layer to relatively warmer temperatures (remaining below 0°C) during the pulsed warming events and lower freezing temperatures (below 0°C) after the warming pulses (Figure 1). In contrast, the observed soil temperatures at 5 and 10 cm in the lysimeters with snow (SL-WS and LS-WS) indicated that, as expected, the snow cover had an insulating effect which prevented temperature fluctuations and FTCs (Ruan and Robertson, 2017).

The formation of ice cover on the soil surface and the freezing and thawing of porewater also resulted in a gradual decrease of soil moisture at the -5 and -10 cm depths during the winter in the snow removed lysimeters (SL-SR and LS-SR) (Supplementary Figure S1). In the lysimeters with snow cover (SL-WS and LS-WS), the soil moisture was relatively constant during the winter phase (Supplementary Figure S1). The decrease in soil moisture in the loamy sand snow removed lysimeter (LS-SR) over the winter was matched by higher discharge compared to its counterpart loamy sand with snow cover lysimeter (LS-WS) (Figures 5, 6).

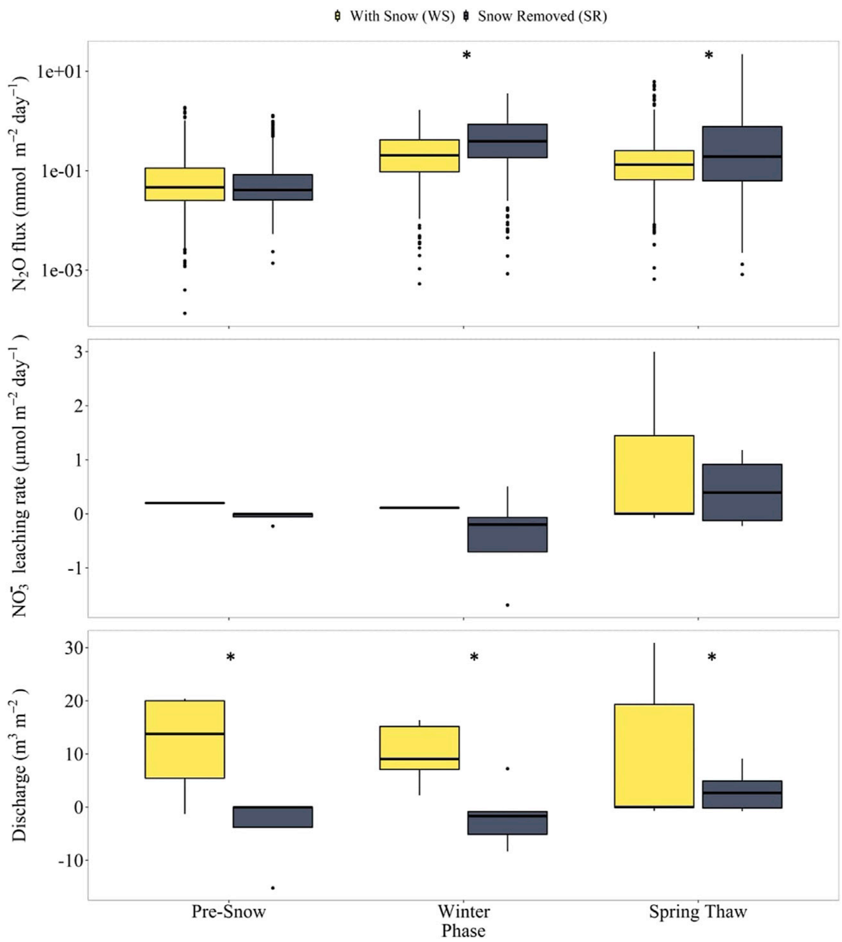

FIGURE 5
Box plots of N_2O fluxes (top panels), NO_3^- leaching rates (middle panels), and discharge rates (bottom panels) in silt loam lysimeters SL-SR and SL-WS during the pre-snow, winter with/without snow, and spring-thaw phases. The *y*-axis for the N_2O fluxes is a log-axis (top panel only). An * above the boxplots signifies median values that are statistically significant between the SR and WS lysimeters. Values are statistically significant when $p \le 0.05$.

Snow cover and its effect on the number of over-winter FTCs had a clear impact on dissolved NO_3^- concentrations in the lysimeters. In the two snow removed lysimeters (SL-SR and LS-SR), the FTCs at the soil surface were accompanied by higher increases in NO_3^- concentrations with the start of the spring-thaw compared to the lysimeters with snow cover (SL-WS and LS-WS), likely explaining the higher N_2O fluxes in snow removed lysimeters (Figure 2). A likely explanation for the higher NO_3^- concentrations is that the FTCs caused the physical disruption of soil aggregates, microbial cells, and/or fine roots, which increases the availability of labile dissolved organic N, including osmolytes, and NH_4^+ to the soil microbial community, which are then transformed to NO_3^- (Risk et al., 2013; King et al., 2021). In contrast, the insulating effect of the snow cover and lack of pulsed warming events in SL-WS and LS-WS reduced the FTCs that the upper soil layer experienced, and therefore lower dissolved N concentrations were observed over-winter.

In the silt loam (SL-SR and SL-WS) lysimeters, the increase in porewater NO_3^- concentrations and N_2O fluxes in the snow removed (SL-SR and LS-SR) *versus* with snow (SL-WS and LS-WS) treatments, likely driven by the increased number of FTCs, was not only restricted to the winter season, as the effect was also seen throughout the spring thaw period (Figures 2, 4). This indicates that the physical, and by extension chemical, modification of the stability of soil aggregates by FTCs in the winter impacts soil C and N availability in the spring thaw period, which has also been observed by others (Dietzel et al., 2011; Risk et al., 2013). In contrast, in the loamy sand (LS-WS and LS-SR) lysimeters, the effect of the increased number of FTCs was not observed during the spring thaw period. The continued effect of the snow removal into the spring thaw in the silt loam but not the loamy sand lysimeters is

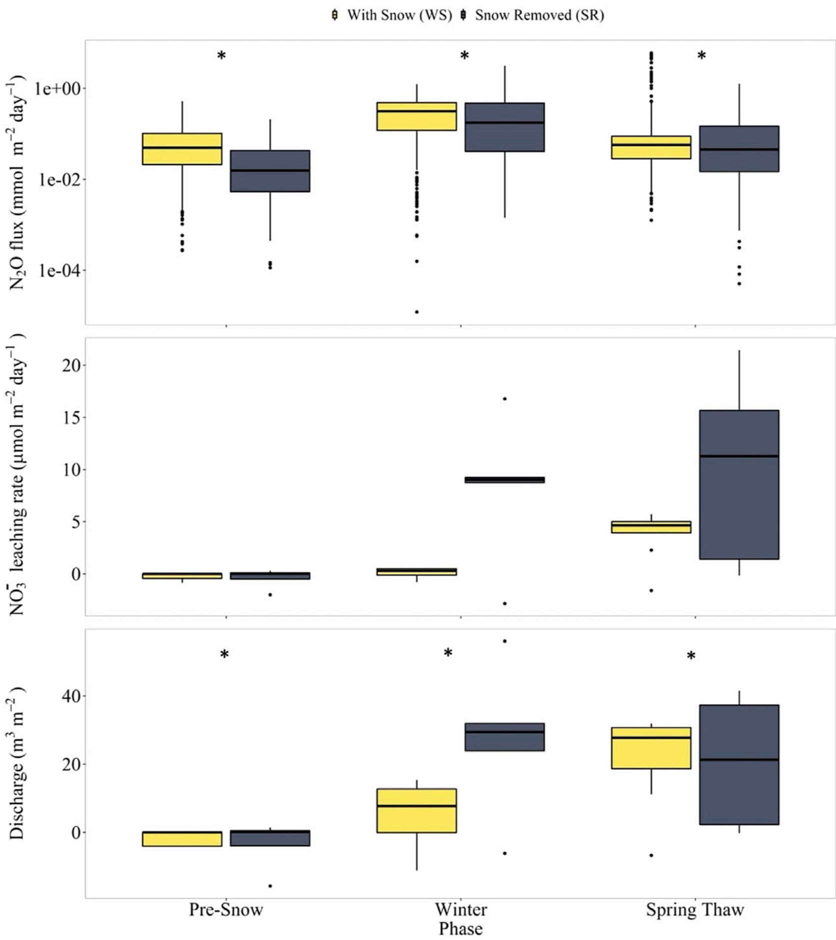

FIGURE 6
Box plots of N_2O fluxes (top panels), NO_3^- leaching rates (middle panels), and discharge rates (bottom panels) in loamy sand lysimeters LS-SR and LS-WS during the pre-snow, winter with/without snow, and spring-thaw phases. The *y*-axis for the N_2O fluxes is a log-axis (top panel only). An * above the boxplots signifies median values that are statistically significant between the SR and WS lysimeters. Values are statistically significant when $p \leq 0.05$.

likely due to the higher soil organic C, and therefore also soil organic matter-containing aggregate, content of the silt loam soil (Table 1). Thus, in more clay and silt-rich soils like the silt loam soil studied here, the prior winter conditions need to be considered when looking to predict soil C and N availability and N_2O fluxes during the spring and summer growing season.

4.3 Snow removal had contrasting impact on N loss route in silt loam *versus* loamy sand

In the silt loam lysimeters, the higher median winter N_2O fluxes observed in the snow removed (SL-SR) compared to the with snow (SL-WS) lysimeters can be largely attributed to the higher number of FTC events and *de novo* N_2O production during the thawing period of the FTC events (Congreves et al., 2018; Risk et al., 2014; Brin et al., 2018). This interpretation is supported by the higher observed NO_3^- concentrations in the snow removed treatment, given that microbial NO_3^- reduction can produce N_2O *via* incomplete denitrification.

In the loamy sand lysimeters, the effect of snow removal on winter N_2O fluxes was opposite to that of the silt loam lysimeters; the snow removed lysimeter had lower median winter N_2O fluxes. However, the over-winter water discharge and NO_3^- leaching rates were higher in the snow removed lysimeter (SL-SR) than in the with snow lysimeter (SL-WS) for the loamy sand. Thus, in the loamy sand lysimeter, FTCs suppressed winter N_2O emissions but enhanced winter NO_3^- leaching. For both the loamy sand and silt loam lysimeters, the effect of snow removal and increased FTCs was more N lost from the lysimeters over the winter. In the loamy sand, the N was lost to leaching, while in the silt loam, the N was lost as gaseous N_2O emissions. This different effect of the FTCs on the N loss route in the loamy sand *versus* the silt loam was consistent with the lower water retention capacity and higher hydraulic conductivity of the loamy sand. In the loamy sand, warming pulses increased soil temperatures, which led to higher water and solute transport rates relative to the with snow cover scenario, where soil was insulated from air temperature, which is consistent with the results of Kieta and Owens (2019). NO_3^- is particularly prone to leaching due to charge repulsion between its intrinsic negative charge and the prevalence of negatively charged soil particles (Di and Cameron, 2002). The dissolved N produced by FTC-induced processes was thus carried with the water and lost *via* leaching. In the silt loam system, the higher water retention capacity meant that dissolved N produced by FTC-induced processes had a longer residence time in the soil porewater spaces, where it could be used by the microbial community in denitrification and/or nitrification reactions, which produce N_2O. Furthermore, high water retention capacity also leads to less O_2 diffusion into the soil and a high abundance of anoxic pore spaces and microsites in silt loam soil due to its high clay content, which favours denitrification, and potentially N_2O production by incomplete denitrification (Groffman and Tiedje, 1988; Harrison-Kirk et al., 2013).

Overall, the winter pulsed warming and increase in FTCs enhanced N loss from the soil by releasing more dissolved N *via* freezing-induced processes from the soil N compartments that would have otherwise retained N (e.g., plant roots, microbial biomass and/or soil aggregates). As a result of enhanced dissolved N release, there was enhanced N loss from the soil *via* two potential routes: leaching to groundwater and/or loss as gaseous N_2 and N_2O. Here, we focused our analysis on N loss *via* N_2O fluxes, given that N_2O is a significant greenhouse gas. The dominant N loss route in the silt loam in the snow removed scenario was as N_2O, while the dominant N loss route in the loamy sand was NO_3^- leaching. The contrasting effect of winter pulsed warming-induced FTCs on N_2O fluxes and NO_3^- leaching rates in the two different soil types is interesting and will need to be considered in field-scale N cycling models which aim to predict N loss routes and rates from cropped fields (*e.g.,* Ingraham and Salas, 2019). Both loss routes have important implications for society and the environment; N loss to groundwater can have negative impacts on downstream streams and lakes that receive groundwater discharge, and/or the NO_3^- can accumulate in groundwater as legacy N (Van Meter et al., 2016), while N loss as N_2O increases the burden of N_2O in the atmosphere, which enhances the greenhouse effect.

5 Summary and conclusion

In this study, we simulated the impact of climate change warming-induced snow cover reduction on soil N cycling in cold region agroecosystems using experimental lysimeter systems. We compared the effect of snow removal *versus* snow cover and the effect of soil type, as well as their interactions, on soil surface N_2O fluxes, soil porewater N species concentrations with depth in the soil profile, soil temperature, soil moisture, water discharge, and NO_3^- leaching rates to assess the interactive impacts of snow cover and soil type on soil N cycling. Our results show that N losses from the lysimeter systems were higher in the treatments where snow was removed because there were more freeze-thaw cycles, which caused dissolved N release from soil N pools and subsequent loss of dissolved (NO_3^-) or gaseous (N_2O) N species from the systems. In the silt loam system, this released dissolved N was subsequently lost from the system as N_2O, while in the loamy sand system, the dissolved N was lost *via* NO_3^- leaching. In the silt loam, we attribute the freeze thaw-enhanced N_2O fluxes to *de novo* processes rather than gas build up and release based on the experimental design and the frequency of freeze-thaw events induced. These contrasting N loss routes by the different soil types highlight the importance of considering soil type in field-scale models of N cycling. Overall, our results show that the increased number of freeze-thaw cycles expected in cold temperature agricultural soils because of climate change and reduced snow cover will enhance N loss from soils by some combination of enhanced NO_3^- leaching to groundwater and enhanced N_2O emissions.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://doi.org/10.20383/103.0637 Federated Research Data Repository.

Author contributions

CW, HH, and FR designed the lysimeter winter pulsed warming experiment. SJ carried out the field monitoring and porewater and gas sampling. DG performed the sample and data analyses and prepared the manuscript. SS helped with leaching rate calculations and figures preparation. PVC and FR supervised the data analyses and helped DG to interpret the data. All authors contributed to the preparation of the manuscript and have approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1020099/full#supplementary-material

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